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Fostering grid-connected solar energy in emerging markets: The role of learning spillovers

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Abstract

Growing energy demands and rapid urbanization alongside an increasing urgency for climate change mitigation and resiliency make grid-connected distributed photovoltaics (PV) a critical solution in many emerging economies. However, adoption of distributed PV in these contexts has been slow due to its high upfront cost. As policies to kick-start the distributed PV market directly are often costly, this paper shows how a policy that first supports cheaper utility-scale PV deployment can create spillovers that lead to complementary cost reductions in distributed PV. Specifically, through interviews with experts in the PV industry, this paper finds that strong utility-scale deployment helps build local PV competencies and ecosystems, thereby facilitating the networks, scale, and value chains needed for distributed PV markets to develop. Harnessing these spillover effects can also reduce the upfront cost of distributed PV significantly and cost-effectively. Results of a dynamic bottom-up techno-economic model based on spillovers across PV components indicate that, in the presence of application spillovers, public financing used to initially support utility-scale PV deployment can leverage significant distributed PV cost reductions. By accelerating the profitability of distributed PV, application spillovers also enable more widespread and equitable distributed PV adoption. The paper concludes with recommendations to policymakers wishing to support more widespread distributed PV adoption in emerging and developing country contexts, with a particular focus on strategies for fostering application spillovers.

Keywords: Solar photovoltaics, Spillovers, Deployment policy, Local learning

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1 Introduction

The deployment of utility-scale photovoltaic (PV) technologies in developing and emerging economies has rapidly increased in recent years, driven largely by strong national deployment policies (e.g., auctions or feed-in tariffs) [1,2]. These deployment policies have proven effective in pushing utility-scale PV down its experience curve [3], resulting in cost reductions due to technological learning [3–6] – or the build-up of capabilities and experience with a technology – as well as through scale effects as the market matures [7–9]. The drastic drop in utility-scale PV costs has only accelerated its diffusion in emerging markets worldwide, further reinforcing its cost-competitiveness [10].

In contrast, grid-connected distributed PV[2] deployment has lagged in many emerging markets, despite several developing countries enacting policy frameworks to specifically support distributed PV generation [11,12]. Several factors have driven these low adoption rates. First, the per Watt cost of distributed PV remains more expensive than utility-scale PV. The high upfront costs of these smaller-scale PV systems – coupled with the often low purchasing power and access to finance in many developing countries – poses a significant barrier to their adoption [13]. Second, many developing countries have implemented net metering policies to support distributed PV adoption [14]. However, often electricity tariffs in developing countries are subsidized, resulting in unviable returns under such a policy [15]. Finally, there is often a lack of knowledge and capacity, both by potential adopters and in the market (e.g., installers, suppliers), which has slowed the development of the necessary ecosystems to support a distributed market [13].

Given the lower cost of policies to support utility-scale PV, debates surrounding whether policymakers should remove specific support for distributed PV deployment have arisen [16]. Much like arguments for technology-neutral climate policies, the rationale behind an "application-neutral" [17,18] solar PV deployment policy is to minimize the cost of meeting renewable energy targets.

[2] For a definition of utility-scale and distributed PV used in this paper, please see section 3.

However, developing countries facing both increasing energy hunger and rapid rates of urbanization would likely benefit from deployment of *both* PV applications. While centralized utility-scale PV offers advantages in terms of generation cost, distributed PV sited close to loads can save electric utilities investment in bulky grid infrastructure [19–21]. In many rapidly growing emerging economies, energy demands have outpaced the ability of (typically financially-constrained) utilities or municipalities to make the necessary infrastructure investments, leading to economically crippling blackouts [22,23], high losses in transmission and distribution, and often inequitable access to public services [24]. In some cases, standalone diesel generation may be used as back-up power, which is both costly and detrimental to local air quality [25]. Consequently, distributed PV offers an opportunity to improve electricity reliability in contexts in which electricity services have deteriorated. In addition, while both PV applications would contribute to climate change mitigation, distributed PV provides greater resiliency in a context of growing uncertainty and incidence of climate change-related natural disasters [26–28]. Finally, distributed PV may be supported as a means to promote economic development of communities, either through employment (e.g., in installation) or to generate additional household income in the case that households can sell electricity to the grid [29].

Furthermore, supporting PV deployment in *both* utility-scale and distributed applications could realize synergies from a policy cost perspective. Previous research has suggested that, given discrepancies in a technology's competitiveness across applications, policymakers can meet technology deployment targets cost-efficiently by exploiting spillovers across technology applications [30]. In theory, deployment of a technology in one application can push it down its experience curve, reducing its cost and making it eventually more competitive in a broader array of applications [30,31]. Strategically sequencing support for technologies according to their application with the lowest profitability gap – or the gap between investment returns and costs that would need to be covered by an investment incentive such as a feed-in tariff – therefore leverages technology cost reductions most efficiently.

While previous studies have investigated the impact of application spillovers on the cost of deployment policies [30] or technology selection [18], these studies simply assumed perfect spillovers across applications. Instead, this study seeks to determine the extent and mechanisms by which spillovers from utility-scale to distributed PV occur in practice, as large- versus small-scale applications can potentially exhibit different learning dynamics [32]. Specifically, through qualitative interviews, it analyzes how strong utility-scale deployment helps build local PV competencies and ecosystems, thereby facilitating the networks, scale, and value chains needed for distributed PV markets to develop. The paper also quantifies the potential impact of spillovers in reducing distributed PV costs and improving its profitability across different income groups, thereby helping distributed PV meet the multiple sustainability objectives of cost-effectiveness, environmental protection, and social inclusiveness.

The rest of the paper is structured as follows. Section 2 provides an overview of experience curves for solar PV and the theoretical rationale for cost-efficient policy design through policy sequencing. Section 3 presents the methods used to qualify and quantify the spillovers across PV applications, while section 4 presents the results. The paper concludes with a discussion of the implications for policymakers wishing to support more widespread grid-connected distributed PV adoption in developing countries.

2 Theoretical and empirical background

This section provides the theoretical argument for sequencing PV deployment policies using the concept of experience curves and spillovers across technology applications.

2.1 Experience curves for solar PV

An experience curve establishes a functional relationship between the cumulative production or deployment of a technology and its decrease in unit cost [33]. This relationship most commonly takes a log-linear form (see Equation 1) characterized by a parameter known as the learning rate (LR), or the percentage reduction in the cost of a technology with each doubling of cumulative deployment (X).

$$C_t = C_o \left(\frac{X_t}{X_o}\right)^{\frac{\ln(1-LR)}{\ln(2)}} \qquad (1)$$

Initially, literature treated this relationship as a black box, focusing on empirically fitting production and cost data to derive learning rates for specific technologies or firms for strategic purposes [34]. For electricity generation technologies too, literature adopted the concept of the experience curve and derived learning rates for applied purposes, including endogenizing technical change in economic models used for policy analysis and energy planning [35–37].

Reviews of these empirical studies, however, have underlined the wide variation in learning rates that have been found for energy technologies and consequently have highlighted the need to unpack the mechanisms underlying experience curves [7,38,39]. Generally, deployment can bring cost reductions through two primary mechanisms: (i) learning and (ii) scale effects. For the former, deployment of a technology provides opportunities for value chain actors to accumulate technological and organizational capabilities through learning-by-doing [40], learning-by-using a technology [41–43], or learning-by-interacting with other actors along the technology value chain [44–46]. The knowledge gained from this experience, when fed back into the technology design, production or deployment process, can lead to subsequent technological improvements and cost reductions. For the latter, economies of scale in production or plant size (see e.g., [7]) or degree of competition within the industry [47] can also influence the price a customer must pay for a technology.[3]

Reducing the complexity of these dynamics to a single-factor (as in Equation 1) can risk misestimating the relationship between technology deployment and cost, resulting in an incorrect extrapolation of future cost developments [48,49]. In response, several more nuanced functional forms of experience curves have been proposed. One form that is particularly relevant for PV technologies involves breaking down a technology-level experience curve into its individual components [50]. A component experience curve is particularly suited for solar PV, both because PV is highly modular – meaning that technological learning tends to happen on the component, rather than technology-level [51] – and because PV components differ substantially in their learning rates and learning mechanisms.

[3] Note that most experience curves use price data as a proxy for costs [50]

Specifically, learning dynamics differ between components sourced from global value chains and components and services sourced from local value chains [52,53]. For globally sourced commodities, including the module and inverter, learning-by-doing in manufacturing processes and economies of scale at a firm- or plant-level drive cost reductions [2,54]. Suppliers of these components gain competitiveness by upscaling production and tapping into global demand markets. In contrast, locally-sourced balance-of-system (BOS) components (e.g., mounting and racking systems) and services contributing to "soft costs" (e.g., installation, permitting and inspection) typically involve coordination from multiple downstream value chain actors [55]. Learning-by-doing in deployment processes and learning-by-interacting – in the sense of developing shared routines, practices and standards, or through learning to effectively govern transactions amongst value chain actors – help foster cost reductions of these components [56,57]. Scale effects are not achieved due to scale in a single production facility, but from market development factors such as greater competition [8] or the formation of supply chain networks [58]. Consequently, whereas *global* PV deployment drives cost reductions in the module and inverter, *local* deployment is needed to push BOS and soft costs down their experience curves [52,53,55].

While module and inverter prices have experienced rapid cost reductions, BOS and soft costs have not declined as drastically in smaller distributed applications [59]. As a result, these localized costs have grown increasingly important drivers of overall installed PV costs [60]. Especially in immature distributed PV markets, the local value chain tends to be quite fragmented, hindering coordination and learning, ultimately resulting in high transaction costs [57,58] that are passed onto customers. Given these high initial upfront costs, kick-starting the market typically requires a combination of attractive adoption incentives (e.g., a high feed-in tariff as in Germany [61]) and a residential market that can afford these upfront costs and their associated risks [13,62]. Without allowing for these high investment returns, which are costly from a public perspective, grid-connected distributed PV adoption is often limited to the richest segments of the population, resulting in both low deployment and an inequitable distribution of the potential benefits of PV [13,63].

