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Towards a local learning (innovation) model of solar photovoltaic deployment

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Abstract

It is by now familiar that in the deployment of solar photovoltaic (PV) systems, the cost dynamics of major system component like solar cell/module is subjected to experience curve effects driven by production learning and research and development at the supplier side. What is less clear, however, is the economics of system integration or system deployment that takes place locally close to the user, involving other market players, in the downstream solar PV value chain. Experts have agreed that suppliers of solar PV system must *customize* their flexible characteristics to address local unique users' and applications requirements and compete on price/performance basis. A lack of understanding of the drivers of the economics of system customization therefore is a deficiency in our understanding of the overall economics of this renewable energy technology option.

We studied the non-module BOS cost for grid-connected small PV system using the experience curve framework. Preliminary analysis of PV statistics of the US from IEA seems to suggest that learning in one application type is taking place with respect to the *cumulative installation among all types of grid-connected small PV projects*. The effectiveness of this learning is also improving over time.

A novel aspect is the interpretation of such experience curve effect or learning pattern. We draw upon the notion of *product platform* in the industrial management literature and consider different types of local small-scale grid-tied PV customization projects as adapting a standard platform to different idiosyncratic and local application requirements. Economics of system customization, which is user-oriented, involves then a refined notion of *inter-projects* learning, rather than volume-driven learning by doing.

We formalized such inter-projects learning as a dynamic economy of scope, which can potentially be leveraged to manage the local and downstream aspect of PV deployment. This dynamic economy may serve as a focus of *energy policy* having implications on standardization of design and training for installation, facilitating knowledge reuse among different integration projects and enabling inter-projects learning.

Keywords: Downstream PV deployment; Product platform; Economy of customization

1. Introduction

As energy resources and global environment issues are emerging domestically and aboard, the importance of carbon-saving renewable energy such as solar photovoltaic (PV) is ever increasing. Yet, introduction of renewable energy such as solar PV to replace or reduce existing fossil fuel energy regime faces different types of barriers (Beck and Martinot, 2004), and the first and foremost of these is the higher production and transaction costs of renewable energy compared with existing fossil fuel-based incumbents.

The cost barriers arise due to the discrete and decentralized nature of renewable energy projects. A fundamental challenge is that the deployment of solar PV is different from centralized generation based on the fossil fuels. While some have promulgated deployment of solar PV should take the product path rather than the power plant path (REPP, 1998), PV projects are by nature customization oriented as system integration and installation remains site and applications driven. This somewhat

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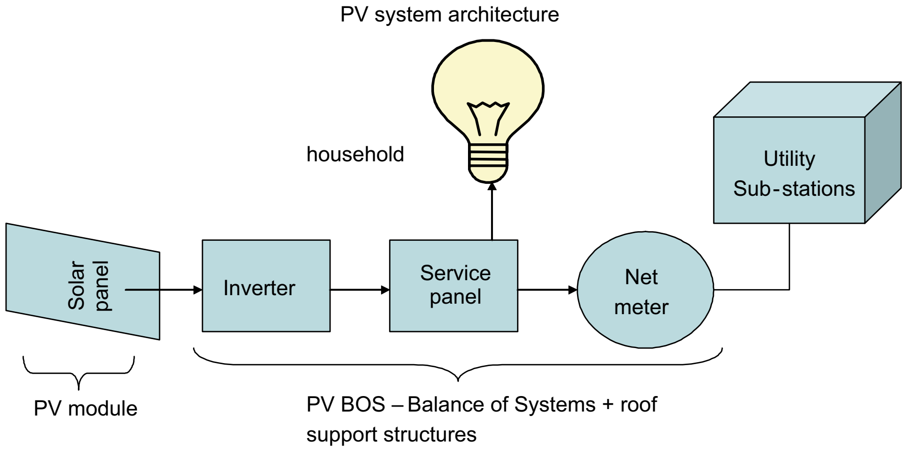

Fig. 1. A simplified grid-tied small PV system (~3–5 kW) schematics.

makes a "standardized" product path embodied mass production type of regime less applicable; in addition, as the scale of a solar PV project is usually much smaller than a centralized fossil fuel generation plant, scale-based advantages in construction, project administration and others will also be negligible. Neither the economy of production associated with product nor plant is applicable to small-scale grid-tied PV systems.

The challenge of deployment of solar PV, or for that matter, any type of small-scale distribution energy projects utilizing local renewable resources close to users, is therefore how to create an economy of customization complementing the economy of factory production of the more standardized constituent components within a solar PV system.

This paper proposes a platform-based customization framework to address this issue. A [product] platform (McGrath, 2001), by itself, is not a product. It is a collection of the common elements, especially the underlying defining technologies, implemented across a range of projects or products. In general, a platform is the lowest common denominator of relevant technologies in a set of products or customization projects. Customization based on a platform strives to minimize the dis-economy of the one-off nature of many smaller-scale renewable energy projects, especially when there are mechanisms to share and re-use knowledge gained from different project and application contexts. Economy of platform-based customization or system integration during deployment at user side can potentially serve as a counterpart to economy of mass production of many of the components within a solar PV system at the supplier side.

The rest of the paper is organized as follows: Section 2 reviews existing studies on cost dynamics of small-scale grid-tied PV residential system; Section 3 reviews the innovation literature at-large to position the platform-based customization framework; Section 4 illustrates our framework by an empirical analysis of the non-module BOS or system integration cost learning for the small-scale grid-tied PV residential system in the US using the experience curve framework; Section 5 suggests policy implications of our proposed economic model. Section 6 summarizes.

2. Existing studies on cost dynamics of PV systems

A typical grid-tied small-scale solar PV system with a generation capacity of a few kW consists of the PV modules and the so-called balance of system (BOS) as shown in Fig. 1. It is the prime subject of this paper as it is neither a completely standardized product/appliance nor a project that needs to be totally customized. The economy of such a system is intermediate between standardization due to commodity components and customization due to site-specific conditions.

BOS is equipment that is needed to integrate the modules and convert the direct current from solar module to alternating current for either consumption in the user's system or feeding into the local distribution grid. BOS contains different components for different categories of applications. The cost of BOS and installation of the modules are the major cost drivers of a PV system and these two are of the same order of magnitude (Fig. 2). The PV modules remain a significant proportion of system prices (generally about 50–60% for grid-connected systems IEA 2004)[1] and, compared with 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. The learning patterns and mechanisms for these two cost drivers are therefore expected to be different as well.

2.1. Existing studies on PV modules cost dynamics [2]

Research and development (R&D) plus actual experimentation (technological learning) or learning by doing are

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[1] For comparison, for the installation of wind farm, 65–85% of total costs are based on turbine cost, the remaining parts consist of foundation, grid-connection and project management.

