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Executive Summary

PV's historically rapid cost reduction is exceptional among technologies. Further cost reductions could play a major role in increasing deployment in the future. To enable such cost reductions, new modeling frameworks are needed to understand the determinants of innovation in PV. In this project, we study the mechanisms driving PV module and system cost reductions, delving deeply into the specific technological innovations that have occurred in the past and the policies that encouraged them, and also opportunities for future cost reduction and widespread deployment. The project contributes new fundamental insight on the determinants of technological innovation by developing novel methods and insights that are generalizable and can therefore be applied to other technologies. The results will allow policy makers, engineers, and other stakeholders to better prioritize their efforts and investments in the future. The project is organized around four journal articles as described below.

The first article [1] identifies 'low-level' (e.g. conversion efficiency improvement) and 'high-level' (e.g. R&D efforts) mechanisms of cost reduction in PV systems (Tasks 1-4). This work builds on a previous DOE grant, where we developed a framework for technological innovation leading to PV module cost reduction [2]. We advance a method to disentangle the contributions of physical ('hardware') and non-physical ('soft technology') changes. Our results uncover reasons behind the relatively slow evolution of soft technology and can inform new innovation approaches to these technologies.

The second article [3] identifies specific engineering or institutional innovations that enabled the low-level mechanisms of cost reduction in PV module and balance-of-systems (BOS) (Tasks 5, 9, 10). We identify 85 innovations and connect them to the cost variables they affected. By developing an innovations typology, this study shows the differences between the types of innovations affecting PV modules and BOS components. Finally, by analyzing the industry origins of innovations, this study also finds that PV was well-positioned within an ecosystem of continuously advancing technologies.

The third article [4] studies prospective cost reduction opportunities (Task 10). We explore how design approaches that emphasize standardization and automation, such as plug-and-play PV systems, can create cost reduction opportunities by reducing interactions and speeding up activities with high process costs. We show that this can lead to cost reduction in cost components with the most untapped opportunity for improvement such as installation labor, overhead, electrical BOS, and customer acquisition.

The fourth article [5] analyzes how various policies supporting PV deployment and R&D contributed to PV's cost improvement by enabling high-level mechanisms, specific innovations, and ultimately low-level mechanisms of cost reduction (Tasks 8, 13, 14). We investigate examples from different countries and connect these policies to quantifiable cost change mechanisms. Our study sheds light on the roles that different nations played over time, through a diverse set of policy approaches.

Contents

Background

PV cost improvement and innovations in solar energy technology been studied by several research communities. Experience curve studies have shown that the cost of modules has declined more rapidly than that of many other technologies [6]. For non-module or balance-of-system costs, however, studies have found both slower improvement rates than for modules [7], and comparable rates [8]. Other statistical studies of PV system prices have found that lower prices are more common for larger systems (due to scale economies), for systems installed with new construction, in areas with greater installer density and experience, and in markets where customers receive more quotes [9, 10, 11]. However, cost-reducing factors have been shown to vary between low- and high-priced systems [12], pointing to a need to uncover the mechanisms underlying local price distributions.

Another group of studies has constructed bottom-up models of PV system costs in individual countries to identify the cost categories that differ across countries. Cost differences between the U.S. and other countries have been attributed primarily to soft costs, including customer acquisition and installation costs, design costs, and financing costs [13, 14, 15, 16]. While these studies have consistently pointed to soft costs as causes of cost differences, their focus is on individual points in time. Understanding where cost differences originate, however, requires a consideration of cost drivers over longer time periods. For example, studies have shown that German and Australian workers take less time to install PV systems [15], but it remains unclear whether this was always the case, or resulted from improvement efforts that could be replicated elsewhere.

Previous work has also developed hypotheses on the processes shaping hardware and soft cost behaviors more generally. Global knowledge production and exchange through international supply chains, as well as technology standardization, have been associated with processes of hardware cost reduction [17]. In contrast, soft costs are rooted in the regional context, and affected by the co-evolution of installer, financer, insurer, as well as PV system operator and owner competences [18, 19, 20]. However, while these studies have postulated that hardware and soft costs change through different processes, they have not asked how these processes affect rates of cost improvement.

There is also a rich literature on the role of policies in driving technology evolution. Papers have studied the complementary innovative activities stimulated by government R&D support and market expansion policies [21], the importance of public funds to support 'risky' R&D on early-stage technologies [21, 22], and the importance of combining different types of policy instrument to stimulate a variety of innovative efforts (e.g. [23, 24]).

Our project brings together insights from and closes gaps in previous literature on the drivers of PV cost change and technology evolution more broadly. First, we extend the cost change modeling framework developed in [2] from modules to PV systems and develop a new method to disentangle the contributions of changing hardware and soft technology to the overall cost change observed in a technology [1]. This part addresses shortcomings in previous work that examined PV soft costs through correlational analyses (e.g. [9]) and bottom-up models at individual snapshots in time (e.g. [14]) but did not identify the fundamental drivers of soft cost change and how they relate to PV cost differences across countries. Doing so requires a model to connect changes in the characteristics of equipment (hardware features) and deployment processes (soft technology features) to changing hardware and soft costs. In developing and applying this model, we begin to address knowledge gaps on the relationships between hardware and soft technology, which affect not just PV but several energy technologies with rising shares of soft costs [1].

Second, we used the PV system cost equation as an organizing framework to identify specific innovations that have influenced PV cost variables and led to cost reductions [3]. This is the first study to examine in-depth the micro-level changes in PV module designs and manufacturing, inverters, and other components that have contributed to PV's cost decline. This work builds on previous studies on the state of PV technology (e.g. [25]) to reconstruct the timeline of innovations. We expand the literature on energy technology innovation by characterizing innovations along a number of dimensions that haven't been studied previously. We examine what type of technology evolution PV innovations have induced (automation, standardization, component integration, etc.), in which industry they originate, and whether they drive change through changes in hardware or in processes ('soft innovations').

Another goal of this project was to use insights from the historical cost evolution of PV to identify avenues for future innovation. To achieve this we studied in depth one proposed PV design that is representative of broader industry and research efforts to automate and standardize PV installation—plug-and-play systems. We characterized the reduction in system complexity achieved by plug-and-play-like designs by taking a new approach that quantifies the change in interactions between various elements of a PV system (e.g., system components, actors) relative to standard rooftop system designs [4]. In this way we build understanding of the design changes and related cost reduction mechanisms plug-and-play and other design efforts to automate and standardize PV deployment could support. While our approach draws on the systems engineering literature (specifically on design structure matrices [26]), it differs from previous studies on plug-and-play systems. These studies have either estimated market sizes [27] or demonstrated the cost and technical feasibility of plug-and-play systems [28, 29], but have not asked how the design changes introduced in plug-and-play systems alter conventional system architectures and promise cost reductions. Doing this has enabled us to develop an approach that can be applied to study design changes in any technology for which a design structure matrix can be populated.

