Renewable and Sustainable Energy Reviews 69 (2017) 948–960

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Cost dynamics in the deployment of photovoltaics: Insights from the German market for building-sited systems

Lars Strupeit*, Lena Neij

The International Institute for Industrial Environmental Economics, Lund University, P.O. Box 196, SE-221 00 Lund, Sweden

ARTICLE INFO

Keywords:
Photovoltaic
Deployment
Soft costs
Balance-of-system (BOS)
Inverter
Experience curve

ABSTRACT

In most studies on technology change, the analysis of cost reductions of new energy technologies has been narrow and has often neglected essential processes related to the deployment of new technologies, such as photovoltaics (PV). However, in the case of distributed PV systems, other costs than for the PV modules – aka the deployment or balance-of-system costs – are significant. This review study identifies the long-term dynamics of "hard" and "soft" costs associated with the deployment of building-sited PV systems in Germany since the early 1990s. The results show that the costs for central hardware components such as inverters and mounting systems have decreased by 70–87% since the 1990s. Results also show that "soft deployment costs" such as planning and installation decreased by 65–85%, and the corresponding experience curve has a progress ratio of 88–90%. The results imply that both hard and soft deployment costs have decreased with cumulative experience. Generally speaking, deployment processes, and support for such processes, are essential for the assessment of the overall cost dynamics related to the implementation of new energy technologies such as PV.

1. Introduction

Competitive renewable energy technologies such as solar photovoltaics (PV) will be essential for progression towards a low-carbon economy. However, the diffusion of these technologies has faced numerous barriers such as high investment costs [1] and various transaction costs [2], and it is not until recently we have seen an accelerated diffusion of renewable energy technologies. Due to the combined effects of a dramatic decline of PV system costs [3,4] and the support from various policy programmes, PV technology has recently gained notable shares in an increasing number of electricity markets [5]. PV has achieved grid parity in several regions and, with continued cost reductions, grid parity can soon be the norm in much of the world [6]. Continued cost reductions will also be required to compensate for the scheduled phase-out of incentive programmes and to accommodate costs for grid services and other fees and levies that legislators are expected to pass on gradually to PV system operators [see e.g. 7–9].

The decrease in PV costs has been presented predominantly as a reduction of hardware costs and, in particular, a steep decline in the price of PV modules [10]. Relatively little attention has been paid to the cost dynamics of other crucial hardware components of PV systems, such as inverters, mounting systems, cabling, etc. Likewise, less emphasis has been placed on the soft deployment costs[1] related to customer acquisition, technical and legal-administrative planning, installation work as well as the transaction costs associated with financing. Soft costs are significant in the cost structure of PV, and constitute 20–64% of residential and small commercial PV system prices [11–14]. To broaden and deepen our understanding of the cost dynamics of PV systems, we need to go beyond the scope of PV modules and develop assessments related to processes of PV deployment.

Research literature drew attention to the importance of deployment costs as far back as the 1970s and called for dedicated efforts to reduce such costs [15]. Since then, a growing number of publications have explored the nature, sources, scale and cost reduction potential of various deployment items and processes. Recent literature has focused on the mapping and benchmarking of PV soft costs [16,17] and their variations in different geographic contexts [14,18–21]. This literature has advanced our knowledge on various deployment procedures required and also highlights the need to streamline such procedures in order to reduce PV costs [18,19]. Particularly in the U.S., various initiatives were launched to achieve governmental soft-cost targets [22]. These have addressed the role of standardized systems designs to facilitate planning and installation work [23], streamlined business processes [23], model standards and policy design criteria for inter-

* Corresponding author.
E-mail address: lars.strupeit@iiiee.lu.se (L. Strupeit).

[1] In the literature, these "soft costs" are – together with the costs for inverter, mounting system and cabling – commonly referred to as "balance-of-system (BOS) costs" or "non-module costs". However, the concept of the BOS is not uniformly defined and therefore "BOS costs" are not comparable across different studies.

http://dx.doi.org/10.1016/j.rser.2016.11.095
Received 26 November 2015; Received in revised form 29 June 2016; Accepted 4 November 2016
1364-0321/

connection and net-metering [24] as well as efficient permitting processes [25,26].

Based on benchmarking and bottom-up analysis, scholars have also explored the future potential of soft deployment cost reductions [22,27–29]. Beside their direct effects on PV system prices, some of the sources of soft costs may have additional, detrimental effects. For example, Brundage and Miller [30] point out that fragmented permitting and inspection processes impede solar installers from working across jurisdictional boundaries, reducing competition and allowing greater profit margins.