[2] In this section, PV means PV cell or module.

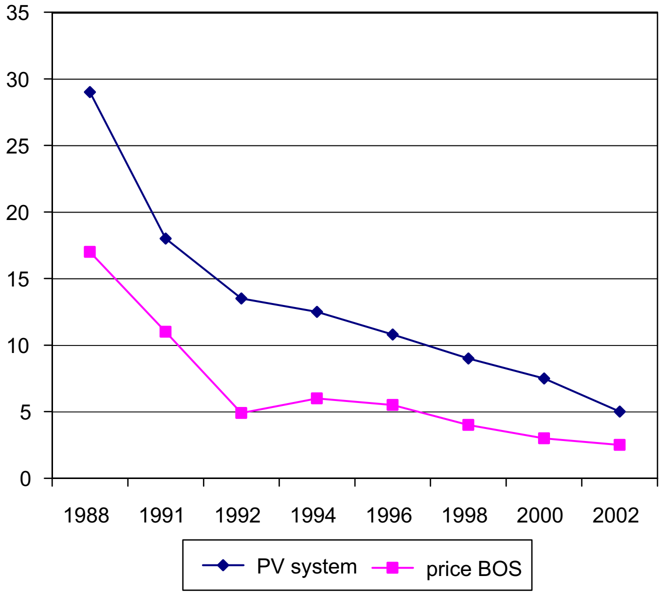

Fig. 2. A typical structural breakdown of cost in a small grid-connected solar photovoltaic systems (Schaeffer and De Moor, 2004) depicting also the learning dynamics of constituents. *The unit on the vertical axis being price* (*€-2000/Wp*).

the 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. It has been empirically demonstrated that there is a 36% reduction in PV cost per each doubling of cumulative production (Watanabe, 1995). 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 cumulative production experience), there is a 54% drop in PV costs per doubling of cumulative expenditures. In other words, the cost learning for PV module can be conceptualized as driven by production learning and technological stock of R&D. A quantitative model of such combined learning has also been demonstrated using a multi-factors learning model (Nagamatsu et al., 2006).

This learning effect can be summarized at a more aggregated level in terms of the experience curve (Wene, 2000), which provides a rational and systematic[3] methodology to describe the historical development and performance of technologies. The most important implication of experience curve, from a policy point of view, is that of the notion of *learning investment* (Wene, 2003), which is the financial resource necessary for the new technology to ride down the experience curve and which will bring its cost to a suitably defined breakeven or target point. Learning investment is expected to become the dominant resource[4] for technology development in later stages or in market transformation program, the objectives of which are to overcome cost barriers and make technology affordable and commercialized.

The above discussion of learning at PV module level makes no distinction between global and local learning. Since most of the module manufacturing is done by internationally operating companies and there is extensive exchange of scientific and technological information on module technology, it is expected that there will be knowledge spillover in research and development, despite the fact that spillover may be incomplete as knowledge may be sticky.

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 0% and 40% of their local demand). This suggests that PV module production learning will also spillover among countries. Statistics also show that there are now a number of examples of imported modules selling for considerably less than the local production. This suggests that while production learning may be local and that companies may have different costs, there will be one worldwide or global price[5] for module and which is outside the control of local (country) PV program (Wiser et al., 2007).

Since solar photovoltaic is a system consisting of several components, it may be necessary to look at the learning system as a compound system consisting of two or more learning subsystems (Wene, 2000). The learning curve for the larger system depends on the curves for the subsystems it contains. While we have concerned about the learning for a PV module in this section, we will next turn to discuss learning for the BOS aspect. As we will argue, BOS learning is mostly local in nature, rather than the relatively global nature of that of module.

2.2. 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. It 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. It also involves support structures and all the

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[3] See, however, Section 2.3 on some of the dissenting opinions of experience curve.

[4] In this vein, an obvious issue is who is to provide such financial resource for a new energy technology. Learning investments are primarily provided through market mechanisms, and they always involve commercial actors on the market. There may be overlap between learning investments and government expenditures for research, development and demonstration. A more refined issue is the relative roles of government and market should play in the deployment end of the innovation chain for new energy technology.

[5] We are very grateful for an anonymous reviewer for suggesting to us to clarify the difference between global price and local cost.

cost of labor involved in system installation. BOS cost discussed in this paper subsumes all these components, it is similar in definition to that of non-module cost in (Wiser et al., 2007) and that of system cost of Maycock and Bower (2004).

The cost learning of BOS has not been studied as widely as the cost learning of PV cells or modules. For grid-connected residential systems, Schaeffer (2003) found that the BOS experience curve is sustaining a progress ratio of 0.78 during 1992–2000. However, unlike PV module learning, which is 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. Cost learning in these components is exhausted except for that due to discrete technological innovation, which results in discontinuous reduction in cost rather than experience effects.

Therefore, BOS learning can mostly be attributed to cumulative experience of system design, integration and installation attained through greater system integration and a reduction in the number of BOS parts. According to Harmon (2000), this system-oriented learning is equal to or even greater than that of modules. This is reinforced by a recent study from Wiser et al. (2007, p. 76) that the learning in non-module cost (BOS cost) for customer-sited PV system in the California Energy Commission rebate program largely accounts for the reduction in average pre-rebate installed costs over time. It is therefore reasonable to assert that the system-oriented learning in non-module cost or BOS cost, rather than the negligible learning in the individual component making up the BOS, largely drives the cost learning in the overall PV system.[6]

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 characterization of BOS learning being: is it *local or global* in character? Inverter part is partially an international market as several manufacturers deliver inverters to several leading user countries. On the other hand, there are substantial differences in national standards for dealing with islanding and connectors. There are also differences in building norms, practices and regulations. All these result in non-ideal and less than perfect system engineering knowledge spillover effects among countries (Beise, 2004) or even applications categories (Schaeffer, 2003), complicated by individual users' requirements. As a result, the locus of cost learning of BOS is local or even application driven. This in turn may be facilitated by standardization or the emergence of a dominant design architecture, which influences system design, planning and grid interfacing (ADL, 1999) in local or application-driven context and which will greatly improve the focus of continual process (system integrating) innovation and learning (Abernathy et al., 1975).

Another way to understand the differences in cost learning between the module subsystem and BOS subsystem is in terms of differences in the extent of users' participation (Table 1). The production of module is basically dominated by module manufacturers with minimal participation of the users. In this regime, production scale, learning by doing, research and development, production yield become the primary concerns in cost learning. As discussed above, BOS subsystem learning is driven by experiences in system design and integration, project management or an outright reduction of BOS component counts. Design, planning and integrating an actual working system involves other market players and users or in general needs interaction with local institutions (Nagamatsu et al., 2006; Shum and Watanabe, 2007a, b). The BOS subsystem cost learning will take place along the rest of the solar photovoltaic supply chain rather than in the confines of a factory. This is further complicated by the fact that a successful strategy for solar photovoltaic needs to capitalize on leveraging its unique characteristics of modularity and value proposition to address unique site conditions and application requirements at the users' side in terms of BOS engineering.