Lastly, we examined the high-level mechanisms that drove PV cost change in the larger context of government policies that supported R&D and market expansion. Through a comparative analysis of policies in the U.S., Germany, Japan, and China, we study the complementary nature of policy support for R&D to improve PV technology, and policy support to expand markets and drive down equipment and installation costs through economies of scale and learning-by-doing [5].

Project Objectives

The goal of the project is to understand in detail the causes of cost reductions achieved in the PV industry in the past, in order to inform the future development of PV and develop fundamental understanding of technological innovation. We study how specific previous technical innovations and public policies affected PV cost historically. From this we derive recommendations for further improvement.

The project is organized around three main objectives. The first is to identify 'low-level' (e.g. conversion efficiency improvement) and 'high-level' (e.g. R&D efforts) mechanisms of cost reductions in PV systems. This work extends a framework, which we had built during a previous DOE grant (SEEDS I) [2], to PV systems. The second objective is to identify specific engineering or institutional innovations that enabled the low-level mechanisms of cost reduction. The third objective is to understand how various policies supporting PV deployment and R&D contributed to PV's cost improvement by enabling high-level mechanisms, specific innovations, and ultimately low-level mechanisms of cost reduction. The research requires both retrospective and prospective analyses, identifying determinants of past evolution and elucidating future pathways for PV. These analyses are informed by extensive datasets, and each objective involves data gathering.

This work produces methods to explain the dramatic innovations seen in the PV industry over the past few decades, and develops insights on how to sustain these trends. SEEDS II funding allows us to build directly on research results produced with funding from a SEEDS I grant. We now extend this effort beyond the scope of PV modules to PV systems, and to understand specific innovations that affected module costs, and how different policies supporting R&D and deployment supported innovation in PV.

Our retrospective modeling provides important insight into how innovations emerge and spread, and how innovations impact costs. We will develop a comprehensive and foundational understanding of solar technology evolution by combining theories of technological change from economics, engineering, and management science. Our prospective modeling efforts leads to an improved understanding of potential opportunities for and limits to future cost decline in PV modules and BOS (hard and soft cost components); and recommended strategies to prioritize R&D.

The results inform public policy supporting PV diffusion (market based mechanisms, command and control policies, and a variety of subsidies). More generally, the knowledge created is expected to help numerous other private and public actors effectively channel their resources (time, money) into accelerating clean energy development. These include high-level government officials formulating energy and climate policy, technical researchers working on developing PV, and decision makers at private firms who need to understand the future direction of the industry.

Our methods are generalizable and can therefore be applied to other technologies that are of interest to the US Department of Energy. This outcome supports the FOA objectives by providing actionable tactics for PV development and adoption through the analysis of the successes and failures of past policies.

Another outcome is a new data set capturing the rich history of PV's cost decline and key determinants, from advancements in the laboratory to legislative innovations. This data are made public in our publications. This outcome is in line with the objectives in the FOA and will help build the foundation for further quantitative analysis.

Below is the summary of the tasks within the Statement of Project Objectives (SOPO) for the entire project, including the milestones and go/no-go decision points.

Task	Activity
	BUDGET PERIOD 1
T1	Develop cost model for PV systems
ST1.1	Collect cost model data
ST1.2	Develop cost equation for PV systems
M1.1	Finalize cost equation for PV systems, which describes cost components as completely as possible given the available historical data, and captures variables that are most important for identifying the drivers of cost reduction. The cost equation will be reviewed by a minimum of three industry experts as a check to ensure it represents the industry. The final equation along with written feedback from the industry experts will be shared with the DOE through a grant report and a quarterly presentation.
T2	Develop cost change equations
ST2.1	Derive cost change equations
ST2.2	Develop computer code to implement cost change equations
M2.1	Cost change equations to accurately quantify the contribution of key variables to PV systems cost reduction have been obtained. The cost change equations have been thoroughly checked to ensure they are derived correctly and that the code obeys a variety of validation checks. These include standard checks such as making sure that data has been entered correctly, that equations have been implemented in the code correctly, and that the code produces reasonable results when variables are changed (e.g. when efficiency is changed by a certain percent in a year, the contribution of efficiency to the cost change should be reasonable in terms of sign and quantity). The final cost change equations will be shared with the DOE through a grant report and a quarterly presentation.
T3	Estimate effect of low-level mechanisms for PV systems
ST3.1	Perform low-level estimation
ST3.2	Perform sensitivity analysis of low-level mechanisms
ST3.3	Review literature for low-level mechanisms
M3.1	Estimated contributions of each low-level mechanism have been obtained using cost change equations. The uncertainty in results due to methods and data has been studied through sensitivity analyses. The results have been checked by a variety of validation tests. These include standard checks such as making sure that data has been entered correctly, that equations have been implemented in the code correctly, and that the code produces reasonable results when variables are changed. Sensitivity analysis will let us probe the uncertainty in results due to methods and data. The results will be shared with the DOE through a grant report and a quarterly presentation.
T4	Estimate effect of high-level mechanisms for PV systems
ST4.1	Perform high-level estimation
ST4.2	Perform sensitivity analysis of high-level mechanisms
ST4.3	Review literature for high-level mechanisms
M4.1	Estimated contributions of each high-level mechanism have been obtained and the uncertainty in the results due to methods and data has been studied. The correctness of our calculations will be verified by thorough a variety of validation checks: verifying that the data has been entered correctly, that the categorization of low-level variables has been implement accurately, seeing that the code produces reasonable results when variables are changed, and seeing that estimates for high-level mechanisms make sense numerically given our estimates for low-level mechanisms. The results will be shared with the DOE through a grant report and a quarterly presentation.
T5	Preliminary innovations classification and hypotheses
ST5.1	Develop classification scheme for innovations and preliminary table
ST5.2	Develop hypotheses about important innovations
M5.1	A classification scheme for innovations has been developed and used in the preliminary innovations table, and hypotheses about most important innovations have been generated. The findings will be shared with the DOE through a grant report and a quarterly presentation.
T6	Graduate student training
T7	Research dissemination
M7.1	Research has resulted in at least one journal publication to help disseminate results to industry, academic, and policy communities to help influence solar development, and researchers will have presented their results in at least one conference. Opportunities for press outreach have been exploited.
Go/ No-Go 1	Cost change contributions for PV systems for low- and high-level mechanisms have been estimated, results have been assessed for their sensitivity to model assumptions and sources of uncertainty (including the values of fixed parameters and low-level variables); the cost equation has been reviewed by at least three external experts; computer code and quantitative estimates have been thoroughly checked and observed to satisfy consistency checks; the results have been compared with existing hypotheses within the literature on determinants of PV system costs; preliminary hypotheses regarding innovations and policies have been developed.
	BUDGET PERIOD 2
T8	Preliminary policies classification and hypotheses
ST8.1	Develop classification scheme for policies and preliminary table
ST8.2	Develop hypotheses about important policies
M8.1	A classification scheme for policies has been developed and used in preliminary table, and hypotheses about most important policies have been generated. The findings will be shared with the DOE through a grant report and a quarterly presentation.