2.2 Applications spillovers and cost-efficient policy sequencing to support distributed PV adoption

In contrast to the slow development of distributed PV markets, utility-scale PV is booming in many developing countries – both in terms of added generation capacity and cost-competitiveness. In upper-middle income countries such as Mexico and Argentina, for example, solar PV bids submitted in 2017 dropped below 5 USD cents per kilowatt-hour; similarly competitive prices can be expected to emerge in Sub-Saharan Africa, with the lowest bid submitted in Zambia's 2016 auction falling around 6 USD cents per kilowatt-hour [64]. Utility-scale PV, unlike distributed PV, has achieved such low prices due to several factors. Firstly, economies of scale allow utility-scale PV projects to spread overhead costs over a larger volume of capacity and provide greater efficiency in some aspects of project development (e.g., logistics, installation labor utilization), leading to lower per-watt installation costs (see Figure 1). Secondly, with the appropriate policy framework, many PV projects in developing countries attract international investors [22,32]. These international players not only have access to cheaper finance, but also often have established relationships that give them access to well-priced quality modules and inverters. Furthermore, the ability to attract international players has also led to fierce competition for PV projects, leading to lower profit margins for project developers [64,65]. Finally, utility-scale projects increasingly compete in single markets (e.g., as in a centrally-administered solar PV auction), which creates price transparency and further lowers profit margins. In contrast, many distributed PV markets suffer from information asymmetries, or informational gaps on the consumer side [66–68], allowing PV service providers to maintain higher margins. As utility-scale PV prices have converged with the levelized cost of traditional large-scale electricity generation technologies, the policy support required to incentivize its deployment often comes with a lower price tag than overcoming the profitability gap of distributed PV – particularly given that electricity tariffs in developing countries are often subsidized.

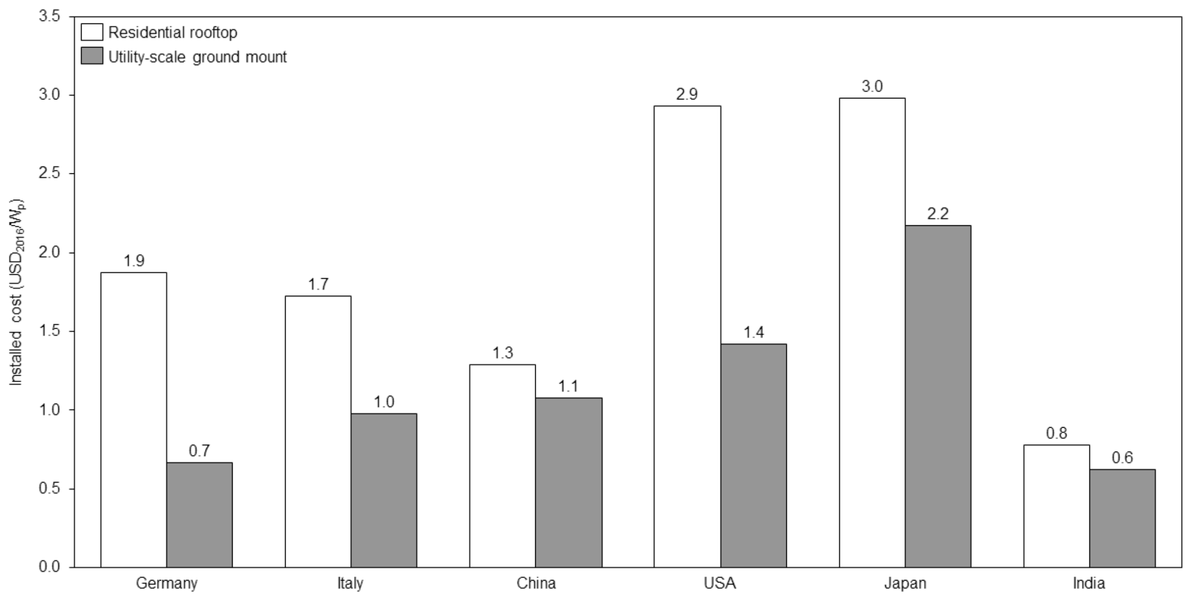

Figure 1: Comparison of installed costs of utility-scale and residential rooftop PV systems in 2016 in selected countries (data from IEA-PVPS (2016); Bridge to India (2017)).

In a recent study, Battke and Schmidt [30] argued that policymakers can actually take advantage of such profitability gaps across technology applications. The authors demonstrate that, by strategically supporting technologies in their application with the lowest profitability gap, policymakers can minimize the cost of achieving certain deployment targets. This argument holds true in the presence of spillovers across technology applications, or under the condition that the deployment of a technology in one application will push that technology down its experience curve, reducing its cost and improving its profitability in an application with lower economic returns.

This paper applies the concept of application spillovers to the case of solar PV and, specifically, to the locally sourced cost components of PV. The deployment of utility-scale PV drives locally sourced components down their experience curves (see Component A in Figure 2a), resulting in a cost reduction of ΔC. In the presence of perfect spillovers across PV applications, this utility-scale deployment would result in a complementary cost reduction of ΔC of this component for distributed PV, effectively shifting its cost curve from A to A' (see Figure 2b) and reducing the overall upfront cost of the technology. While investment in utility-scale PV is needed to kick-start this process (see shaded area in Figure 2a), these investments – which tend to come from private firms – can leverage significant distributed PV investment savings for private households in developing countries (see shaded area in Figure 2b). In addition to savings in private investments, harnessing application spillovers can result in lower costs from a policymaker's perspective. As noted earlier, the profitability gap between the levelized cost of electricity[4] (LCOE) for utility-scale PV and traditional baseline technologies is rapidly closing (see Figure 2c). If spillovers across PV applications are sufficiently high, the public cost to support the initial utility-scale PV deployment (shaded area in Figure 2c) could theoretically even be offset by the savings gained by sequencing support for distributed PV once its profitability gap has been reduced (shaded area in Figure 2d).

However, given that spillovers will not be perfect across all components, understanding the actual impacts of policy sequencing requires one to unpack the spillover mechanisms from utility-scale to distributed PV applications as well as quantify their magnitude. The module manufacturers and processes for utility-scale and distributed PV are the same, resulting in essentially "perfect" spillovers for the module hardware itself. However much less is understood in literature around the overlaps between other processes. In many markets, installers, or engineering, procurement, and construction (EPC) companies,[5] operate in both market segments, and local banks lend to both type of projects. However, the landscape is generally much more varied, with some of these downstream firms specializing in one market segment. Consequently, it is unclear to what extent firms can leverage their experience and knowledge across different solar PV applications. Section 3 outlines the methodological approach taken to better understand and quantify these spillovers.

[4] The levelized cost of electricity is the present value of the lifetime costs of a power generation technology divided by its lifetime electricity production
[5] EPC companies are responsible for the engineering design; procurement of all necessary materials, equipment and services; and construction of a solar PV project

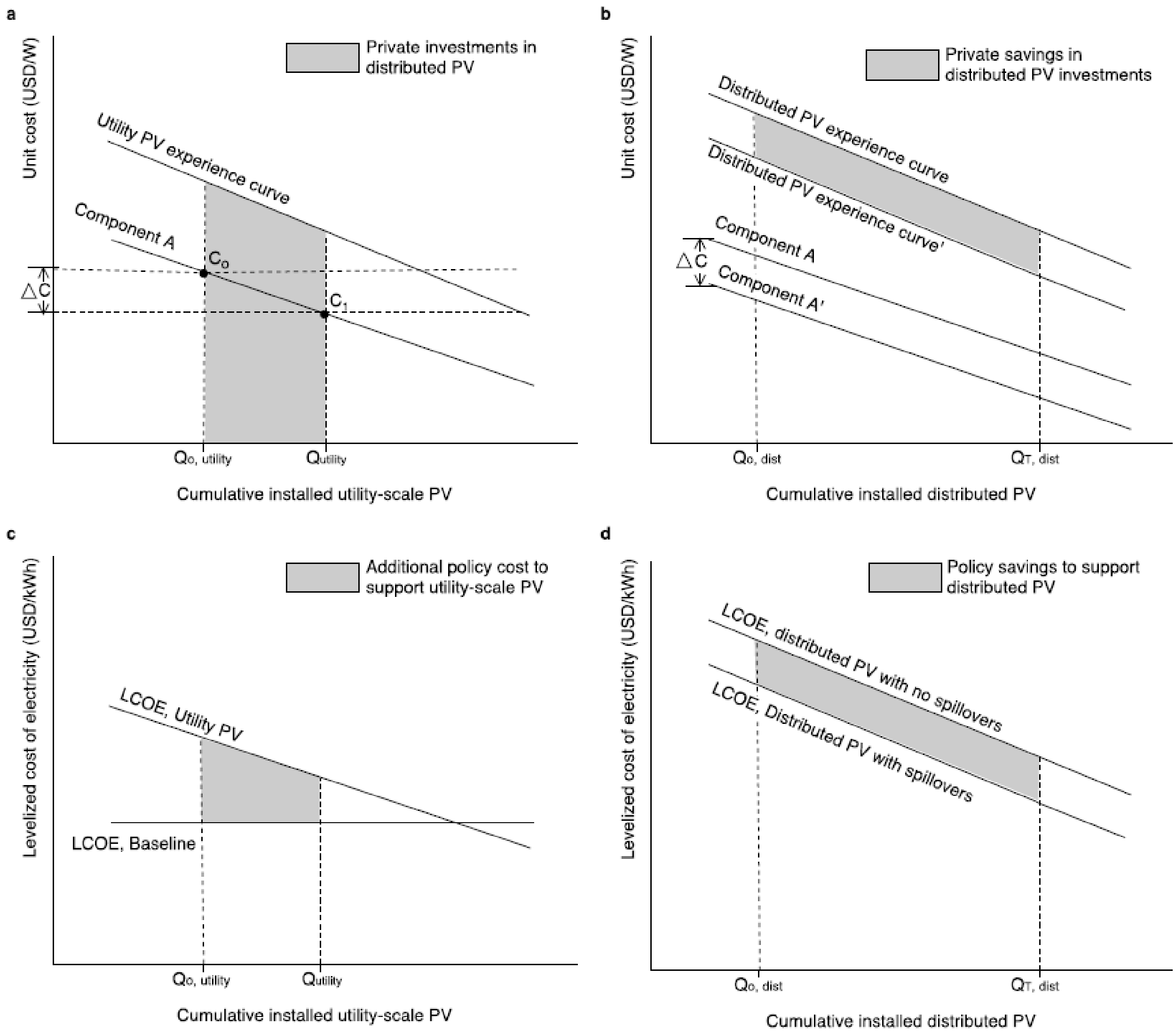

Figure 2: Experience curves for (a) utility-scale PV and (b) distributed PV and the resulting levelized cost of electricity for (c) utility-scale PV and (d) distributed PV.