The economics of deployment of solar photovoltaic, in terms of cost learning of the BOS subsystem, must therefore overcome the diseconomy of users' customization requirements and transactional inefficiencies in the

Table 1
Comparison and contrast of learning characteristics of major subsystems (Wene, 2000) in a solar photovoltaic system

	Module subsystem	BOS subsystem (system integration)
Locale of learning	Upstream in factory	Downstream along rest of value chain and involving other market players and users
Spillover of learning	Global but incomplete	Local and applications
Economics of learning	Mass production and R&D: dynamic economy of scale	Mass customization; knowledge reuse among projects; dynamic economy of scope
Partners of learning	Module suppliers driven Learning by doing	Among intermediary systems integrators, utilities and users Learning by interacting
Governance of learning	Firm-specific production, knowledge management routines	Local institutions such as design standards, regulations, systems integrators community, developers forum, etc.

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[6] We thank an anonymous reviewer for suggesting to us to clarify this point.

coordination with other market players and is dramatically different from the commodity and volume-based production style for solar cell in the factory.

One of the major contentions of this paper is that collective BOS cost or non-module cost learning, is systems design and installation oriented, as BOS components are mature. This system learning is local as different countries have different installation and regulation practices dictating system designs consideration. One caveat being that this analysis is based on non-module cost available at the country level; however, since country as a unit of analysis is still rather aggregated, future analysis can be pursued at the level of states or even programs in the spirit of Wiser et al. (2007). Meanwhile, the local nature of our analysis is also reinforced by the fact that this is done in the spirit of international comparison between the US and Japan as reported in other settings (Shum and Watanabe, 2007a, b).

Learning in non-module cost among different categories of grid-tied small PV applications will be facilitated if system integrators all have undergone similar or standardized trainings so that they can draw upon the ''next bench design.'' Next bench design can be seen as shared routines or standardized practices, which can serve as interfaces among professional practitioners. One can rely on the fact that other engineers, or lawyers, or surgeons have made decisions in ways that one can reconstruct by virtue of one's own training or experience (Langlois et al., 2001). This cross-learning can also be facilitated if all the different system configurations are derived from a similar design architecture or platform. There is a downside, however, due to that pre-mature emergence of standards or a dominant design will trade off or forfeit diversity-based or selection-based learning as is informed by the evolutionary theory of technical change (David et al., 1996). With the proviso that such a standard emerge optimally timewise, ex-post learning among integration projects based on the same standard will lead to an economy of customization contingent upon that particular standard. Therefore, these two pre-requisites will become the focus of energy policy in enabling a local learning and innovation model for solar photovoltaic deployment giving rise to an economy of customization in the actual putting together of a on gird small PV residential system.

2.3. Some general dissenting opinions or caveats on the experience curve

While the experience curve is regarded as one of the most regular empirical patterns in the study of technical change, our understanding of the exact mechanisms behind such learning in cost or productivity is not at all comprehensive. In the area of PV, Nemet (2006) developed a so-called bottom-up learning model to identify the most important factors (the observable technical factors) affecting the cost of *PV module* during the period of nascent commercialization from 1976 to 2001. These factors are: module efficiency, plant size, yield, poly-crystalline share, silicon cost, silicon consumption and wafer size. However, they together explained less than 60% of the change in cost in the studied period and that the regression model predicted the actual change (learning) in cost much better after 1980 than it does before 1980. Furthermore, the highest impact factors of plant size, module efficiency and silicon cost are only weakly explained by cumulative capacity, which is used as proxy of learning and experience in the traditional experience curve study framework. A whole host of market-oriented factors need to be complemented with the microscopic observable technical factors in order to explain the drop in PV module cost: shift from space to terrestrial applications, increasing competition, standardization in module offering in the midst of emergence of a terrestrial industry. This comprehensive analysis therefore highly suggested that experience curve, as an empirical regularity in technological change, needs to draw upon a much broader set of influences than experience alone in order to explain the rapid cost reduction of PV module.

The wide latitude of what constitutes learning or cost reduction in PV system is also demonstrated in a recent study by Wiser et al. (2007). Unlike many similar studies in the US or internationally, which often used learning or experience curve to explore how increase in cumulative PV production has driven down costs over time, their study focused on the effects upon actual *pre-rebate per unit total installed cost* of individual PV systems under California's two largest solar rebate programs[7] of various factors such as: (1) time of system rebate application, (2) global changes in module costs, (3) policy levels and design, (4) PV system size, (5) installer and retailer experience and type and (6) installation type. It was found that the aggregate changes in the global module cost translate directly into similar-sized change in pre-rebate system total installed cost. In models that control for global module cost effect, pre-rebate *non-module system costs* have also dropped. According to their studies, pre-rebate system total installed cost for small systems (<30 kW) dropped by US\$0.7/WAC per year, while that of pre-rebate non-module cost dropped by US\$ 0.3/WAC per year. This suggested that reductions in pre-rebate installed costs over time can accounted for almost 40% by reductions in non-module cost or the BOS cost in this paper. This trend in non-module costs confirmed the importance of BOS learning as described in the preceding section irrespective of the actual BOS cost or non-module cost level; in addition this reduction in non-module cost is program specific or local, as contrasted with the cost of module, which are set in worldwide markets and therefore heavily influenced by factors outside the control of the local program (Wiser et al., 2007, p. 77).

These two recently completed analyses defined a wide spectrum of studies, in terms of breadth of scope and depth

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[7] They are respectively overseen by the California Energy Commission (CEC) and the California Public Utilities Commission. Most of the results discussed in this paper pertain to those systems installed under the CEC Program.

of details, of the study of cost dynamics of PV system. While there are needs and advantages to pinpoint and reveal each and every mechanism potentially contributing to cost reduction, there is also a need to make these findings easier to be generalized and conceptualized. Regarding the study of BOS cost or non-module cost learning in this paper, while we have adhered to the traditional experience curve framework (see Section 4), a novel aspect is we have offered a broad interpretation frame or schema, as opposed to very detailed digression, of organizing or facilitating such learning among system integration projects within the same or among different categories of grid-connected small PV systems, using the concept of a product platform. It is expected that future works can study in more detail the micro-mechanisms contributing to cost reduction in non-module cost. Section 3 explains the notion of product platform as an alternative productive organization in the study of economics of system integration and customization of PV systems.