T9	Develop table of innovations and low-level mechanisms
ST9.1	Compile list of innovations
ST9.2	Determine mechanisms affected by each innovation
M9.1	The list of innovations has been completed. The findings will be shared with the DOE through a grant report and a quarterly presentation.
M9.2	The innovations-mechanisms table has been completed. The findings will be shared with the DOE through a grant report and a quarterly presentation. The innovations table has been sent to three outside experts to determine that it is comprehensive of all key historical innovations needed to understand PV system cost evolution.
T10	Study factors conditioning innovations
ST10.1	Quantify effects of innovations
ST10.2	Study factors that help or hinder innovations
ST10.3	Gather data on innovation factors
M10.1	Models to quantitatively relate innovations and low-level mechanisms have been obtained. These models have been shared with outside experts for validation. Results and feedbacks have been shared with the DOE through a grant report and a quarterly presentation.
M10.2	The effect of key innovations have been quantified and the origins have been identified. The findings will be shared with the DOE through a grant report and a quarterly presentation.
T11	Graduate student training
T12	Research dissemination
M14.1	Research has resulted in at least one journal publication to help disseminate results to industry, academic, and policy communities to help influence solar development, and researchers will have presented their results in at least one conference. Opportunities for press outreach have been exploited.
Go/ No-Go 2	A table has been created mapping engineering and institutional innovations to variables of the PV cost equation, factors that help or hinder the development of innovations have been studied and quantified where data is permitting, and lessons extracted for promoting innovation for PV systems. The innovations table has been sent to three outside experts to solicit their input on the level of comprehensiveness of the key historical innovations identified to explain PV system cost evolution.
	BUDGET PERIOD 3
T13	Develop table of PV policies
ST13.1	Compile list of policies
ST13.2	Determine variables affected by each policy
M13.1	The list of policies has been completed. The findings will be shared with the DOE through a grant report and a quarterly presentation. The policy table has been sent to three outside experts to determine that it is comprehensive of all key policies related to PV cost evolution (both historical and current).
M13.2	The table of policies-variables has been completed. The findings will be shared with the DOE through a grant report and a quarterly presentation.
T14	Model the effects of policies
ST14.1	Develop model of policy influence
ST14.2	Gather data on policy factors
ST14.3	Estimate policy effects on costs
ST14.4	Develop policy recommendations
M14.1	The model of policy effects has been developed. This model has been shared with at least three outside experts for validation. The computer code implementation of the model has been put through a variety of checks to ensure that it functions correctly. The findings will be shared with the DOE through a grant report and a quarterly presentation.
M14.2	Estimates of policy effects on cost have been obtained. The findings will be shared with the DOE through a grant report and a quarterly presentation.
M14.3	Estimates of policy effects on diffusion have been obtained. The findings will be shared with the DOE through a grant report and a quarterly presentation.
M14.4	Policy recommendations on policy effects on cost and technology diffusion have been provided. The findings will be shared with the DOE through a grant report and a quarterly presentation.
T15	Graduate student training
T16	Research dissemination
M16.1	Research has resulted in at least one journal publication to help disseminate results to industry, academic, and policy communities to help influence solar development, and researchers will have presented their results in at least one conference. Opportunities for press outreach have been exploited.

Project Results and Discussion

Task 1: Develop cost model for PV systems

In this task we developed a cost equation for PV systems. We model PV system costs in $\$/W_{ac}$ as the sum of BOS costs and module costs. For module costs, we use the model developed in [2]. Our model does not account for subsidies and therefore represents unsubsidized PV system costs to the owner. For BOS, we split total cost into components which are then modeled individually. Tasks that are completed individually for each module, such as electrical and mechanical installation, are modeled as functions of the module number. Design and permitting are completed once per system. Although design drawings were completed by hand in the 1980s, suggesting a dependency of total design costs on the module count, historical sources indicate that detailed drawings on how to fix individual modules on roofs were completed only once per system.

The final result for costs in units of \$ per AC watt produced by the PV system is

$$C_{sys} = \frac{1+p_{op}}{K_{inv}\eta_{inv}} \Bigg[\underbrace{c_M K_s}_{\text{Module costs}} + \underbrace{c_{inv} K_s}_{\text{Inverter costs}} + \frac{1}{\eta_w} \Bigg(\underbrace{K_s \phi_a p_a}_{\text{racking aluminum costs}} + \underbrace{\frac{K_s \alpha}{A\eta_m n_{mc}\sigma}\phi_w p_w}_{\text{wiring costs}} + \underbrace{\tau_s w_s}_{\text{system design costs}} + \underbrace{\frac{K_s \alpha}{A\eta_m n_{mc}\sigma}\sum_{i=1}^{2}\tau_i w_i}_{\text{mechanical and electrical installation costs}} + \underbrace{\tau_{PII} w_{PII}}_{\text{PII labor costs}} + \underbrace{c_r}_{\text{residual racking costs}} + \underbrace{c_{oe}}_{\text{other el. hardware costs}} \Bigg) \Bigg] + \frac{1}{K_{inv,ac}\eta_{inv,ac}} \Bigg(\underbrace{c_{PII}}_{\text{PII fees}} + \underbrace{c_{sc}}_{\text{supply chain costs}} + \underbrace{c_{stax}}_{\text{sales tax expenses}} \Bigg), \tag{1}$$

where total system costs are written as the sum of module costs (c_M) and BOS costs. The product $K_s\alpha/\sigma n_{mc}A\eta_m$ gives the number of modules per system, which is multiplied by τ_i (per-module task durations) and w_i (task-specific wages) to give total labor costs (see Table 1). Module costs c_M are modeled as the sum of silicon costs, non-silicon material costs, and plant-size dependent costs [2]:

$$c_M\left(\frac{\$}{W}\right) = \frac{\alpha}{\sigma A\eta_m y}\left[Av\rho p_s + cA + p_0\left(\frac{K}{K_0}\right)^{-b}\right]. \tag{2}$$

The variables of our model are given in Table 1, which shows that in addition to cost components (e.g., installation costs) individual variables can be classified as either hardware or soft. Hardware variables such as module efficiency describe features of physical equipment (see Fig. 1) and are ‘embodied’ therein—for a given design, these variables do not change significantly after leaving the module manufacturing factory gate. Once hardware features are improved, this improvement is retained and can be shared across locations that use the same equipment. Soft variables, in contrast, describe features of processes and services. Because process features (e.g., the durations of installation tasks) are not predetermined by hardware design, soft variables can differ across locations and change over time even for the same hardware. For example, how quickly a PV module is roof-mounted can depend on location-specific levels of installer experience, or vary for the same installer crew due to site-specific conditions.