3 Methods

This study takes a mixed methods approach in order to understand and quantify the impact of spillovers from utility-scale to distributed PV applications. A review of technical literature as well as semi-structured interviews with PV experts provided a qualitative understanding of application spillovers. Structured interviews with PV industry experts and a dynamic bottom-up techno-economic model based on component experience curves explores the impact of these spillovers on distributed PV costs and affordability. For the purpose of this study, utility-scale applications were defined as ground-mounted systems connected to the medium-voltage grid, and distributed applications were defined as rooftop systems connected to the low-voltage grid.[6]

3.1 Interviews with PV experts

In order to understand the potential spillovers and spillover mechanisms that can occur from utility-scale PV to distributed PV, interviews were conducted with 14 experts working in the PV industry. Interview partners were either individuals working in EPC firms, vertically-integrated solar companies, PV financiers, or technical consultants, with knowledge of both low-voltage distributed and medium-voltage centralized PV installations. Partners also represented a mix of markets, including Europe, the United States (US), and emerging markets (see Table B.1 for a breakdown of interviewee backgrounds). These partners were targeted given their overview of the entire PV value chain, as well as their ability to comment on both utility-scale and distributed PV systems.

This interview process proceeded as follows. First, an initial understanding of the PV values chains for each PV application was developed using technical literature. This understanding was refined through seven semi-structured interviews in which interviewees were also asked to explain the drivers of costs and potential application spillovers along these value chains. Developing cost categories according to value chain processes provided a framework for breaking down the overlaps across PV applications – both in terms of the processes involved in each value chain step as well as the actors responsible for managing these processes. Once refined through the semi-structured interviews, these cost categories were then utilized in a second set of seven structured interviews with PV experts. In these interviews, interviewees were asked to quantify the degree of overlap between value chain processes for distributed and utility-scale PV on a Likert scale ranging from 1 to 5, with 1 representing no overlap between processes and 5 representing a perfect overlap between processes. These responses were then transformed into values between 0 and 1 (i.e. with a Likert response of 1=0; 2=0.25; 3=0.5; 4=0.75; 5=1). These transformed

[6] Generally, the structural application of a PV system does not limit whether it is utility-scale or distributed. However, given the tendency for utility-scale PV to be ground-mounted and distributed PV to be rooftop systems, this definition was adopted in interviews in order to provide a clear definition of value chains for the two applications.

values served as an input (α, see section 3.2.1) to quantify the impact of spillovers on the upfront cost of distributed PV (see Equation 2 and Equation 3). In addition to these quantitative responses, interviewees were asked to provide an explanation for their response, providing further qualitative insights into the factors that increase application spillovers (see Appendix B for sample interview questions).

3.2 Quantifying the impact of spillovers from utility-scale to distributed PV

3.2.1 Model structure

Once an understanding of the mechanisms and magnitude of spillovers was established, the impact of these spillovers was quantified using a bottom-up techno-economic model based on component-level experience curves. In this model, the installed cost of PV is broken down according to the costs and experience curves of its individual components:

$$C_t = \sum_{i=1}^{n} C_{o,i} * \left(\frac{X_{t,i}}{X_{o,i}}\right)^{\frac{ln(1-LR_i)}{ln(2)}} \tag{2}$$

where C_t is the installed cost of PV at time t, comprised of n cost components. $C_{o,i}$ is the initial cost of component i at time $t = 0$, and $X_{t,i}$ and $X_{o,i}$ represent the cumulative deployment of component i at time t and $t = 0$, respectively. Component learning allows each component to be characterized by a specific learning rate, LR_i. Component learning rates for the module and the inverter were taken from existing literature [53,71,72] and component learning rates for the BOS and soft costs were derived using distributed PV data from the US [73] assuming a single-factor log-linear functional form (see Appendix A for details).

In addition to the ability to model component-specific learning rates, setting up the model using component-level experience curve provides two main benefits. Firstly, it allows to separate out the components that are subject to global learning, namely the module and inverter – which are driven down their experience curves by cumulative *global* deployment – from those components subject to local learning through *local* PV deployment. Secondly, component experience curves allow for the incorporation of component-specific spillovers across PV applications:

$$X_{t,i} = X_{t,i,d} + \alpha_i X_{t,i,u} \tag{3}$$

where $X_{t,i,d}$ is the cumulative local deployment of distributed PV, $X_{t,i,u}$ is the cumulative local deployment of utility-scale PV, and α_i is a parameter taking a value between 0 and 1 representing the spillovers between utility-scale and distributed PV for each cost component. A value of 0 translates to no spillovers and 1 translates to perfect spillovers. The value of α derives from data collected from the structured interviews with PV industry experts.

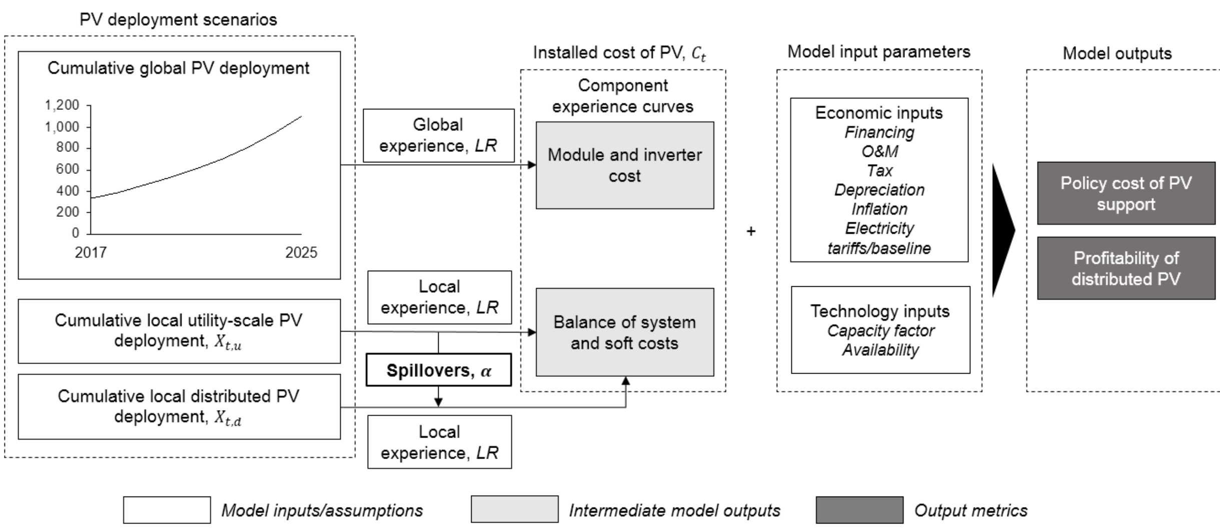

Figure 3: Structure of component-learning model

The calculation of the installed cost of solar PV using these component experience curves clearly depends on the assumed cumulative global and local PV deployment. The assumed global PV deployment is taken from the International Energy Agency's World Energy Outlook [74], and does not vary across the scenarios explored in this analysis. The cumulative local deployment of utility-scale and distributed PV, which drives reductions in BOS and soft costs, are explored as scenario inputs for the model, described further in section 3.2.2 below.

The installed cost of solar PV[7] (C_t) – an intermediate model output – as well as technology and economic parameters (see Appendix A for details and Appendix C for a sensitivity to input assumptions) provide the

[7] Note that these calculations do not take into account the intermittency of solar PV. Taking intermittency into account would increase the profitability gap of solar PV, however would affect the profitability of both applications.

inputs for calculating the levelized cost of electricity (LCOE) of each solar PV application. The LCOE is then used to calculate the cost of support required to close the profitability gap of PV in each application and the profitability of distributed PV investments under a net metering policy (see section 3.2.2 for details). Figure 3 summarizes the conceptual logic of the model.

3.2.2 Policy cost of PV support

In order to estimate the impact of spillovers from a policymaker perspective, the model explores two scenarios for meeting a target of 300 MW of distributed PV capacity by 2025[8]: (i) a case in which 1 GW of utility-scale PV is deployed over 2 years[9] prior to distributed PV deployment and (ii) a case with no utility-scale deployment.[10] In each scenario, the model calculates the upfront cost of distributed PV over time (see equation 2 above). For the first scenario, the model also calculates the policy cost of utility-scale PV deployment required to bring about these cost reductions. The policy cost is calculated as:

$$Policy\ cost = \sum_{t=1}^{2} \frac{Elec_{utility\ PV} \times N \times \left(LCOE_{utility\ PV,t} - LCOE_{baseline,t}\right)}{\left(1+K_p\right)^t} \tag{4}$$

where the utility-scale baseline is assumed to be combined-cycle natural gas generation, which due to the relatively low cost of natural gas and speed of construction of natural gas plants, is increasingly deployed in countries with rapidly growing electricity demands [75] (see Appendix C for sensitivities to the baseline), K_p is the public cost of capital, $Elec_{utility}$ is the yearly electricity generation of utility-scale PV, N is the PV system lifetime, and LCOE is the levelized cost of electricity in year t calculated as follows:

$$LCOE = \frac{SE \times C_t + \sum_{\tau=1}^{N} \frac{O\&M_\tau + Debt_\tau}{(1+K_e)^\tau}}{\sum_{\tau=1}^{N} \frac{Elec_\tau}{\left(1+K_E\right)^\tau}} \tag{5}$$

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[8] While this target is hypothetical, it is in line with distributed PV targets set in several middle-income countries. This includes, for example Egypt (300 MW of distributed PV by 2022 [88]) or Ghana (200 MW of distributed PV by 2030 [89]).