3. Some general economic principles in the deployment of solar PV

In the promotion of renewable energy, energy experts and policy makers agree that subsidies such as rebate to renewable must continually decrease and that renewable markets must be *self-sustaining* without reliance on prolonged subsidies. A more progressive and innovation-oriented perspective on the sustainable diffusion of renewable energy technologies is that they should be deployed as solutions to concrete systemic problems rather than as a form of technology in search of application. This can be facilitated by a user-oriented innovation policy, targeted at developing specific solutions to customers or users' local energy problems (Tsoutsos and Stamboulis, 2005). This perspective has special relevance to the engineering and innovation in the BOS system as this is the subsystem that interfaces with different local application requirements and delivers unique values to users' renewable energy needs. The implications are that there will be *scattered* electricity generation from a *variety* of small PV systems at the customer site integrated with existing infrastructure. This, however, will also pose production efficiency challenges since most of such distributed systems or projects are less standardized than a commodity product.

In addition, one of the most conspicuous differences from a factory production organization is that there will be more interactions among users and integrators than just an arms-length transaction of buying and selling a commodity product using the market. This will lead to transactional inefficiency. In such cases, we have to concern about the quality of such interactions or mediations. These interactions can be understood as social learning processes between the various actors involved in the joint development and adoption of technologies, which may lead to a better match of design features and practices of usage and are crucial for the successful dissemination of technologies. In fact, as explained above, the more PV has to adapt to local installation conditions in order that it become economically advantageous by enhancing its value, the more important it is to manage such interactions in the context of small PV systems customization projects. However, these learning processes often happen in a non-systematic and barely reflected and structured way, and in many cases do not make sufficient use of the available potential of user experiences and expectations for further product improvements (Ornetzeder and Rohracher, 2006).

Among projects, due to their unique nature, spillover learning among them is also hard to be facilitated or that knowledge among projects cannot be reused, if they are designed in an ad hoc or one-off manner. While spillover can be seen as an economic externality not necessarily favorable to capturing of economic rents thus weakening incentive to innovate leading to its under-production, the emergence of standard at the industry level, like a public good, reused among distributed systems integrators, will facilitate spillover learning leading to efficiency at the industry level. There is a trade-off that needs to be balanced by policy-makers.

To the extent that industry-level innovation efficiency is desired, facilitation of such spillover learning is one of the unique challenges facing the deployment of most users-oriented renewable energy applications that receive scant attention in the literature. What we will try to explore in the rest of this section is to suggest a framework that can address how to facilitate spillover learning among unique, small-scale customization projects that may give rise to an economy of deployment of solar PV. We will first review two other models of economy of production first: mass production and complex products systems or CoPS before we propose the platform-based customization model.

(1) Mass-produced products—the production characteristic is that of high volume and large batch; managerial objective of operations is focused on incremental and continuous process improvements within a single firm or a closed alliance network such as in a lean production organization. Production economy is driven volume based. Innovation is dominated by suppliers and users are minimally involved. For the case of productizing PV using this strategy, PV module embedded building materials that can be mass produced by manufacturers fall into category of operations; concerning BOS, 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. Japan's PV productizing focus upon small residential grid-tied PV system and an emphasis on systemic optimization leverages heavily upon this mass production regime.

(2) CoPS projects (Hobday, 1998)—the production characteristic is that of project that is one of a kind; project *scale* rather than volume is the important leverage. The key management objective of operations is that of systems integration by the supplier and management of multi-firms alliance. Innovation is user-oriented and user–producer interaction is frequent. The social technology is usually in terms of a project organization that is a temporary coalition of firms involving variety of knowledge and skills. The project itself is embedded within production networks where alliances are formally developed to structure and coordinate innovation. As mentioned above, in the context of PV productizing, utility-scale or grid-tied centralized station subscribes to this category of production paradigm. However, given the fact that this category will amount to about 5% of PV installation and the fact the renewable energy such as solar PV should take advantage of local renewable resources and is modular in nature, this mode of productizing PV seems not be able to leverage the inherent advantages of the decentralized properties of renewable energy.

(3) Platform-based small customization projects—the production characteristic of this can be seen as a combination of both the mass production model and CoPS model applied to small-scale projects. The mass production logic and its associated production organization apply to the volume production of the hardware platform itself. As we have explained in the introduction, a (product) platform, by itself, is not a product (Fig. 3). It is a collection of the common elements, embodying underlying defining technologies, to be implemented across a range of projects or products. In general, a platform is the lowest common denominator of relevant technologies in a set of products or customization projects. A product platform seeks to mitigate the tradeoffs between product differentiation and cost due to variety and is an important product and project management strategy. In the case of PV deployment or productizing, the PV product platform consists of PV cells and the basic BOS components of which every PV system will use. The production of such elements is subjected to mass production type of factory learning. The CoPS logic applies to the

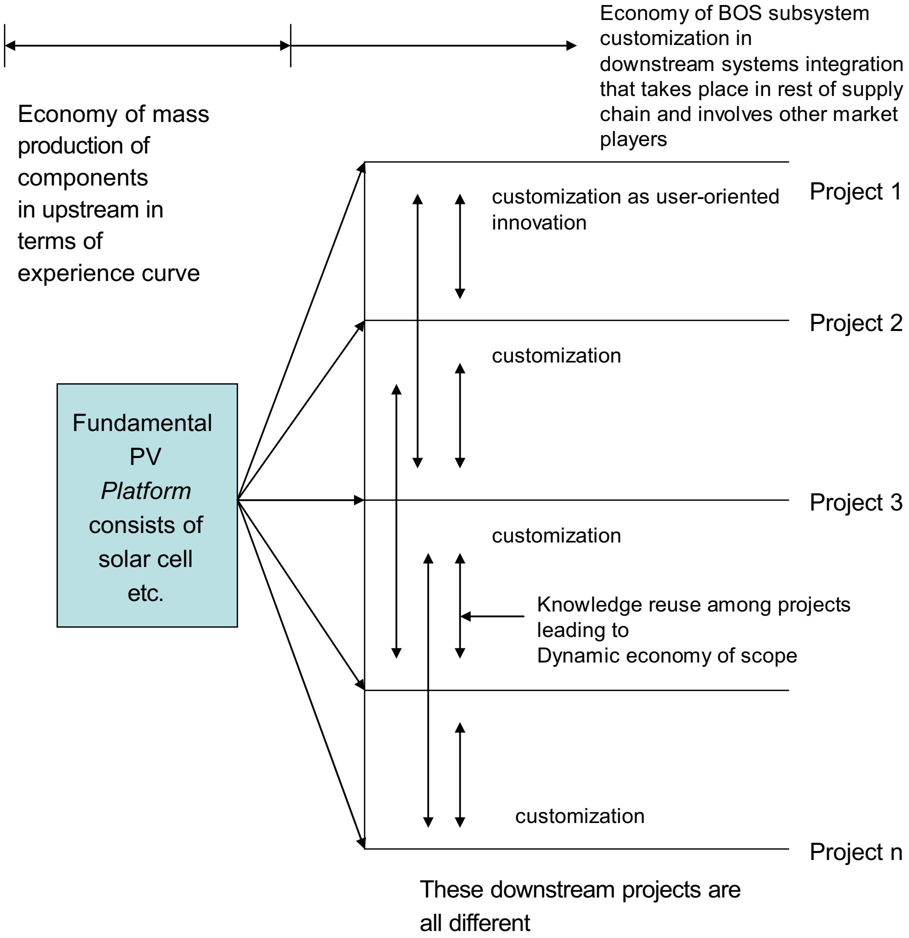

Fig. 3. A platform-based customization schema for solar photovoltaic projects; knowledge reuse or inter-projects learning will lead to a dynamic economy of scope or economy of customization. Adapted from Shum (2003).