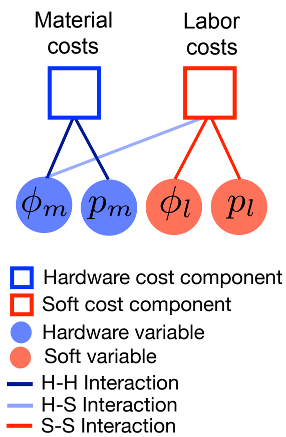
The distinction between hardware and soft variables is not categorical. It depends on the chosen system boundary. In this work we draw the system boundary around individual installation projects and model all costs incurred during project development (e.g., design, permitting) and installation. Soft costs represent the costs of soft technologies (services and processes) used within the system boundary to design and install the PV system, and hardware costs are the costs of physical equipment. In accordance with this boundary choice, we define module- and inverter-related variables as ‘hardware’ because they do not change after the module and inverter manufacturing factory gate. From the perspective of installers and consumers, modules and inverters arrive as one piece with fixed hardware features at the installation site. We note that with a different system boundary module manufacturing processes would involve soft technology components such as labor processes that likely changed over time and contributed to changing costs. Thus to apply this method one must choose a system boundary. We also note, however, that soft costs have not yet presented a barrier to module cost decline, and we choose the boundary with this in mind, to focus on soft costs that dominate PV systems. We also explore the effects of expanding the boundary to include module manufacturing soft costs in a sensitivity analysis.

We can view the relationships described in (1) as a network of dependencies between a PV system’s hardware and soft cost components and its hardware and soft variables (Fig. 2). As apparent in Fig.2, hardware variables, such as inverter efficiency or module efficiency, tend to affect many cost components, while many soft variables affect just a few (e.g. mechanical installation time). As this representation makes clear, what we term interactions are between cost components and the variables that influence them. We do not consider another kind of interaction here, which is that of shifting costs from one cost component to another. However this could be studied in future research starting from the same equation and teasing out the dependencies across cost components, as needed depending on the research questions being addressed.

Task 2: Develop cost change equations

Building on the cost equation for PV systems we derived cost change equations to quantify the contribution of individual low-level mechanisms to overall PV system cost reduction between 1980 and 2017. We describe these equations below. We use a method previ-

Variables, cost components, and conceptual technology cost equation



Term	Definition	Examples
Hardware (H) variable	Describes features of equipment	Efficiency Materials usage Device dimensions
Soft (S) variable	Describes features of process, services	Task durations Wages
Hardware cost component	Gives cost of of equipment	Module cost Inverter cost
Soft cost component	Gives cost of of service or process	Labor costs Permitting fee
Interaction	Variable affecting cost component	Materials usage affecting labor costs

$$C_{\text{technology}}\left[\frac{\$}{\text{unit}}\right] = \boxed{\phi_m \; p_m}\left[\frac{\text{g}}{\text{unit}}\frac{\$}{\text{g}}\right] + \boxed{\phi_m \; \phi_l \; p_l}\left[\frac{\text{g}}{\text{unit}}\frac{\text{h}}{\text{g}}\frac{\$}{\text{h}}\right]$$

Figure 1: General technology cost model for a technology comprised of one material (using ϕ grams per unit at a price of p per gram) and built in one production step (taking τ hours per gram at a labor cost of w\$ per hour). Hardware cost components are functions of hardware features. Soft cost components are often functions of hardware *and* soft features, because equipment design choices and resulting hardware features affect how a technology is deployed. The above model can be expanded to represent more complex technologies by adding hardware and soft cost components representing additional materials and production steps, if their costs combine additively.

ously developed for PV modules [2] to attribute changes in the total cost of a technology to changes in individual variables that affect costs.

The total cost C of a technology is given as a sum of *cost components* c_i, which are functions of a vector $\vec{r}^t = (r_1^t, r_2^t, \ldots)$ of explanatory variables at time t: $C(\vec{r}^t) = \sum_i c_i(\vec{r}^t)$. Often the cost components are products of functions of the explanatory variables, $c_i(\vec{r}^t) = c_{i0} \prod_j g_{ij}(r_j^t)$. The method of attributing cost changes to the explanatory variables is based on an approximate expression for the change in $C(\vec{r})$ as sum over cost change contributions from individual variables. It can be shown that the change in the total cost between two points in time, t_1 and t_2, due to a change in the variable z between t_1 and t_2, is

$$\Delta C_z \approx \sum_i \left(\tilde{C}_i \, \ln \frac{g_{iz}(r_z^2)}{g_{iz}(r_z^1)} \right), \tag{3}$$

where r_z^1 and r_z^2 represent the values of r_z at the two points in time [2]. $\tilde{C}_i$ is a representative value of the cost component i in the time period, and it can be shown that $\tilde{C}_i = (C_i^2 - C_i^1)/(lnC_i^2 - \ln C_i^1)$ is a particularly good choice [2], where C_i^1 and C_i^2 are the values of the cost components at the beginning and end of the time interval considered. With this choice, total cost change can be written as a sum of cost change contributions from individual variables, $\Delta C = \sum_z \Delta C_z$.

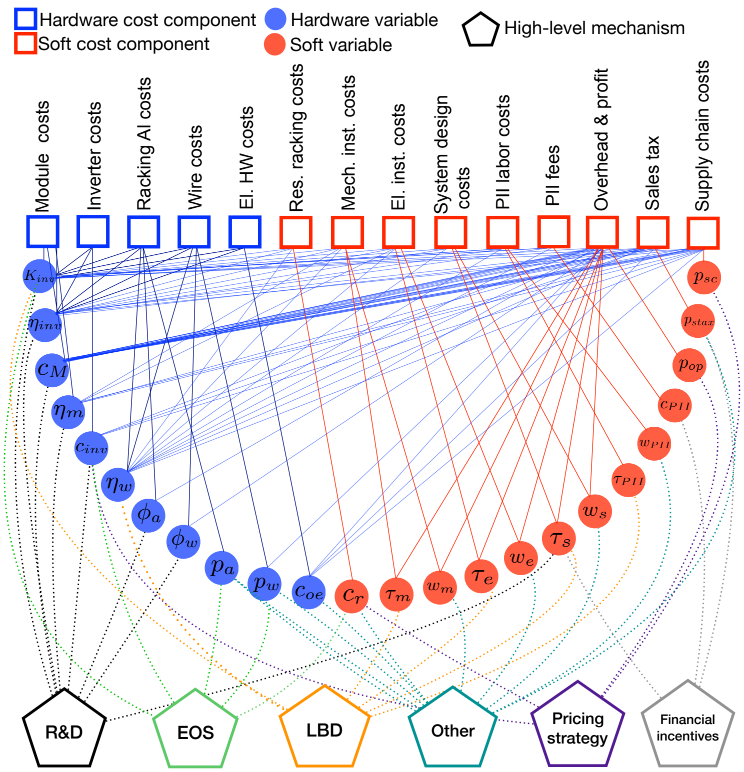


Figure 2: Relationships between cost components (squares), low-level mechanisms (circles), and high-level mechanisms (pentagons) of cost change in PV systems. A line from a low-level variable to a cost component indicates that the variable appears in the expression for the cost component in (1). A line from a pentagon to a circle means that a high-level mechanism influenced a variable during the 1980-2017 period. Light lines indicate that a hardware variable influenced a soft cost component (H-S interaction, see Fig. 2). Dark lines indicate that a hardware or soft variable influenced a cost component of the same type (H-H and S-S interaction, Fig.2). High-level mechanisms (R&D: research and development; EOS: economies of scale; LBD: learning-by-doing; Other; Pricing strategy; Financial incentives) are the higher order innovation processes that likely changed individual variables over time, and are discussed on p. 6.