[9] This volume is in line with the annual volumes of capacity currently deployed in many emerging markets. For example, Argentina approved about 900 MW of PV capacity under its first two rounds of auctions [64] and South Africa awarded about 1.5 GW of PV capacity in the first two years of its auctions [90].

[10] While this may be an extreme case, as of 2016, only around half of non-Annex I countries had any utility-scale renewable energy projects [91], and deployment is unlikely to occur without creating the appropriate policy frameworks.

where the N is the system lifetime, K_E is the cost of equity, SE is the share of equity, $O\&M$ are the yearly fixed operations and maintenance expenses, and $Debt$ is the principal and interest payments on debt (see Appendix A for details on parameters).

3.2.3 Profitability of distributed PV

While the policy cost is presented for a generic case, in order to demonstrate the applicability and impact of spillovers in specific country context, the profitability of distributed PV investments with and without spillovers is presented for the case of Malaysia. At the time of this analysis, Malaysia had recently replaced its feed-in tariff policy with a net metering policy in order to stimulate distributed PV adoption [76]. However, Malaysia – like many countries – utilizes an increasing block electricity tariff, with higher consumption customers paying more per unit of electricity. While this cross-subsidization is intended as a redistribution mechanism – as energy consumption typically correlates with income – it can lead to an inequitable adoption of distributed PV under a net metering policy [77]. To show how spillovers may improve the accessibility of PV investments, the profitability, calculated as the net present value (NPV) of a distributed PV investment divided by investment cost, is calculated across the different tariff brackets:

$$\frac{NPV}{Investment\ cost} = \frac{\sum_{\tau=1}^{N} \frac{Tariff_\tau \times Elec_\tau}{(1+K_e)^\tau} - SE \times C_{t,d} + \sum_{\tau=1}^{N} \frac{O\&M_\tau + Debt_\tau}{(1+K_e)^\tau}}{SE \times C_{t,d}} \qquad (6)$$

While this analysis uses Malaysia as a case study, this case is meant to be illustrative of the challenges many emerging markets face with respect to kickstarting the development of distributed PV markets in the face of low electricity prices and underdeveloped downstream value chains. Profitability, however, will vary across country contexts and solar application sites, as it is highly dependent on capacity factors [78] and the electricity tariff [15].

4 Results

This section presents the results of the interviews and model. Section 4.1 provides a qualitative description of the spillover mechanisms across the value chains for utility-scale and distributed PV. Section 4.2 then quantifies the impact of spillovers on reducing the cost of a distributed PV support policy and improving the profitability of distributed PV investments to households of different income levels.

4.1 *Spillovers across PV applications*

The literature review and expert interviews informed the definition of eight cost categories derived from the local PV value chain. These categories, shown in Figure 4, include the following costs: supply chain; electrical BOS; structural BOS; customer acquisition; installation; permitting and inspection; grid interconnection; and margin (see Table 1 for definitions of each cost category) [60,73,79,80]. The results from the qualitative interviews indicated that utility-scale PV market development can lead to spillovers to distributed PV across nearly all stages of this downstream value chain (see Table 1 for summary). These application spillovers may arise through three primary mechanisms: scale effects, learning-by-interacting, and learning-by-doing.

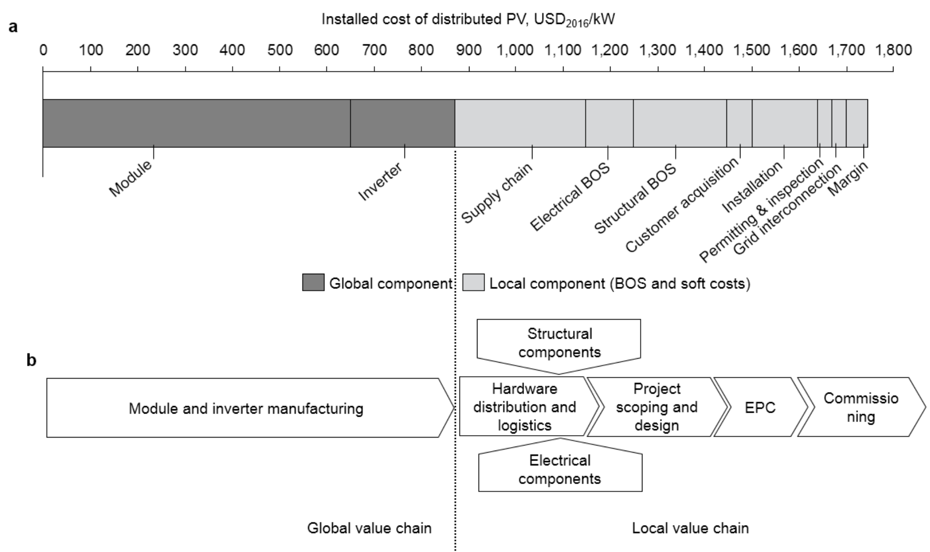

Figure 4: Installed costs of distributed PV and PV value chain: (a) Breakdown of distributed PV costs (data from IEA-PVPS (2016)) and (b) PV value chain steps

4.1.1 Scale effects

Scale effects, including the realization of economies of scale and the development of a competitive local PV ecosystem, prove most relevant for value chain activities in which overhead and fixed costs are key drivers. For example, generally bulk procurement of imported panels and inverters decreases *supply chain costs* by reducing small-scale procurement premiums and allowing firms to spread overhead costs of logistics over a larger volume of equipment. While this effect certainly holds for within firm operations, it also can occur on an industry-scale. In particular, economies of scale help accelerate the establishment of local module and inverter supply chains. While a quality supply chain may develop in the absence of a utility-scale market, the higher volumes associated with utility-scale PV often make it more attractive for quality international module and inverter suppliers to enter the market at an earlier stage, allowing smaller developers of distributed PV to then tap into these quality local supply chains. In some cases, these supply chain spillovers can occur directly, resulting in especially high spillover values. For example, in instances in which utility-scale solar EPCs over-procure equipment, they may coordinate with local rooftop EPCs, as one interviewee explained that "it's just not worth it to move [the PV modules] to a warehouse or to get them back to the factory. It [would] be better to give them away for free in some cases." This coordination can also happen intentionally within firms that operate across both small- and large-scale PV applications, where companies piggyback equipment procurement for small-scale jobs on their utility-scale jobs in order to share overhead expenses and leverage the buyer bargaining power of large-scale procurement agreements.

For *margins*, interviewees noted that increasing competition in utility-scale markets worldwide has undoubtedly squeezed EPC margins. However, decreasing utility-scale margins appear to have little impact on distributed PV margins, particularly in countries in which regulatory frameworks differ considerably across applications,[11] as the hurdle in adapting a PV business model tailored to these frameworks often creates barriers for solar firms to horizontally diversify by entering the distributed PV market if the utility-scale market is saturated. However, in markets without these barriers, one can observe a convergence of business models, with local utility-scale EPCs and project developers diversifying into the distributed market, thereby increasing competition in this segment as well.

4.1.2 Learning-by-interacting

Learning-by-interacting is a crucial spillover mechanism for value chain steps that involve transactions between multiple stakeholders. In nascent PV industries, many processes such as *permitting, inspection and grid interconnection* are not yet standardized. As a result, the administrative and legal processes of

[11]For example, some states in the US have a net metering policy for distributed PV, but a renewable portfolio standard for utility-scale PV.

commissioning a PV project can lead to back-and-forth interactions that ratchet up project costs. However, increasing interaction between the regulator and the PV project developer builds a better understanding of how to govern this relationship more efficiently. For example, one solar firm noted that in developing their electrical diagrams for approval from the utility, "the same person is doing the designs and auto CADs on the one line [diagrams] for [both types of project] sites, and so he knows now what the utility wants, whether it's for a small-scale or a large-scale. So that knowledge [...] is helpful in both."

Additionally, learning-by-interacting and the development of a mutual understanding of stakeholder needs can lead to the eventual standardization of contracts and permitting procedures to reduce these transaction costs. Typically, early movers in the PV industry will have to provide some education to local municipalities and distribution companies regarding how to streamline regulatory processes [81]. This process is generally facilitated if it comes through a more centralized industry body, rather than the dispersed structure of many immature distributed PV industries.

Finally, to some extent, learning-by-interacting spillovers occur between PV users and producers. Often firms have used their reputation or track record in a market as a way of demonstrating the viability of solar to consumers. In this way, the awareness created due to the success of utility-scale PV may indirectly lead to lower *customer acquisition* costs, however interviewees indicated that this effect is highly context-specific, not very significant, and difficult to quantify.

4.1.3 Learning-by-doing

Aside from these purely market scale effects, learning-by-doing spillovers occur for value chain steps that are largely process-driven (i.e. labor- or manufacturing-intensive). The most straight-forward example is learning-by-doing in *installation* processes, as has been noted in previous literature [82]. The interviewees indicated that, while installation processes between utility-scale and distributed PV are not identical, many of the installation steps necessitate similar technological capabilities and training. As a result, solar firms active in multiple PV market segments can utilize at least some members of the same crew for both installations. Many large-scale solar PV firms operate their own training programs, thereby bringing in a coordinated and often high-quality training regime to the local labor market. In contrast, many newly formed distributed markets utilize installers with more generic capabilities, such as electricians. The fragmented nature of these installers and lack of quality standards in installations often slows this process of learning-by-doing.

In the supply of *balance-of-system components* such as electrical or structural components, learning-by-doing also is important to foster the build-up of capabilities within local component suppliers. According to several interviewees, often both electrical and structural BOS suppliers are horizontally integrated local firms with competence in a related field (e.g., aluminum structures for structural BOS suppliers); expanding their business to solar PV components typically requires some small degree of learning to ensure components meet industry standards. However, in order for local firms to take the decision to enter the PV market, the market size has to be large enough to justify the additional investments required to serve this new market. In this way, a utility-scale market, which provides greater market volumes, can also help kick-start this process of local learning-by-doing for BOS component suppliers.