user-oriented customization and differentiation portion (BOS subsystem or non-module aspect) of the solar PV system involving third-party independent *systems integrators*, situating in-between the platform components suppliers and the end users. Customization activities concerns with various applications and site-specific system design and installation issues. The key enabling organization of production or social technology (Nelson and Sampat, 2001) in this mode of production paradigm at the industry level is that driven by a community of developers engaged in *sharing and reusing* knowledge in system design and best practices. The economy due to re-use of knowledge among different small-scale integration and installation projects can be conceptualized as dynamic economy of scope (Shum and Watanabe, 2004, see also Fig. 3) in contrast to volume-based dynamic economy of scale or production learning for the hardware platform. Alternatively, this can be conceived as a community that enables spillover learning much like the *Open-Source* community continually developing new applications based upon a kernel common and sharing knowledge among developers (von Hippel and von Krogh, 2003). Two particular prerequisites are necessary for the working of this community of practice-cum-social technology; namely, the assimilative capacity of individual systems integrators which can be enhanced via (1) formal training and educations and (2) the existence of standardized practices of PV system design and engineering based on a design architecture or standard. This is especially important, as the standards will serve as *code of communication* among developers and to put them into the same cognitive frame as they exchange knowledge.

4. US solar PV experience as a case study

The US solar PV market is not a commodity or homogenous market, compared with that of Japan where over 85% of her PV deployment is in the grid-tied small PV residential system, but rather a collection of regions and applications where value proposition is most attractive (Jager-Waldau, 2004). This is a representative of the customization approach to deploy solar PV. As of FY 2003, PV cumulative installation in the USA reached 275.2 MWp with approximately 95.6 MWp installed as on grid-distributed application. In fact, USA PV installation in the small systems category (exclusive of on grid-centralized application) is well distributed among off-grid domestic, non-domestic and on grid distributed (Fig. 4). The characteristic of PV market development in the USA has been dominated by off-grid applications (~60% of total cumulative application). These off-grid installations include remote residential power, industrial applications, telecommunications and infrastructure, such as highway and pipeline lighting or buoys. For these applications, they are competitive already since costly grid extension is avoided and appeal more to the value aspect of solar PV.

The drawback of this is that these applications are mostly non-standardized and systems integration is project

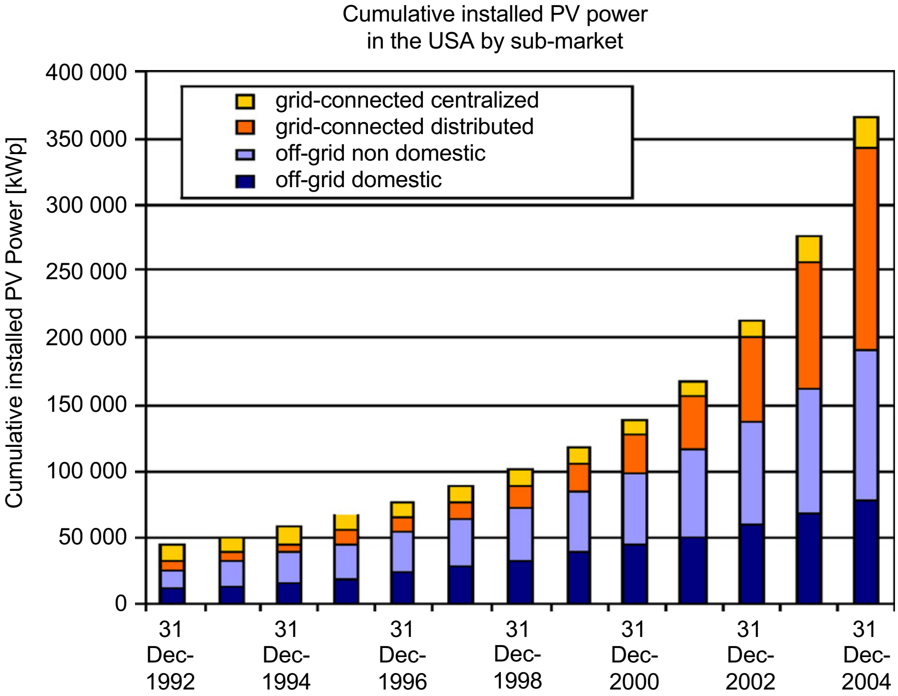

Fig. 4. A "customization" or user-oriented approach to deploy solar PV in the USA diversifying into various applications categories (Maycock and Bower, 2004).

by project rendering any type of systemic learning impossible. Even though design for off-grid applications are different from those of on grid[8] and spillover effects to other application categories may be limited, the lack of any standardization experience hampers the development of the [relatively] more standardized grid-tied application, which appeals more to cost and which have increased tremendously in recent year and is expected to have the largest potential for growth in the USA.

In addition, for the case of the US, a long history of PV spending on R&D to bring down the cost of PV cells and modules has created an industry focused primarily on component manufacturing. As a result, the majority of engineers employed in the PV industry in the USA are engaged in technology development rather than product development or system integrations and engineering issues. A large percentage of PV sales to final customers flows through small systems integrators who assemble custom systems for individual customers (Ingersoll et al., 2000). This is in marked contrast to the case of Japan, where solar PV is mostly installed as on grid small-scale residential system by house construction companies using a very integrated PV value chain (Jager-Waldau, 2004).

The US solar PV value chain, especially the portion related to systems design, integration, installation, servicing and financing, is very fragmented and each small company lacks the economies of scale and scope in engineering and administration of the large manufacturer. The small companies serving end-use markets do not have the resources to manufacture and further innovate upon standardized PV products and can therefore serve a few customers, preventing them from moving into other segments. This hampers solar PV development at the local level.