Despite this emerging body of knowledge, only very limited work has been done on mapping the historical dynamics of non-module costs, especially soft costs. In particular, we lack understanding about whether and how soft deployment costs decrease with cumulative experience and in which spatial context these dynamics may occur. It has been suggested that the geography of deployment-related processes and cost dynamics differs from the processes that characterize the dynamics of PV module costs. For example, studies on technology learning propose that global knowledge production and exchange, technology standardization as well as wide-ranging international supply and distribution chains all shape the processes of hardware cost reduction [31,32]. Conversely, soft deployment costs appear to be highly embedded in the national and sub-national context [20,33]. Hence, new knowledge about the dynamics of the complex and diverse set of deployment costs is critical for national and local actors and policymakers who seek to improve the competiveness of PV.

The objective of this paper is to provide new insights into the processes and patterns of cost reductions related to the deployment of solar PV. Specifically, we present a review of the nature, scale and dynamics of deployment costs of building-sited PV systems in Germany, which has one of the most competitive residential solar PV markets in the world. By the end of 2013, 35 700 MW_p of PV capacity had been installed in Germany, accounting for about 25% of the global cumulative capacity and covering 5.8% of the country's net electricity demand [34]. This market development has been enabled through a variety of different support schemes, enacted and provided by federal, state and local governments [35–40]. By 2012, about 75% of cumulative capacity had been installed in buildings [41], primarily as add-on systems on pitched and flat roofs.

Compiling a set of long-term price data, we describe the dynamics of deployment costs, covering for the first time a period of more than two decades since the early 1990s. To the best of our knowledge, only a few studies have highlighted the historic trajectory of such costs. In addition to our analysis of monetized costs, we identify various transaction costs associated with PV deployment and describe in qualitative terms the trajectory of these costs over time.

In addition, we complement this review of deployment cost trends with the concept of experience curves. Specifically, we correlate cost data associated with PV deployment against the number of cumulative installations as well as cumulative capacity, thereby creating two experience curves. Cost dynamics as a function of cumulative experience have been illustrated and analysed by numerous studies for the case of energy technology hardware components, such as wind turbines, photovoltaic modules and bioenergy technologies [see e.g. 1,32,42–44]. So far, few experience curves have been developed for the soft deployment costs of new energy technologies. Such curves could, however, provide insights into whether cost targets are likely to be achieved under a business-as-usual scenario or whether additional policy action is needed in order to accelerate the rate of (soft) cost reduction. Understanding the learning rate of soft deployment costs will also allow for a better-informed and more realistic setting of cost targets.

The remainder of this paper is organized as follows: In Section 2 we describe methodological aspects related to PV costs, briefly review the experience curve concept and describe our materials and methods. In Section 3 we present the results of the analysis, namely the historical trajectories of deployment costs. In Section 4 we discuss the results and in Section 5 the paper finishes with conclusions.

Table 1
Typology of PV life-cycle costs at the project level[2]; in this paper we focus on the most important *"hard"* and *"soft"* deployment costs.
Source: compiled from [10,46].

Upfront costs	PV module costs	– PV modules
	"Hard" deployment costs	– Inverter – Mounting system – Electrical cabling – Meter (not needed in net-metering schemes) – (Transformer, for larger PV systems) – (Battery system for off-grid applications / enhanced self-consumption in grid-connected applications)
	"Soft" deployment costs	– Processes related to choice of business partner and technology / customer acquisition – Processes related to technical planning – Processes related to legal-administrative planning, permitting, grid connection – Installation work – Processes related to financing and support schemes
Operating costs		– Spare parts (e.g. inverter) – Maintenance work (cleaning, inspection, repair) – Insurance – Metering – Legal-administrative work (e.g. processes related to taxation) – Capital costs (interest & amortization)
End-of-life costs		– Decommissioning

2. Materials and methods

In this section we present the framework applied to define the costs of deployment and the methods applicable for collecting such cost data (2.1), the concept of experience curves applied to illustrate cost dynamics (2.2) and a description of methods and the types of data collection employed in this paper (2.3).

2.1. Definition of the costs of deployment

Numerous cost items impact the cost of the PV life-cycle, see Table 1. In this paper we focus on the costs related to deployment – i.e. the hard deployment costs and soft deployment costs, but we also briefly introduce the reader to transaction costs essential for the deployment of PV systems. The "hard" investment or upfront costs have two components: the PV modules and the hardware that is necessary to deploy or integrate standardized PV modules into the local infrastructure. Empirically, hard costs can be quantified relatively easily, as they are monetized in business transactions and reported in price lists, surveys, in public support schemes as well as in the research literature. Price is generally taken as a proxy for cost.

Compared to the hardware costs, soft deployment costs are much more diverse and include, for example, labour costs, permit and

[2] At the electricity system level, additional costs and benefits related to PV technology need to be considered. These can include (1) the capacity credit and additional capacity cost of PV, (2) costs and benefits of PV on the capacity of transnational transmission corridors, (3) operating reserve cost of PV and (4) costs and benefits of PV on distribution network capacity and losses [45].