4.1.4 Evidence for spillovers in local financial institutions

Finally, alongside spillovers that result in reductions in the installed cost of PV, interviewees explained that utility-scale PV experience can debottleneck financing for distributed applications. As mentioned previously, lack of access to debt finance is a major barrier to PV adoption [13,83]. Even in countries that have functioning commercial and micro-finance institutions, lending for distributed PV is often limited and expensive due to a lack of understanding of PV technology and its risks. Interviewees involved in the financing of PV noted that the success of utility-scale PV projects can address this either by providing a track-record for PV technology in a new market or, in case local financial institutions are directly involved in financing utility-scale projects, can even foster learning-by-doing in financing PV. One financier noted that their small-scale PV lending business had "taken a lot of the learnings from the funding of the utility-scale renewable projects. We try to down-scale those, simplify them – taking the principles but not necessarily the due diligence heavy side of it." Spillovers in financing PV projects can potentially play an instrumental role in bringing down the lifecycle cost of distributed PV. However, due to the context-specificity of this effect, it was not considered in the model.

4.1.5 The magnitude of application spillovers

Figure 5 presents the results from the quantitative interviews, showing the distribution of interviewee responses for the magnitude of spillovers in each value chain step. Generally, spillovers are higher in the upstream value chain steps, including supply chain and supply of electrical BOS components, and lower in downstream value chain processes such as customer acquisition and installation. This result supports the idea of conceptualizing PV systems as a product platform [58], or a system comprised of several standardized components forming the "platform" and several customized components used to tailor the system to a specific application. While it has been argued that a product platform helps reduce system costs by allowing for mass production and economies of scale in these common components, the results from the interviews also show the importance of these common elements in fostering application spillovers – including in learning-by-doing in common processes. Standardizing processes, or expanding the common product platform, can therefore play a role in enabling greater spillovers in the future, as discussed further in section 5.

Several cost categories exhibit a relatively large spread in reported spillover values, including structural BOS and permitting and inspection. Interviewees explained this is often due to specific factors related to how markets evolved. For example, in contexts with a national regulatory framework for supporting renewables, spillovers in permitting and inspection are typically higher than in contexts where regulations are set at the subnational level (e.g., the US). For structural BOS, spillovers are typically higher when a market has developed technical standards for systems. This suggests that policymakers can design frameworks to foster greater spillovers, as explained in section 5.

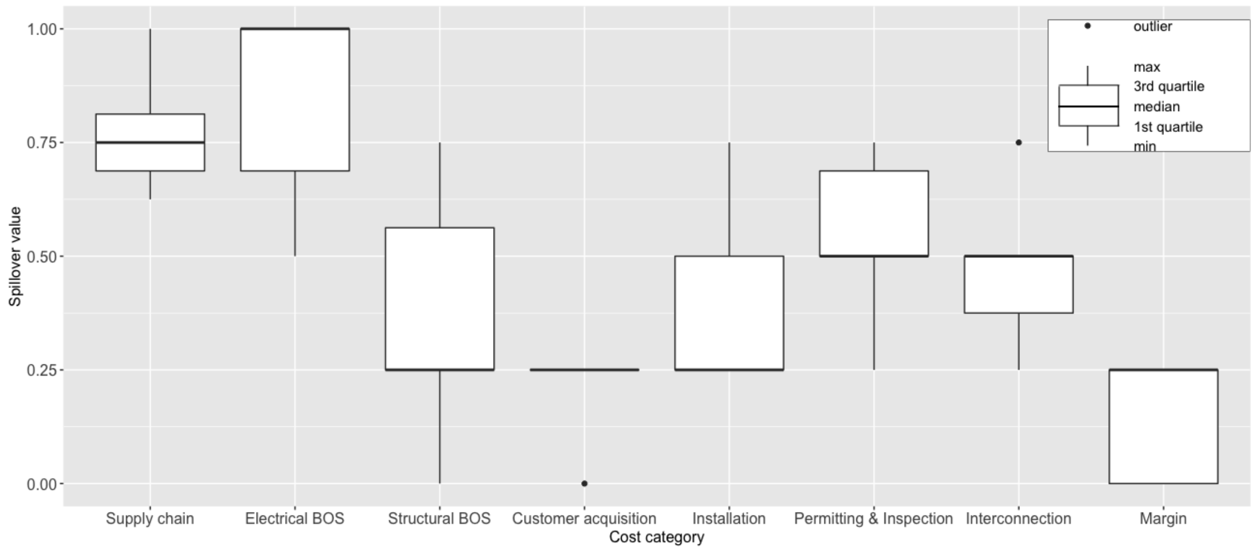

Figure 5: Boxplot of spillover values across solar PV applications as reported in structured interviews

Table 1: Summary of application spillovers across the PV value chain

Cost category	Definition	Key spillover mechanism	Exemplary quotes	Spillover average, α
Supply chain	Cost of modules and inverters above the factory-gate price	Scale effects: • Improved access to technology suppliers • Economies of scale in procurement • Stability of demand	"Without the [utility-scale] program, pricing [of modules] would still be higher. The small developers would've struggled to get quality products...which would've resulted in more project failures, which would've impacted on confidence in the industry, which would've made for significantly slower roll out." "[a utility-scale program] develops the value chain in the country, so you have more available products on sale in that market"	0.79
Non-inverter Electrical BOS	Cost of non-inverter electrical equipment required to deliver energy generation from the module (DC) to the load or grid (AC)	Learning-by-doing Scale effects • Sufficient volumes for business diversification	"The reality is that the components that you have in a small-scale PV system, all of those you have in the utility-scale. In the utility-scale you also have much more."	0.90
Structural BOS	Cost of physical system that holds the modules against natural forces (e.g., gravity, wind) and deters theft	Learning-by-doing Scale effects • Sufficient volumes for business diversification	"A lot of these businesses have developed off existing businesses. People that have aluminum plants have gone into framing." "If players are very small, I think a lot of them are not using the equipment right, they would even be soldering their own structures, racking systems...instead of using standardized systems that could, in the longer term, reduce prices even more."	0.40
Customer acquisition	Cost of generating project leads and tailoring PV systems to customer specifications	Learning-by-interacting Learning-by-doing in PV system design	"The positive has just been creating awareness, so the fact that big PV projects are being built has been, to the general public...just introduced them as technologies that exist and can work." "All the high-level models and templates for proposals are shared across the board"	0.21
Installation	Cost of labor and installation equipment associated with system integration	Learning-by-doing • Development of standards Scale effects • Efficient utilization of installers	"Installing one kilowatt of solar modules on a roof is probably more expensive than installing one kilowatt of solar on the ground, but you still need workers to do that, with the same capabilities, with similar training, similar skills."	0.38
Permitting & inspection	Cost associated with administrative and legal processes to obtain permits and approval for installation	Learning-by-interacting	"Some of the things that help us in that is relationships and reputation. So if one side or the other gets on the bad side of the local jurisdiction it makes it tough for the other side. So small-scale, large-scale, whatever. If the permitting office no longer	0.56

			trusts your company, or something like that, it makes it a lot harder to get permits and approval.”	
Grid interconnection	Cost associated with administrative and legal processes of interconnecting to the electric grid	Learning-by-interacting • Development of standards	“Standardizing contracts...having something created that works for all stakeholders – that takes part of the legal [cost] out of the process. If the utility isn’t happy...then there’s a lot of back and forth.”	0.46
Margin	Margin incurred throughout the value chain to cover overhead expenses and profit	Scale effects: • Competition	“[you see] ever-decreasing margins and ever-increasing competition... On your suppliers you’ve got these [development] arms and they’re now competing with us...you’ve got the traditional contracting entities that are taking on this EPC role, you’ve got [Independent Power Producers] who are investing in this space, buying up EPC companies and so it’s a highly competed business”	0.13

4.2 Quantifying the impact of application spillovers

The following sections present the results of the model that illustrates the potential impact of application spillovers from both a policymaker perspective as well as a household investor perspective.

4.2.1 The impact of spillovers on the cost of a distributed PV policy

Figure 6 shows the impact of spillovers on the upfront cost of distributed PV assuming utility-scale deployment of 1 GW over two years and distributed PV deployment of 300 MW by 2025 (see Section 3.2.2). Compared to the case without any utility-scale deployment (i.e. no spillovers), by 2025, spillovers result in a reduction of upfront distributed PV costs of 13.33 US $cents_{2025}$ per Watt, with the largest cost reduction levers being the supply chain cost and the installation cost. Permitting, inspection, and grid interconnection costs, as well as the customer acquisition and margin result in very few spillovers, both due to their low spillover value as well as their relatively low contribution to the overall upfront cost.

This utility-scale deployment results in a positive policy cost, stemming from the cost of support needed to close the profitability gap between utility-scale PV and the assumed baseline technology. This policy cost can be thought of as the required subsidy to reduce the upfront cost of distributed PV by 13.33 US $cents_{2025}$ per Watt. If this policy cost is divided by the volume of distributed PV deployed, it results in an equivalent subsidy of 0.11 US $cents_{2025}$ per Watt of installed distributed PV capacity– nearly 130 times less than the resulting per-Watt reduction in PV cost due to the spillovers it induces, as seen in Figure 6. In this way, employing a utility-scale PV deployment policy can leverage significant reductions in the upfront cost of distributed PV – and potentially large policy savings for countries that have intended to increase distributed PV adoption by directly providing upfront subsidies or credits for distributed PV investments.