In terms of the platform-based customization model introduced in this paper, a combination of fragmented PV value chain and diversity of end user applications renders systematic inter-projects learning at the industry level hard to be coordinated. The more fragmented the industry value chain and the more diverse the applications is, the more difficult it is to reuse knowledge *along the value chain and across applications*, unless there are some standardizations in the systems integration, installation, servicing or even contracting practices that will facilitate BOS subsystem or non-module cost learning as mentioned in Section 3. This type of economy in the deployment process, beyond that of module production, receives scant attention and is a deficiency or challenge to a comprehensive policy to promote solar PV or other small-scale renewable energy technologies with a significant component of value added due to customization at the end of the innovative value chain.

Looking at the further developments of solar PV, which will see increasingly more functionality, such as communication, added upon a basic PV module or system for various innovative energy services, the downstream engineering and customization issues will become ever more significant and prominent compared with the commodity nature of module. In addition, from a service point of view, both the BOS components of inverter and battery or storage device most likely need continual servicing due to unstable performance characteristics. These reinforce the fact that the economics of solar PV is above and beyond the cost of solar modules and involves other cost components in the rest of the system, incurred during and in the ex-post installation along the rest of the value chain and over its life cycle. This justifies an economic framework of cost learning and innovation of the relevant [BOS] subsystem in the downstream.

4.1. Dynamic economy of scope

This section attempts to elucidate the source of dynamic economy of scope arising from platform-based customization of small-scale solar PV projects.

Inter-projects learning among different solar PV projects emphasizes a productive relation among a *variety* of projects. A familiar category of economic benefit rooted in variety is that of static economy of scope. It is important to clarify the differences between static and dynamic economy of scope.

We can base our explanation in a manner similar to reasoning the difference between static and dynamic economy of *scale*. Static economy of scale refers to the economy that arises from building one large project rather than a number of smaller ones to produce the same level of power output; in general, these economies are due to spreading a fixed cost among an increasing level of output. Dynamic economy of scale, on the other hand, results from learning to build the *same* power plant project more efficiently as experiene accumulted. The $(N+1)$th project, despite the same as the Nth project, uses lesser labor, less cost, etc. due to cumulative learning or learning by doing (Hayes et al., 1984, pp. 59–61).

Economy of scope is said to arise when the same resource can be used to build a *variety* of different projects. In the industrial engineering literature, Beckman (1997) suggested that in high mix–low-volume production settings associated with different variety of products or models, utilization of flexible production processes must leverage upon economy of scope, driven not by individual production output, but by the *sum* of output of each variety.

Goldhar and Jelinek (1983), Talaysum et al. (1986), in their studies of Computer Integrated Manufacturing (CIM), suggested that economy of scope can be leveraged due to design and process control *information* is encoded in software and that the *marginal cost* of modification of such information for different production runs and varieties is software driven rather than labor driven. In essence, if marginal increase of cost due to additional variety is minimal, then the same fixed cost can reasonably be

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[8] One noted difference is that on grid application does not need storage device or battery.

assumed to be spread across increasing variety, achieving economy of scope. These scope-based advantages, however, involve no learning.

Inter-projects learning in the context of a platform-based customization regime, as is emphasized in this paper, refers to the application of knowledge learned from one project to other installation projects (and vice versa) based on or derived from the same standardized PV platform. The locus of learning may cover the entire value chain of system design, integration, installation, maintenance, servicing, financing, etc.

The economic benefits are accrued from reusing the knowledge gained during the application of a technical platform to a project to *another* project of different requirements. While the requirements of the $(N+1)$th project may be different from the Nth project due to unique conditions, the knowledge gained by using the platform to solve the Nth project can be reused on the $(N+1)$th project if the latter can as well be addressed by the same general technical platform. This is the basis of platform-based dynamic economy of scope.

In addition, if the *same* set of stabilized or standardized processes or infrastructure or value chain is used to operate upon a variety of projects, inter-projects knowledge transfer will be more likely (Pine, 1997) as there involves lesser variables or uncertainties, which will hinder organizational learning. So, there are two critical determinants to dynamic economy of scope: the same technical platform and the same infrastructure or value chain are used across a large variety of projects. The former can be generalized as a physical technology or recipe to solve a technical problem and the latter a social technology or social division of labor (Nelson and Sampat, 2001).

This combined notion of social technology and physical technology can be summarized in terms of a 2 × 2 matrix (Fig. 5) to manage inter-projects learning in the BOS subsystem or non-module aspect of a grid-tied small PV residential system essential to the economics of its deployment.

To summarize:

(1) Static economy of scale is scale driven, spreading a fixed cost among higher level of output and involves no learning.
(2) Dynamic economy of scale resulting from learning by doing, at a given scale, due to cumulative production experience.
(3) Static economy of scope resulted from spreading a ex-ante sunken fixed cost among a variety of products; alternatively, the marginal adjustment cost due to producing a new variety is minimal and negligible compared with the fixed cost.
(4) Dynamic economy of scope resulted from ex-post inter-projects learning among different variety of projects. This is concerned about sharing and reusing of knowledge and knowledge relatedness among different solar PV projects from the same platform or among different similar platforms. The knowledge relatedness is, in turn, due to using a *similar or the same* platform. Projects derived from similar architecture or platforms are related by similar problem-solving heuristics or logics. This is analogous to the notion of technological paradigms or trajectories. In addition, if the same set of players is involved in different projects, likelihood of inter-projects are also more likely. Alternatively, if different players are involved, drawing upon the same training or stock of knowledge will allow them to draw upon "next bench design" greatly enhancing likelihood of inter-projects learning.

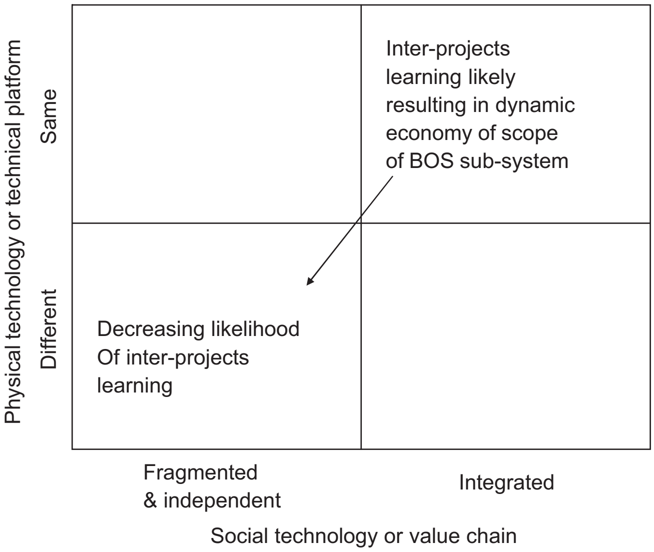

Fig. 5. Determinants of dynamic economy of scope among projects in customization-based BOS subsystem learning [same means the same physical technology platform is used in the different projects and vice versa].