Table 1: Cost equation variables and cost components inside the large bracket in Eq. 1. Cost components are shown in brackets. All cost components given in 2017$ are divided by $K_{inv,ac}\eta_{inv,ac}$ to give the final cost per unit of ac power. Module efficiency (η_m) affects PV system cost components other than the module. Module area is computed as wafer area divided by module area utilization.

Symbol	Meaning	Unit	Type
PV system			
p_{op}	Overhead/profit margin (%)	unitless	S
K_{inv}	Inverter ac power output	W_{ac}	H
η_{inv}	Inverter ac efficiency	unitless	H
c_M	Module costs	2017$/W$_{dc}$	H
K_s	System power	W$_{dc}$	H
c_{inv}	Specific inverter cost	2017$/W$_{dc}$	H
η_w	Wiring efficiency	unitless	H
ϕ_a	Specific aluminum use	2017$/W$_{dc}$	H
p_a	Aluminum price	2017$/kg	H
ϕ_w	Wire use	m/module	H
p_w	Wire price	2017$/m	H
τ_s	System design time	h/system	S
w_s	System design wage	2017$/h	S
τ_m	Mechanical installation time	h/module	S
w_m	Mechanical labor wage	2017$/h	S
τ_e	Electrical installation time	h/module	S
w_e	Electrical labor wage	2017$/h	S
$\tau el, w_{el}]$			
τ_{PII}	Permitting, inspection, and interconnection (PII) time	h/system	S
w_{PII}	PII wage	2017$/h	S
c_r	Residual racking costs	2017$	S
c_{oe}	Other el. hardware costs	2017$	S
c_{PII}	PII fees	2017$	S
c_{sc}	Supply chain costs	2017$	S
s_{tax}	Sales tax in percent	unitless	S
c_{tax}	Expenses for sales tax	2017$	S
Module			
α	Area utilization	unitless	H
σ	Solar constant	W$_{dc}$/ m^2	H
A	Module area	m^2	H
η_m	Module efficiency	unitless	H
y	Yield	unitless	H
v	Silicon usage	m	H
ρ	Wafer density	g/cm^3	H
p_s	Polysilicon price	2017$/kg	H
c	Non-Si materials cost	2017$/m^2	H
K	Plant size	MW/year	H
K_0	Reference plant size (2012)	MW/year	H
b	Scaling factor	unitless	H
'H'=hardware	*'S'=soft technology*		

For PV system costs, the vector $\vec{r}^t$ contains 31 explanatory variables, which are listed in Table 1. Example cost change equations are listed below for the variables inverter efficiency, inverter costs, and module efficiency.

$$\Delta C_{\eta_{inv}} = \sum_{i=1}^{15} \tilde{C}_i \left(\ln \frac{\eta_{inv}^1}{\eta_{inv}^2} \right) \tag{4}$$

$$\Delta C_{c_{inv}} = \tilde{C}_2 \left(\ln \frac{c_{inv}^2}{c_{inv}^1} \right) \tag{5}$$

$$\Delta C_{\eta_m} = \left(\tilde{C}_4 + \sum_{i=6}^{7} \tilde{C}_i \right) \left(\ln \frac{\eta_m^1}{\eta_m^2} \right), \tag{6}$$

where $\tilde{C}_i = (C_i^2 - C_i^1)/(lnC_i^2 - \ln C_i^1)$ (see [2]).

Task 3: Estimate effect of low-level mechanisms for PV systems

We apply the cost-change decomposition method to BOS costs and PV system costs to study the contributions of different variables to cost change over the period 1980-2017. Hardware variables caused approximately 80% of the reduction in BOS costs over the 1980-2017 period (Fig. 3A), and 90% of the reduction in PV system costs (Fig. 3B) and levelized costs. Two components, the module and the inverter, were responsible for 85% of PV system cost change, approximately one third of which was achieved through hardware-soft cost interactions (light blue bars in Fig. 3). These hardware-soft cost interactions are ones where changes to hardware, such as increased module area, reduced the cost of soft technology, such as installation. Overall, the module alone contributed 70% of PV system cost change (Fig. 3B1), with 3% coming from the effect of changing modules on installation costs. During this time, BOS costs in $/W decreased by 95%, PV system costs by 97%, and levelized costs by 96%.

Zooming into to the BOS costs by subtracting out the impact of module cost change shows an even greater impact of interactions of hardware-soft cost interactions. For BOS, the majority of overall cost decline was achieved through hardware variables affecting soft costs (59%), not directly through changing hardware costs (20%). Although BOS hardware is physically distinct from modules, many BOS soft cost components are functions of hardware module variables including module area and efficiency. Six of the ten most influential BOS cost change mechanisms are therefore module variables. By reducing installation time, profit, supply chain costs, and other soft costs, increases in module efficiency and module area alone contributed 17% to BOS cost change, and 10% to PV system cost change. (Table 2)

Soft variables were less influential, causing about one fifth of overall BOS cost reductions, and about 10% of overall PV system cost reductions since the 1980s. The contributions of soft variables stem primarily from reductions in system design time. System design benefitted from R&D efforts to develop circuit and system design guidelines and performance simulation tools, which began to be published in the mid-1970s (e.g. [30, 31, 32]), and later informed the development of standardized design software. Efforts to improve