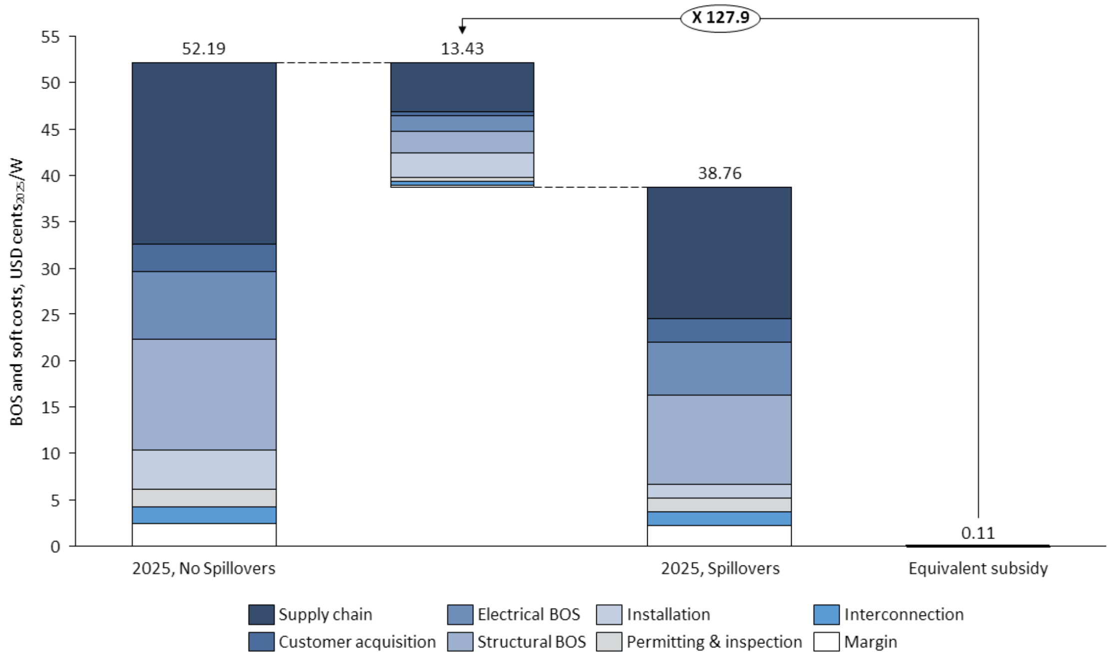

Figure 6: Impact of application spillovers on the BOS and soft costs of distributed PV

4.2.2 The role of spillovers in fostering more equitable PV adoption

Reducing the upfront cost of distributed PV represents only one lever to improve its investment case: profitability also depends highly on the economic *returns* of this investment. In the case of a net metering policy, the economic returns are the value of the avoided cost of electricity spending. Consequently, a higher electricity tariff provides a more attractive investment case. Figure 7 illustrates this effect using the case of peninsular Malaysia. A high difference in tariff levels exist between the block of high electricity users consuming more than 900 kWh per month and low electricity users consuming less than 200 kWh per month, with tariffs set at approximately 14.8 US cents per kWh and 5.7 US cents per kWh, respectively.[12] As a result, in the absence of spillovers, distributed PV proves highly profitable for high electricity users, yielding an initial NPV per investment cost of 4 that increases over time (see Figure 7a). For the lowest consumption bracket, however, distributed PV investments remain unprofitable until 2023, and only barely realize an NPV greater than zero by the end of the modelling period. Figure 7a also shows the profitability for the *average* domestic tariff of 7.1 US cents per kWh. The NPV considering this

[12] Tariffs for domestic consumers as of February 2018 were taken from the Tanaga Nasional Berhad website and were converted using exchange rates as of February 2018 of 0.26 MYR = 1 USD

average tariff is positive already in 2019, it also provides an indication of the distribution of consumers across the tariff blocks, illustrating that a large share of consumers fall in the tariff block in which solar PV is not profitable.

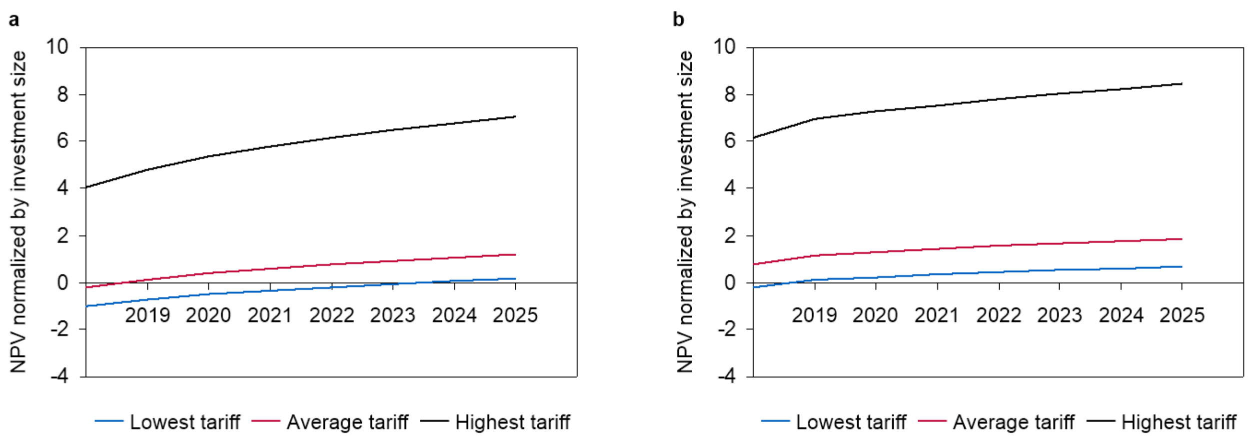

Figure 7: Profitability of distributed PV investments across tariff brackets in Malaysia represented as the net present value of the investment divided by the investment cost (a) with no application spillovers and (b) with application spillovers

Given that electricity consumption typically correlates with income, the large disparity in profitability across tariff blocks raises issues of equity: not only are the higher income households more likely to adopt and reap the benefits of solar PV, their decreased consumption from the electric utility threatens the redistribution mechanism built into the tariff block scheme. As utility revenues from these higher tariff customers decrease, closing this revenue gap must either fall to the public budget or onto lower income households in the form of a tariff price increase. Figure 7b shows the NPV in the case of application spillovers. While large discrepancies between tariff blocks still exist, distributed PV now yields a positive NPV even for the lowest tariff starting in 2019. Although additional policy interventions may be needed to facilitate PV adoption in this lowest income category, such as access to debt finance, this modelling exercise shows how spillovers can lead to more equitable outcomes under a net metering policy.

5 Discussion and conclusions

Rather than the idea that deployment of PV in one application will cannibalize deployment in the other, this analysis has shown how deployment of utility-scale solar can lower the cost of deployment of distributed PV. In addition to providing qualitative insights into the spillover mechanisms across solar PV applications, this paper has found that, by leveraging these spillovers, policymakers can cost-efficiently reduce the cost of distributed PV, helping improve its profitability across different user groups.

In order to maximize application spillovers, policymakers could consider implementing a solar PV deployment policy "package." Such a package should provide sufficient market volumes in its utility-scale deployment program to incentivize the development of local PV value chains, but should send a message to the private sector that a parallel distributed market will also be supported. Sending this signal early allows firms active in the utility-scale PV value chain – including EPC companies, financiers, BOS service providers – to already begin forming relationships, building capabilities, and laying the groundwork for engaging in a distributed PV market. This package could be implemented at the national level or even at the municipal level. For example, municipalities could complement large-scale tenders or community-solar projects with a distributed PV deployment policy.

In addition, given the spillovers across PV applications, such a policy package could have implications for the development of local PV industries. Several countries have implemented utility-scale renewable energy policies with an intent to foster the development of local green industries, often utilizing local content requirements [2,84]. However, in the case of solar PV, local deployment only tends to foster local learning in BOS and soft costs [55]. Consequently, utility-scale policies could specifically support the build-up of capabilities in these downstream activities, which would not only lead to greater spillovers to the local market but would also be further reinforced with distributed PV deployment.

It is important to note that this paper has assumed that implementing a utility-scale PV policy often faces lower barriers due to its lower cost and more centralized coordination. However, several countries are facing challenges with their utility-scale deployment schemes, including opposition from national utilities or unviable bids submitted in renewable energy auctions [85,86]. While in some cases, this stagnation has led utility-scale companies to intentionally diversify into the distributed market (e.g., in China or South Africa), setbacks at an early stage of the utility-scale market could also negatively affect the development of the distributed PV market.

Policy can also play a role in facilitating learning-by-doing and learning-by-interacting spillovers. With regards to learning-by-doing, policymakers should adopt a coordinated approach in which regulatory processes are standardized as much as possible across applications and jurisdictions, as well as coordinate the development of national standards and certification programs for installation. While the development of standards for PV has been proposed as a means of reducing cost (see e.g. [57,58,87]), discussions have largely been limited to standardization within a single PV application. Increasing the commonalities between utility-scale and distributed PV processes will provide greater opportunities for value chain actors to transfer and accumulate knowledge through learning-by-doing in PV project implementation. Regarding learning-by-interacting, interviewees indicated that spillovers are highest and most likely *within* a single entity (i.e. if a firm is involved in both small- and large-scale PV markets). Previous literature also has identified that industry structures in which value chain actors operate in siloes create barriers to knowledge spillovers [31]. While these siloes have been overcome in some cases – particularly in contexts in which a strong PV industry association exists – policy could help facilitate learning-by-interacting by supporting forums and channels for industry exchange. In South Africa for example, a national renewable energy technology center (SARETEC) primarily provides renewable energy training courses, but also acts as a conduit for industry exchange, by establishing partnerships with local universities, industry, and research institutions throughout the country.

Finally, this paper has only considered application spillovers to occur within national boundaries. In reality, spillovers could occur regionally, with a strong utility-scale solar PV market in one country creating spillovers in neighboring countries. Consequently, multilateral development banks could consider implementing solar strategies that seek to create these regional spillovers, by streamlining the processes and providing the support to allow local PV value chain actors to operate both across PV applications and across geographies.

This paper has proposed that policymakers can lower distributed PV adoption barriers by fostering spillovers from local utility-scale PV deployment. This analysis, however, was limited only to the impact of spillovers in reducing the upfront cost of PV systems. However, knowledge spillovers are also possible in the financing of solar PV projects, in the operation and maintenance of PV systems, as well as in creating enabling frameworks for PV investment (policy learning). Future research could explore these channels, particularly as they also pose a key bottleneck in nascent distributed PV markets.

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Appendix A

The model covers the time period from 2017 to 2025, assuming that PV investments are made at 2016 prices, and operation of the PV plant begins in 2017. The following tables outline the input parameters assumed for the model in both the generic case and the Malaysia case.

Table A.1: PV technology parameters

	Unit	Utility-scale	Distributed
Lifetime	yrs	25[1]	20[2]
Availability	%	100%	100%
Depreciation value	%	95%	95%
Population-weighted GHI[4]	kWh/m^2-yr	3000	3000
Capacity factor[3]	%	27%	16%

[1][1]
[2][2]
[3][3]
[4] Note that the population GHI and capacity factors are generally context specific, however typical values for Malaysia were assumed in the generic case as well.