4.2. *Empirical evidence of dynamic economy of scope*

This section attempts to provide some evidence of dynamic economy of scope. We draw upon the BOS system (non-module) cost of US's grid-connected residential system (a particular version of grid-tied small PV system under study in this paper) and the cumulative installation of all grid connected distributed systems available in the IEA PVPS country report (Maycock and Bower, 2004). Our intention is to detect (i) if the local-oriented BOS cost for small on the grid PV system is dependent upon the cumulative installation of *all* on grid distributed systems (but excluding centralized) and (ii) if there is change in the effectiveness of this cross-learning mechanism. To do this, we propose the following BOS cost-learning dynamic model:

$$\ln c_t = c_0 \ln(v_{cuml,t})^{\lambda(t)}, \qquad (1)$$

where c_t is the system or BOS cost for grid-connected small residential PV system, $v_{cuml,t}$ is the cumulative installation for *all* grid-connected distributed applications in the USA;

Table 2
Original data from IEA (2004) and transformed data

t	$\ln c_t$	$z_{1,t} = \ln(v_{cuml,t})$	$z_{2,t} = t\ln(v_{cuml,t})$	$z_{3,t} = t^2\ln(v_{cuml,t})$
1	6.6846	15.9196	15.9196	15.9196
2	6.6528	16.0876	32.1752	64.3504
3	6.5510	16.2134	48.6402	145.9206
4	6.5294	16.4329	65.7316	262.9264
5	6.4769	16.5818	82.909	414.545
6	6.4769	16.8647	101.1882	607.1292
7	6.2633	17.1512	120.0584	840.4088
8	6.1092	17.5192	140.1536	1121.2288
9	6.1092	17.9681	161.7129	1455.408
10	6.0520	18.3756	183.756	1837.56

Table 3
Static and dynamic regression results

	BOS cost learning among projects from the same category and among different but similar categories of applications
Static learning coefficient	$-.277$ ($p<0.01$) Adj. $R^2 \sim 0.90$
Dynamic learning coefficient	$\lambda(t) = -.143 - 0.003\,\mathrm{t}$ ($p<0.01$)[a]1 Adj. $R^2 \sim 0.9$

[a]The regression results of coefficients are with a high t-value at the given significant level and there are minimal positive serial correlations in terms of a Durbin–Watson statistics ~1.63. See e.g. Gujarati (2003, p. 469).

note that this may include several application categories and hence several platforms; $\lambda(t)$ is the learning coefficient. We will analyze the cost data from two perspectives; static and dynamic:

Static:
$\lambda(t) = \mathrm{b}$;
and
Dynamic:

$$\lambda(t) = \alpha_1 + \alpha_2 t + \alpha_3 t^2. \tag{2}$$

We chose this dynamic functional form to represent autonomous technical change assuming a quadratic form.

Taking logarithm of Eq. (1) and substituting Eq. (2) into the resultant, we have

$$\ln c_t = \ln c_0 + \lambda(t)\ln(v_{cuml,t}),$$
$$\ln c_t = \ln c_0 + (\alpha_1 + \alpha_2 t + \alpha_3 t^2)\ln v_{cuml,t},$$
$$\ln c_t = \ln c_0 + \alpha_1 \ln v_{cuml,t} + \alpha_2 t \ln v_{cuml,t} + \alpha_3 t^2 \ln v_{cuml,t}.$$

Rewriting this, letting

$$\ln c_0 = \alpha_0,$$
$$\ln v_{cuml,t} = z_{1,t},$$
$$t \ln v_{cuml,t} = z_{2,t},$$
$$t^2 \ln v_{cuml,t} = z_{3,t},$$
$$\ln c_t = \alpha_0 + \alpha_1 z_{1,t} + \alpha_2 z_{2,t} + \alpha_3 z_{3,t}.$$

We, therefore, regress the system BOS cost data against the z's. The necessary data are stored in Table 2.

The results in Table 3 confirms (i) that local-oriented BOS cost or non-module aspect for small on the grid PV system is indeed dependent on the cumulative installation of *all* on grid-distributed systems validating the cross learning or dynamic economy of scope hypothesis and (ii) this learning effectiveness is increasing over time as is made evident by the term $-0.003t$ (with a negative t-value of ~ -20) It must be emphasized that the analysis here is done in the same spirit as the conventional experience curve analysis where the unit cost of production is regressed against cumulative production. These earlier studies made no particular attempts to identify the exact engineering mechanisms, which give rise to such learning effects. In fact, such learning can be due to product innovation, process innovation, standardization, re-design or all-of-the-above etc. Section 5 attempts to elucidate some mechanisms or institutional innovations that facilitate such learning in the current context of platform-based customization. Our novel aspect is to append a platform-based mechanism as a viable enabler for such inter-projects learning and hence a focus of energy policy.

5. Policy implications

The purpose of this section is to examine several ongoing developments in the solar PV industry in the USA in light of the platform-based customization framework. Two cited factors that impede inter-projects learning are the diversity of applications/lack of standardization and the fragmented nature of the value chain. Both of these can be addressed by the emergence of a standardized PV system assembly architecture and training and certification of systems integrators. We will examine each in turn.

5.1. The emergence of plug and play solar PV system platform

A recent development in the solar PV engineering community is the proposal of an AC PV building block that promises ultimate *plug-n-play* PV system (Bower, 2003b). The concept uses a fully integrated mounting structure that serves as *both* a mechanical assembly that houses the DC connection to the PV modules, the electronic DC to AC conversion, surge protection, communication bus and AC power distribution element *and* all types and shapes of PV modules. The final AC PV building block assembly can snap together or can simplify mechanical construction using screws, bolts, nuts and the like, resulting in a very integrated assembly suitable for building integrated solar PV applications (BIPV). It therefore paves the way to ease practitioner, designer and installer certification requirements and better guarantees or controls quality for code-compliant installations and building integration of PV technologies. The AC PV building block will be a fundamental element upon which all types of PV systems can be built and can provide AC power to any of the existing loads including: the utility grid, mini-grids utilizing other sources of AC generation and even standalone power systems. The success of the AC PV building block draws upon mass production of quality products, integration of all the modules and BOS elements, cabling into a rugged, reliable and proven package thus eliminating many design, installation and transaction or purchasing headaches.

In the context of a platform-based customization strategy, this AC PV building block serves as the technical platform, which is to be reused across many one of a kind integration and installation projects. This platform portability facilitates the transfer of learning across projects thus enabling dynamic economy of scope as well as minimizing the contingencies in each integration scenario. An added advantage of a standardized architecture like the AC PV building block is that it stimulates or makes *independent* innovation of the individual elements making up a solar PV system as long as these innovated components fit into the interface requirement (Baldwin and Clark, 1997). A noted example is the need to develop a micro-inverter topology, which eliminates the need for electrolytic capacitors that are required in conventional inverter before the micro-inverter can be utilized in the AC PV building block.