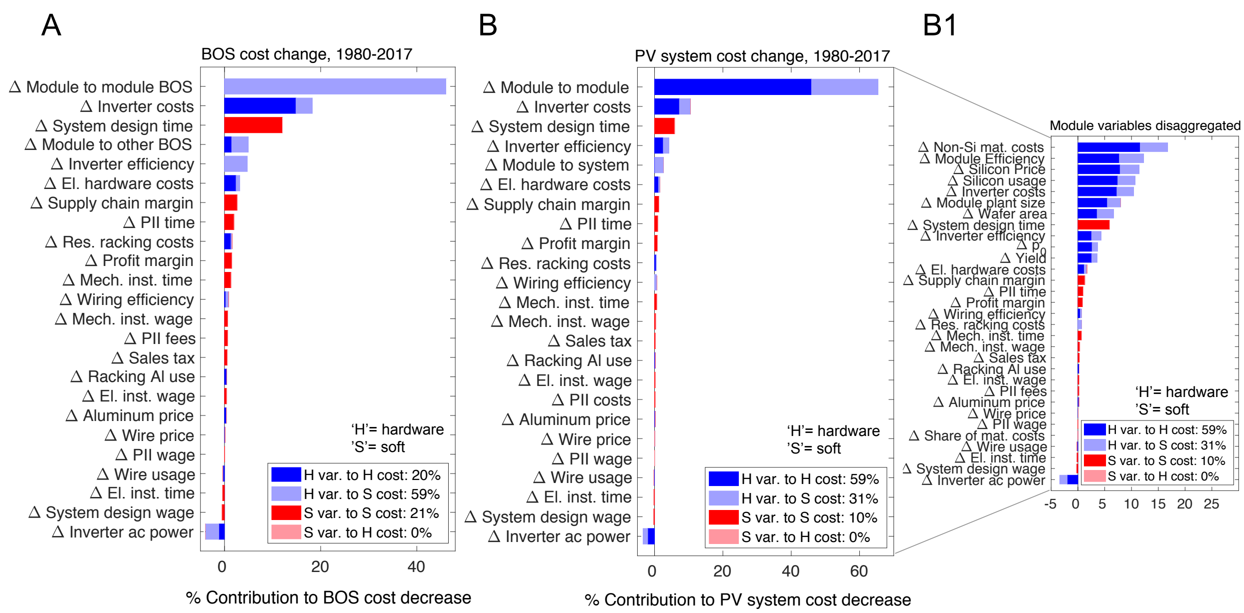


Figure 3: Contributions to cost reduction in residential PV systems in the U.S. over the 1980-2017 period. (A) shows contributions from low-level mechanisms to BOS cost change and (B) shows contributions to PV system cost change. Figure B1 shows the same results as B but with variables that appear in the expression for module cost (Eq. 2) disaggregated to show, for example, the cost change contribution of module efficiency. In all panels, percentages give the fraction of the net cost change over the 1980-2017 period (see Table 2) that was caused by each low-level mechanism. Contributions are negative when they act in the opposite direction to the net cost change over a period. In all periods above, the net change cost was negative, therefore positive contributions correspond to cost-reducing effects and negative contributions to cost-raising effects.

other soft variables, e.g. to reduce installation time, occurred later (based on journal papers published in the 1990s); many inventions to date have not been widely adopted. Examples include PV-integrated roofing materials (e.g. [33, 34]), and automated module deployment (e.g. [35]).

Hardware changes also contributed the majority of LCOE declines. O&M cost reductions were driven mainly by increasing inverter lifetimes, which almost tripled over the 1980-2017 period [36, 37, 38, 39]. O&M labor task durations also decreased (a soft change), but had a smaller influence. The average interest rate charged for PV loans decreased over time [32, 38]. However, due to discounting, as well as the proportionally larger influence of capital costs on net interest payments, this change barely contributed to overall LCOE decline.

Overall, the most important mechanism driving BOS cost decline was the reduction in inverter costs, a hardware variable responsible for 20% of overall cost change between 1980 and 2017. Improved circuit designs and the use of advanced power electronics for switching reduced material usage in inductive components and heat sinks, leading to increased inverter power density and conversion efficiency. As a result, specific inverter weight (kg/W) in 2014 was less than 10% of that in 1995 [40]. Average inverter efficiencies have reached 98% in the U.S. today, compared to 80% in the 1980s [38, 41]. Increasing integration of subcomponents and modular designs, reducing component counts and simplifying manufacturing processes, were also important [41, 42]. Simultaneously, inverter factories reached gigawatt-level outputs in the late 2000s, reducing per-unit manufacturing costs through scale economies [43, 44].

Table 2: Change in PV system hardware costs, soft costs, and total installed costs, and comparison of total installed costs computed here (using Eq. 1) to estimates from the literature. In the absence of a nationally averaged cost benchmark like the one provided by NREL for 2012 and 2017 we give a range of estimates for the year 1980. ΔC_H refers to hardware cost change.

Costs ($/W)	C(1980)	C(2012)	ΔC(1980-2012)	C(2017)	ΔC(2012-2017)	ΔC(1980-2017)	ΔC_H(1980-2017)	$\Delta C_H/\Delta C$
Hardware costs	45.44	1.76	-43.68	0.99	-0.77	-44.45	-38.31	0.86
Soft costs	32.51	1.40	-31.11	1.27	-0.13	-31.24	-20.67	0.66
Total costs								
This paper	77.95	3.16	-74.9	2.26	-0.90	-75.69	-58.98	n/a
Other sources	57.6-114.4 [45, 36]	6.1 [46]		2.35 [38]				n/a

We also decompose cost change over the 1980-2017 period into smaller time intervals. Although module variables were influential in all time periods, their ranking changed. Reductions in module silicon usage contributed more to cost declines prior to 2012; reductions in non-silicon materials costs were more important during 2012-2017. U.S. imports of PV modules from Asia approximately doubled over the 2012-2017 period [47], which also contributed to cost reductions. Similarly, decreasing inverter costs were more influential during the 2012-2017 period, also reflecting increasing imports from lower cost countries. This recent time period also differs from the first three decades in that variables show both cost-decreasing and cost-increasing contributions.

In SI Appendix we also study the sensitivity of our results to data uncertainties and uncertainties in the classification of variables as 'soft' or 'hardware'. Our results are most sensitive to uncertainties in module efficiency, polysilicon price, and non-silicon materials costs. Although data used for soft variables shows greater uncertainty than hardware data, the effect is relatively small because soft variables affect fewer cost components and a smaller fraction of PV system costs in the starting year (1980). We note, however, that rankings of variables according to their impact on cost change are more uncertain over shorter time periods. Our main conclusions therefore focus on the 1980-2017 period.

To better understand how changing the system boundaries might affect our conclusions, we consider a further decomposition of module costs to consider the soft costs incurred in module manufacturing. We draw on historical data on hardware and soft module cost components [48] to estimate a lower bound for the contribution of hardware variables to PV's cost decline. We estimate that hardware variables contributed at least three quarters (instead of 90%) to overall cost reductions during 1980-2017. Similar types of boundary adjustments could be applied to other components.

Cost change in other system sizes and countries. As estimated in previous sections, much of the cost decline in U.S. residential scale PV systems can be attributed to R&D and scale economies and the resulting improvements to hardware features. Since most hardware is traded globally, these results suggest that hardware variables may have been similarly influential for PV system costs in other countries as they were in the U.S. If this is true, however, how did countries with lower soft costs reach their current cost levels? Were improvements in soft variables more influential? To study this question we repeat the cost change decomposition conducted for the U.S. using cost data from residential and utility systems in Germany and Japan. Both countries played a major role in the expansion of PV capacity in the 1990s and 2000s, with Japan leading the market from 1992-2003 with residential deployment growth, and Germany becoming the primary driver from 2004-2012 [49]. Major PV-focused policies in both countries (the 1000-roofs program in Germany and the SunShine program in Japan) also motivated data collection efforts, enabling component-level cost data to span multiple decades [50, 51, 52]. Since the data is not as fine-grained as our U.S. data set, however, we use a simplified cost equation that accounts for the contribution of selected hardware variables (module efficiency, wafer area) to soft cost reductions over time .