Table A.2: Utility-scale PV installed cost parameters and learning rates

	Cost (USD_{2016}/kW)	Learning rate
Total investment cost (2016)	900[1]	
Module	650[2]	20%[3]
Inverter	100[2]	9%[4]
BOS and soft costs	150[1]	24%[4]
O&M cost as percentage of installed cost	1.50%[5]	-

[1]Based on benchmarks from [4–6]
[2]PV insights
[3][7–10]
[4][9]
[5][11]

Table A.3: Distributed PV installed cost parameters and learning rates

	Cost (USD_{2016}/kW)	Learning rate[5]
Total investment cost (2016)	1745	
Module	650[1]	20%[3]
Inverter	220[1]	9%[4]
Supply chain	278[2]	15%
Customer acquisition	53[2]	15%
Electrical BOS	100[2]	12%
Structural BOS	199[2]	12%
Installation	138[2]	31%
Permitting & inspection	30[2]	15%
Interconnection	30[2]	15%
Margin	47[2]	15%
O&M cost as percentage of installed cost	1.50%	-

[1]PV insights
[2]Cost breakdowns were taken from IEA-PVPS survey data from Malaysia, with the additional cost of the module and inverter over the global index allocated to the supply chain cost. The total installed cost is in line with values cited for other emerging

economies including Egypt (1700 - 2000 USD_{2016}/W [12]), Ghana (1600 USD_{2016}/W [13]), Thailand (1100-1800 USD_{2016}/W) or the Philippines (1200-1800 USD_{2016}/W) [14]
[4][7–10]
[5][9]
[6]Please refer to section below for details on learning rates

Table A.4: Financing parameters for PV

	Unit	Utility-scale	Distributed
Share of equity	%	30%	30%
Cost of equity	%	12.0%	6.0%
Cost of debt	%	6.0%	8.0%
Loan tenor	yrs	20	5
Corporate tax rate	%	20%	0%

Table A.5: Assumptions for natural gas baseline technology

Natural gas, combined cycle[1]		
Total investment cost (yr 1)	USD/kW	720
Capacity factor	%	80%
Thermal efficiency, gross LHV	%	51%
Fixed O&M	USD/kW	11
Variable O&M costs	USD/kWh	0.004
Lifetime	years	25
Share of equity	%	30%
Cost of equity	%	12%
Cost of debt	%	6%
Loan tenor	%	20
Fuel price[2]	USD/MWh	14.65
Corporate tax rate	%	20%

[1][15–17]
[2]Based on a benchmark of 5USD/MBtu, which although higher than the price of gas for electricity generation in the US (about 3.3 USD_{2016}/MBtu) is conservatively lower than a European benchmark for prices of gas imported from Algeria (7.8 USD_{2016}/MBtu) [18]

Table A.6: Macro-economic assumptions

Inflation[1]	%	1.5%
Public cost of capital[2]	%	6%

[1]Based on USD inflation rates
[2][19]

Derivation of component learning rates

While some research has looked into learning rates for balance of system components [9], this study considered BOS components (including soft cost components) in aggregate. For this study, it was necessary to have a benchmark of learning rates for individual components as some components – such as structural and electrical balance of system components – will undergo significantly less learning [20]. Benchmarks for components learning rates were calculated based on data from distributed rooftop PV in the US from 2010 to 2016 [5]. While learning rates for BOS and soft costs might be context-specific [21], the US data provides a more realistic of learning dynamics than assigning aggregate learning rates to all components. Due to data availability constraints, however, certain assumptions were needed for assigning learning rates. For example, the BOS hardware components were assigned the same learning rate, as were the soft costs (i.e. customer acquisition, supply chain, margin, permitting, inspection and interconnection).

All learning rates were derived assuming a single-factor log-linear relationship between cost development and cumulative national deployment of distributed PV system measured by installed capacity. The table below summarizes the coefficients and fits. Sensitivities to these derived values can be found in Appendix C.

Table A.7: Component learning rates and fits

Component	Linear fit coefficient	Derived learning rate (%)	R^2
Electrical and structural BOS components	-0.17976	11.7	0.733
Installation	-0.5302	30.8	0.8208
Soft costs	-0.23049	14.8	0.726

Global PV deployment

Global PV deployment assumptions were taken from the World Energy Outlook's Current Policies Scenario, which is used as a benchmark in the report as it considers all policies implemented as of mid-2017. The global PV deployment in this scenario is given only in the years 2016, 2025, 2030, 2035, and 20140. Consequently, global deployment in intermediate years was interpolated assuming the trajectory shown below.

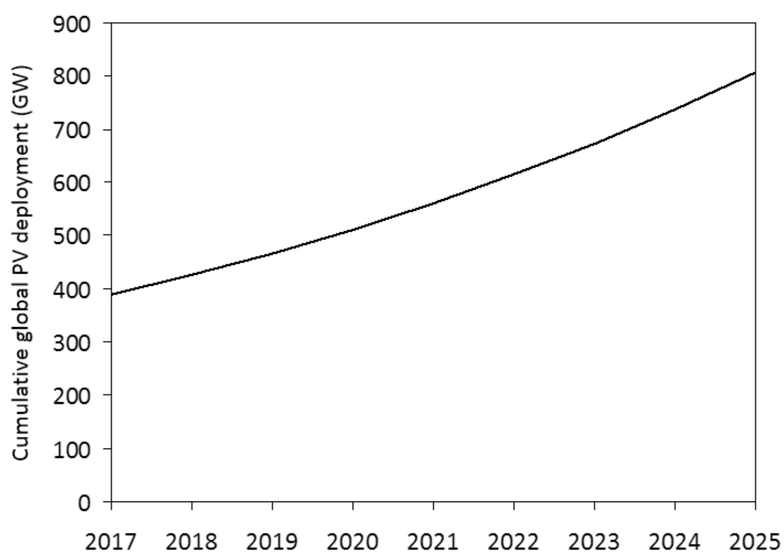

Figure A.1: Cumulative global PV deployment

Appendix B

Structured interview methods

For each cost category, interviewees were given a clear definition of the scope of this category, the key stakeholders and processes involved, and cost drivers, as illustrated in the example figure below. For each of these categories, interviewees were asked three questions: (1) On a scale from 1 to 5, to what extent do the processes/components for small-scale PV overlap with the processes/components for utility-scale PV?; (2) What are the key levers to reduce this cost for small-scale PV?; and (3) Would a cost reduction in this category for utility-scale PV lead to a cost reduction for small-scale rooftop PV? Why or why not?

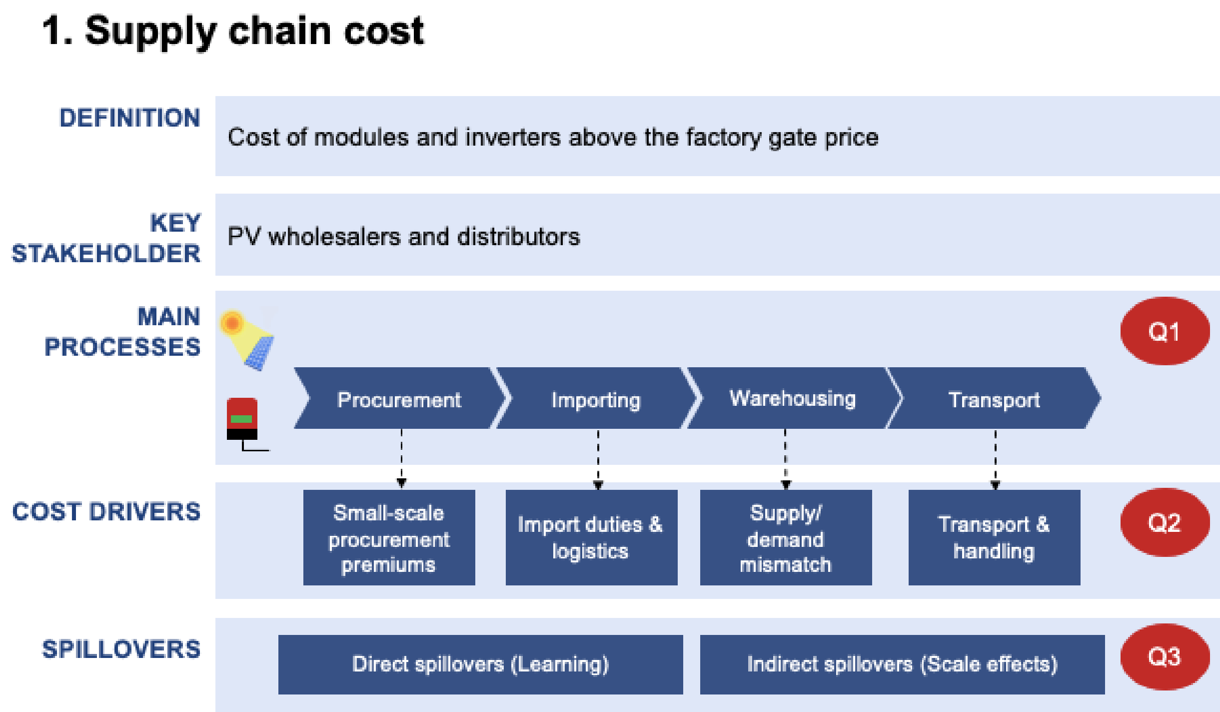

Figure B. 1: Sample structured interview guidance document

Interviewee sample

The table below provides a breakdown of the interviewee sample. In the semi-structured interviews, 4 out of the 7 interviewees were working in an emerging market, and in the structured interviews, 5 out of the seven interviewees were working in emerging markets.

Table B. 1: Breakdown of interviewees

	EPC / Vertically integrated solar firms	Finance	Industry expert / Industry association	*Total*
Emerging economy	5	2	2	9
Europe	1		1	2
US	3			3
Total	9	2	3	

Appendix C

In order to verify the robustness of results to input parameter assumptions, a sensitivity analysis was conducted for (i) the upfront cost of the distributed PV system in 2025; (ii) the profitability index for distributed PV investments in 2025; and (iii) the total policy cost of supporting distributed and utility-scale PV deployment. For all three outputs, sensitivities were assessed by changing the parameters in Table C.1 by +/- 20 percent. Note that some of the parameters are not relevant for all of the outcome variables (e.g., the upfront cost of distributed PV is not impacted by any assumptions about the baseline utility generation cost). The results of the sensitivity analyses are shown in Figures C.1, C.2, and C.3. For the profitability index and the total policy cost, only the 20 most important parameters are shown in the figures.