5.2. The emergence of training programs for systems integrators

The development of the downstream infrastructure to support local integration of solar PV system has been recognized as one of the key requirements of a maturing solar power business. The lack of a fully developed infrastructure is one of the more significant barriers to deployment. Infrastructure is defined to include all the necessary support businesses that help a buyer to design, obtain competitive product information, buy, finance, install and maintain a PV system. The recommendation and emergence of training and certification program by solar electric power association (SEPA, US) deals with the a narrow but important job of building and advocating the network of individuals qualified to install PV systems, addressing buyers' need to secure qualified installers and maintenance contractors. Thus it is an integral component to address the infrastructure issues in order to minimize the downstream transaction cost issues for buyers. The training program will utilize existing standards and training materials that have been developed by DOE, NREL, IEEE, NEC and others. The specific goals are to remove uncertainties in the infrastructure and to improve the quality, cost and consistency of installation and understanding of all infrastructure issues. The program will develop one or more processes where PV system designers, installers and repair/maintenance personnel can obtain needed training, experience, and certification recognized by utilities, financial institutions, insurance carriers, local approval officials and others. These can all be cited as the first-order effects of such training programs.

In the context of platform-based customization, the availability of qualified systems professionals will have a significant *second-order effect* of facilitating knowledge transfer across different projects using the same general PV platform such as the AC PV building block reviewed above. A standardized training program or curriculum will teach students the fundamental set of problem-solving skills regarding solar PV system engineering; this will give them a common language to communicate and will improve their assimilation capacity to understand new developments in the field. A general objective will teach them how to learn and analyze problems. All of these cognitive skills, specific to solar PV issue, greatly facilitate the likelihood of reusing knowledge arise from one integration project to another for the dual objectives of cost learning and innovation of the BOS subsystem critical to the [micro]economics of solar PV deployment in the downstream.

6. Conclusion

A successful strategy for solar photovoltaic (PV) must jointly be based upon an increasing market and demand to drive cost reduction of key component such as solar cell and to capitalize upon PV systems' flexible characteristics to address unique users' requirements in downstream. While we have a reasonably good understanding of the experience curve effects or paradigm behind the production of the solar cell, we lack a correspondingly clear framework about the [local] microeconomics of system integration or customization in the rest of the solar PV value chain.

This paper retains an experience curve framework to study the cost-learning behavior of the non-module or BOS aspect of grid-tied small PV system. Empirically, we have demonstrated that learning or improvement in the non-module BOS cost in a specific category is dependent upon the cumulative installation across categories for the US data. Our novel aspect is to interpret this not as learning by doing but as a refined notion of learning across customization projects enabled by a platform-based productive organization, with the proviso of two facilitating mechanisms.

These mechanisms are the emergence of standardized solar PV system architecture such as the AC PV building block and standardized training programs or curriculum for PV system professionals explained in the body of this paper. These developments allows problem solving using the same platform and corpus of knowledge by system integrators separated by time, space and in applications categories, greatly enhancing the knowledge relatedness and ease of knowledge transfer across different projects achieving a dynamic economy of scope leading to cost learning and innovation [customization] of the non-module BOS subsystem part of the overall system.

Existing frameworks on deployment of solar PV such as the RD3 framework from PCAST (1999) acknowledge that there are unique cost issues in downstream market deployment process above and beyond production cost issues for PV modules. However, there is no coherent framework to address the nature of such downstream BOS or non-module costs in the rest of the chain incurred by customization and other transactional issues. Our platform-based customization model may be a viable and useful first step to address and systemize an economic framework to understand and manage such costs and hence the critical market deployment process driven by users' needs.

Looking at the further developments of solar PV, which will see increasingly more functionality, such as communication (Bower, 2003a, b) added upon a basic PV module or system for various innovative energy services such as the smart grid paradigm (Mazza, 2005; Shum and Watanabe, 2006), the downstream engineering and customization issues will become ever more significant and prominent compared with the commodity nature of solar cell. This suggests a more comprehensive policy framework for the further promotion of solar PV as an integral component to a sustainable energy future must jointly be based upon the economy of mass production and technology development of components of a solar PV system and as a corresponding economy of customization then arises in downstream systems design, integration and functionality development. While our platform-based economy of customization model is far from complete and comprehensive at this stage, we think this is a much-needed development to start to tie up some loose ends in the downstream deployment process for most renewable and sustainable energy projects including solar PV.

On a theoretical front, our work builds upon the fact that a composite solar PV system consists of several learning subsystems (Wene, 2000) each of which may exhibit different learning patterns or even involve different learning partners. While cost learning for solar cell may continue to be production and research and development driven, the learning of BOS subsystem takes place with respect to customization and downstream functionality development and may have to do with the local organization of the deployment process, drawing upon local industrial systems or institutions such as standards and trainings of a distributed set of market players. This disparity of learning patterns and dynamics among subsystems needs to be understood and its implications explored in order to further manage the overall solar PV technological innovation system (Carlsson et al., 2002) for its sustained self-propagating diffusion.

This article also contributes to the so-called learning selection approach to technological change (Douthwaite, 2002). The learning selection model suggests that a technology is more likely to be of benefit and the benefits will be achieved faster in circumstances in which there are more novelty generators and an effective selection and promulgation mechanism. Successful early adoption of technology is facilitated by working with key stakeholders as *co-developers* during the adaptation phase so that they can get the technology working well for their circumstances and begin to feel that the technology is theirs.

This theory is used to explain the contrasting performance of the wind industry in Denmark and the US. US resorts to use a top-down approach relying on R&D and technology development to drive the adoption of this renewable energy. On the other hand, Denmark uses a bottom-up approach relying on interaction of stakeholders interested in the technology leading to the organizational innovation of Association of Danish Wind Turbine Owners, which in turn helped learning selection by providing users with evaluation information about wind turbines. In general, US's government-driven R&D approach have run into problems because they were put together by scientists who underestimated the difficulties of what they were proposing to undertake because the scientists had overestimated the value of scientific knowledge in relation to the necessary complementary inputs from other stakeholders in the downstream. In terms of the learning selection model, the NASA program had limited sources of innovation (von Hippel, 1988), little or no interaction between the researchers and the key stakeholders and a very poor selection mechanism. The platform-based customization model suggested here, along with standardized training of systems integrators and the emergence of a universal PV platform, imposes a structure to coordinate possible interactions among systems integrators who are the important stakeholders, intermediaries and sources of innovation situated between technology developers and end users.

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