As shown in Fig. 4, contributions of hardware variables have been similarly important for cost change in Germany and Japan as they have been in the U.S., causing 90% of overall PV system cost change during 1992-2018 (Germany) and 1993-2005 (Japan) for residential systems. Improving soft variables only contributed 10-15% of cost reductions. We estimate that roughly half of the contribution of soft cost reductions to overall cost declines observed in residential systems during the respective time periods originated in improvements to hardware variables (Figs 4C,E). That is a smaller percentage than in the U.S., pointing to a larger contribution of soft variables to soft cost change in Japan and Germany. Note, however, that the results shown in Fig. 4 likely overestimate the contri-

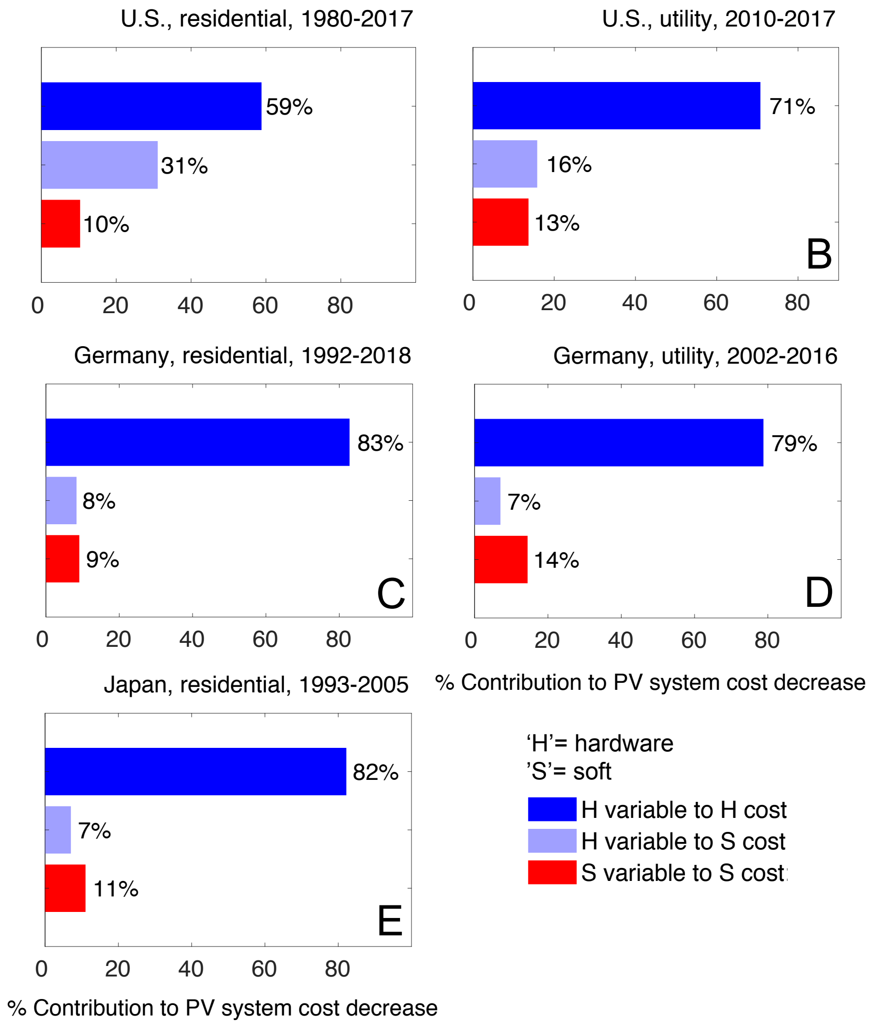


Figure 4: Contributions to cost reduction over different time periods in the U.S. (A: residential-scale; B: utility-scale), Germany (C: residential-scale; D: utility-scale), and Japan (E: residential; no data available for utility-scale). Hardware variables contribute 80-90% to overall PV system cost change in different countries. Soft variables contribute 9-20%.

bution of soft variables due to data limitations, which preclude modeling all interactions between hardware and soft variables and cost components.

The above results provide a deeper understanding of the trends in hardware and soft costs observed across countries (Fig. 5). Hardware and soft costs evolved at similar rates across countries because changes in both cost categories were driven by improved, globally traded hardware. Because this hardware was the primary driver of soft cost declines, countries that started out at high soft cost levels rarely turned into countries with comparatively low soft costs, as that would have required additional contributions from soft variables to soft cost change to reduce costs faster than the global hardware learning curve. Conversely, countries with low soft costs did not reach current costs

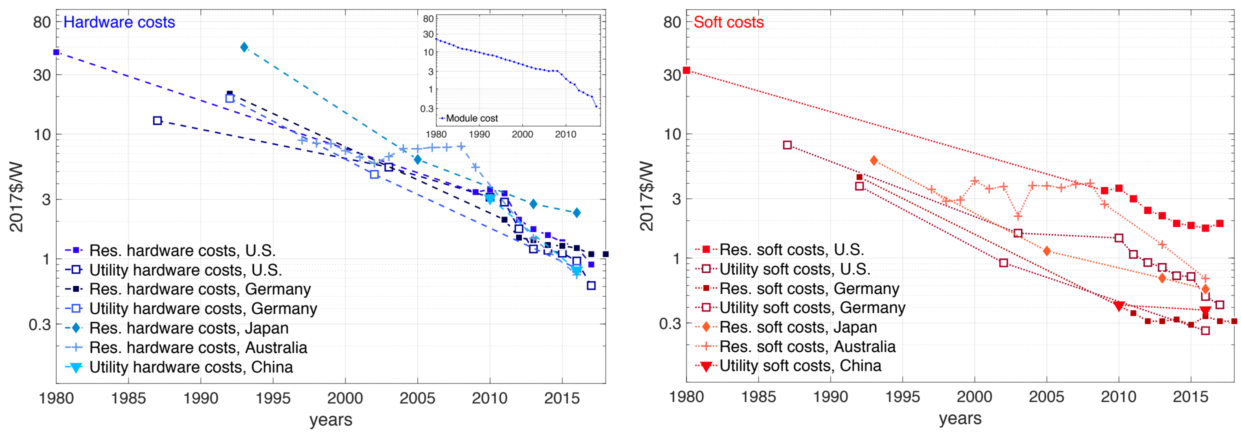


Figure 5: Evolution of total PV hardware costs (left), module costs (left, inset), and total PV soft costs (right) during the 1980-2018 period. Total PV hardware costs include modules, inverters, and other electrical hardware. Soft costs include all non-hardware PV system costs. Hardware costs are similar across countries. Soft costs diverge but have trended downwards at similar rates in all major PV markets (Germany, Italy, Japan, U.S., Australia), likely driven by improvement in globally traded PV hardware (see near-parallel lines in right panel). Countries with comparatively low soft costs today already started out at lower soft cost levels (e.g, Germany, China). The Japanese PV market is characterized by a dominance of domestic brands and a supply chain with high margins [14], which explains the comparatively higher hardware costs in Japan (where part of the difference stems from soft costs but isn't separated out due to data limitations). Time series data was compiled from journal papers, national lab reports, as well as international organizations and country-level solar PV associations. Modules: [38, 2]; U.S.: This paper, [38] (residential); [53, 38, 54] (utility); Japan: [50, 14]; Germany: [51, 52, 55] (utility); [51, 56] (residential); Australia: [57, 15, 58] (residential). China: [59, 55].