Table C.1 Parameters tested in the sensitivity analysis

Baseline full load hours	Fuel price	Installation learning rate	Permitting and inspection learning rate
Baseline investment cost	Initial customer acquisition cost	Installation spillover	Permitting and inspection spillover
Capacity factor	Initial electrical BOS cost	Interconnection learning rate	Public cost of capital
Cost of debt	Initial installation cost	Interconnection spillover	PV lifetime
Cost of equity	Initial interconnection cost	Inverter learning rate	Share of equity finance
Customer acquisition learning rate	Initial inverter cost	Lifetime of baseline technology	Structural BOS learning rate
Customer acquisition spillover	Initial margin	Loan tenor	Structural BOS spillover
Distributed target	Initial module cost	Margin learning rate	Supply chain learning rate
Electrical BOS learning rate	Initial permitting and inspection cost	Margin spillover	Supply chain spillover
Electrical BOS spillover	Initial structural BOS cost	Module learning rate	Thermal efficiency of baseline technology
Fixed O&M of baseline technology	Initial supply chain cost	O&M cost	Utility target
			Variable O&M of baseline technology

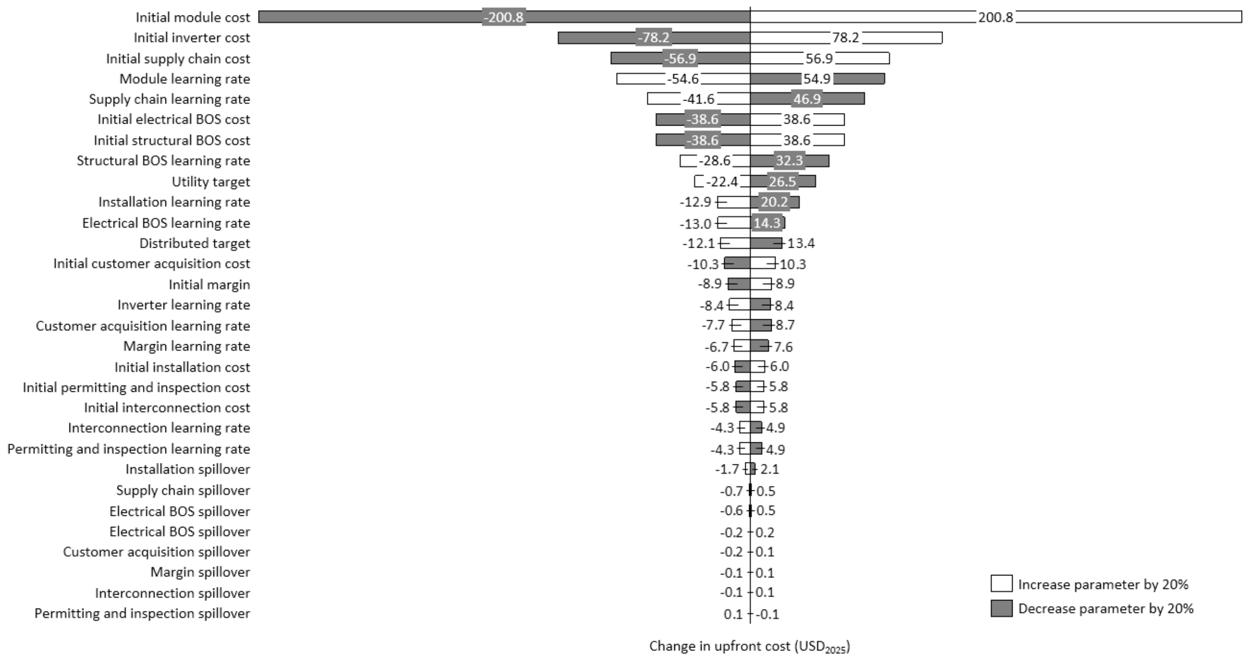

Figure C.1 Sensitivity analysis for the upfront cost of distributed PV in 2025

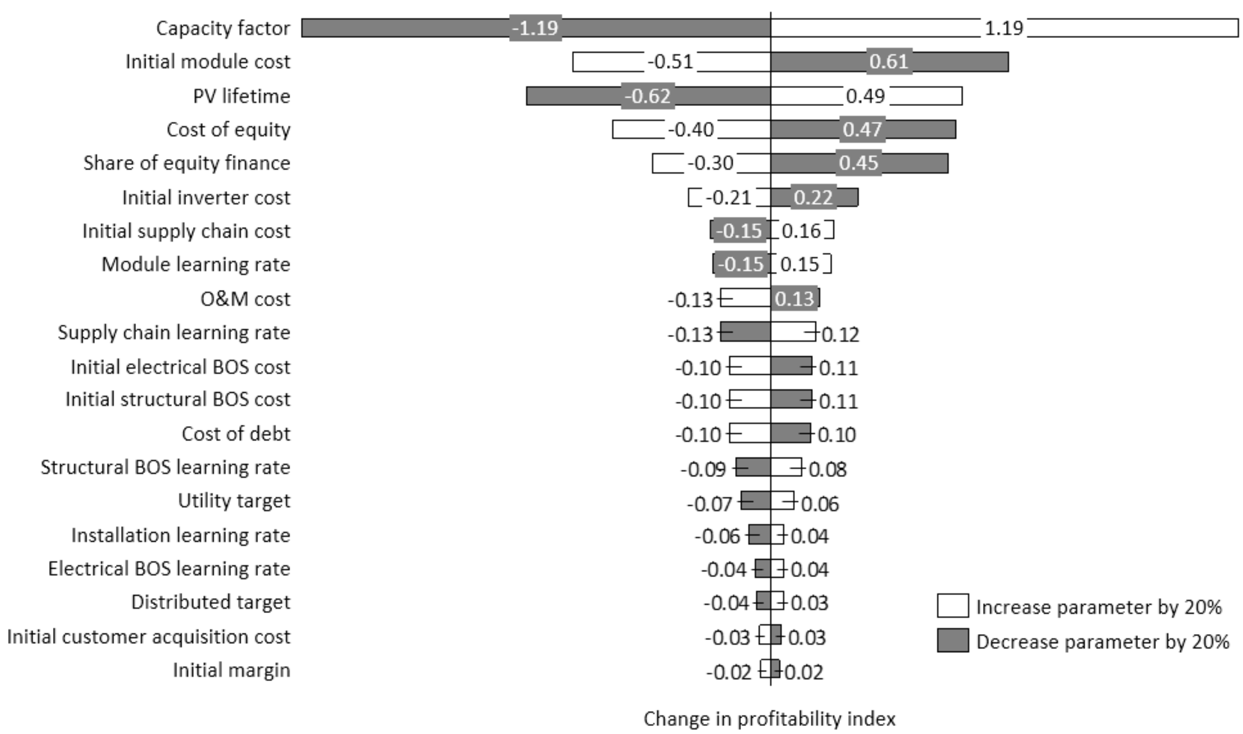

Figure C.2 Sensitivity analysis for profitability index for a distributed PV investment

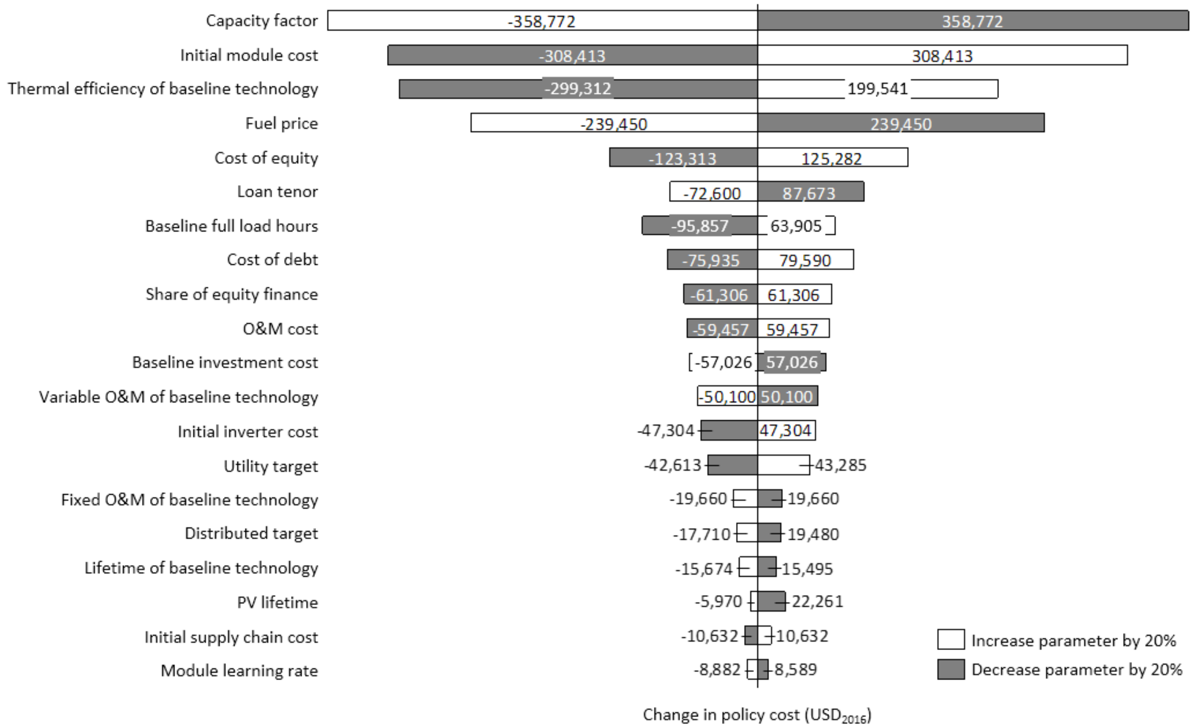

Figure C.3 Sensitivity analysis for the policy cost

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