primarily through rapidly evolving soft technologies—they already had lower soft costs to begin with. Even in Australia, which exhibits the steepest soft cost decline (Fig. 5), soft and hardware costs declined in conjunction, indicating that much of the soft cost decline was driven by hardware cost declines (e.g. due to higher volume purchasing in a rapidly growing residential market during 2009-2014 [15]).

Cost differences between countries today. In the previous section we showed that countries with high soft costs have tended to stay high soft-cost countries. Yet what distinguishes the cost structure of these countries from that of low-cost countries—which variables are most influential for cost differences? Here we address this question by applying the same cost decomposition method to examine the drivers of cost differences between two countries at a single point in time. Germany is currently the country with the lowest installed costs among developed economies [55], and we therefore use cost data from Germany as a baseline. We then compute the contributions of low-level mechanisms to the cost difference between other countries and Germany, and consider scenarios for reducing these cost differences.

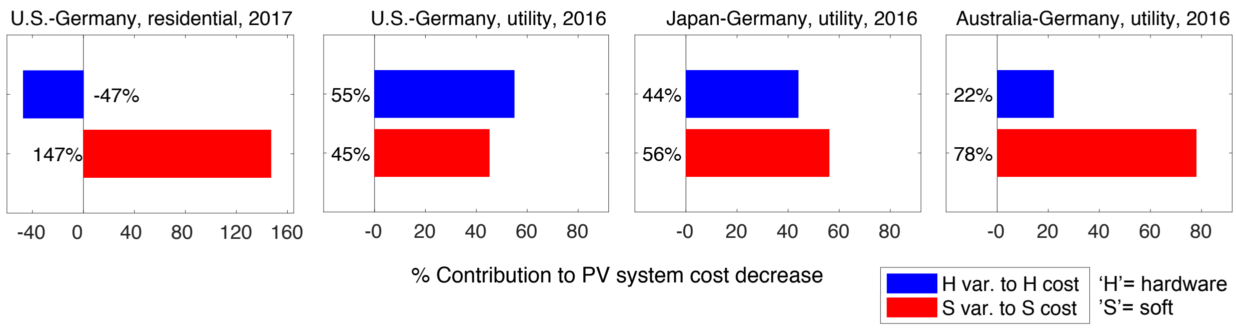


Figure 6: Contributions of low-level mechanisms to differences in installed costs of utility-scale systems between countries. Cost differences are measured between higher-cost countries (U.S., Japan, Australia) and Germany in 2016. Bars show the percentage contribution of hardware and soft variables to hardware and soft cost differences between countries. Contributions of hardware variables to soft cost differences (light blue bars in Fig. 3 and 4) are not shown here because the PV hardware features that affect soft costs tend to be similar across countries due to global trade of hardware.

Consistent with the findings in previous sections, differences in soft cost components and features explain the majority of cost differences between Germany and other countries today (2016, see Fig. 6). For utility-scale systems, longer mechanical installation times are most influential, causing 20-30% of the cost difference between Germany and the U.S, Japan, and Australia, respectively. On-site labor productivity is also lower in developing countries (China, India), although the impact of longer per-component installation times on cost is offset by lower wages.

Differences in soft costs do not fully explain variations in cost, however. Higher-cost countries tend to perform worse across multiple soft cost and hardware cost components. In particular, hardware costs of equipment that is less standardized as compared to modules and inverters (e.g. mounting systems, grid connection hardware) contribute significantly to cost differences.

Task 4: Estimate effect of high-level mechanisms for PV systems

We developed a scheme for assigning low-level mechanisms to high-level mechanisms and used the scheme to estimate the contributions of high-level mechanisms (Subtask 4.1). Variables such as module efficiency, which describe engineering properties and require laboratory and non-routine manufacturing settings to change and are assigned to R&D. Variables that reflect the cost components of manufactured products, such as inverters, but are not explicitly decomposed further in this analysis are assumed to have been affected by a combination of high-level mechanisms.

Variables describing processes that can change due to the repetition of similar work steps and resulting incremental improvements are assigned to the high-level mechanisms learning-by-doing. Variables affecting products used both within and outside the PV industry are affected by mechanisms in other industries and assigned partly to the 'other' category. We also include 'pricing strategy' as a high-level mechanism to capture strategic price reductions by companies responding to market pressures, such as increasing imports of cheaper PV modules and inverters from China. Finally, we assign effects of direct regulatory changes to the mechanism 'financial incentives' to represent cost changes resulting from fees and taxes affecting PV costs to the consumer. Bulk purchasing effects are assigned to economies of scale.

The central idea behind this approach is to ground estimates of the high-level drivers of cost change in a combination of engineering knowledge on the improvement efforts different features are amenable to, and in empirical accounts of these efforts.

Due to the limitations in assigning the cost change contribution of low-level mechanisms into high-level mechanisms without a detailed further decomposition of the low-level variables, the result of this assignment should be viewed as a rough estimate. In line with this view, our core conclusions focus on the low-level drivers of soft technology change and differences across nations rather than emphasizing the high-level mechanism assignments. Nonetheless, the study of high-level mechanisms allows us to begin to explore possible reasons for the differences across nations, which we discuss here as an invitation to further research. We note that a combination of qualitative research and sensitivity analyses can be used to further refine the assignments and estimate error bars to enable additional research questions to be addressed, as has been shown for the case of modules [2].

Using the above approach, most soft variables are assigned to LBD or a combination of LBD, financial incentives, pricing strategy, and other. Workers likely became better at unpacking components, building scaffolding, mounting modules, and connecting wires, through repeated practicing of the same tasks, rather than due to process improvements driven by research. System design time is an exception. Drawing on on well-cited journal publications on design methods and tools in the 1970s and 1980s, we assign changes in system design time to both LBD and R&D. Direct effects of these efforts on system design practices are difficult to prove, but the industry's transition from design drawings to computer-aided PV system design programs indicates that early research efforts had considerable impact.

We assign most hardware variables to R&D, motivated by comparatively high rates of patent and journal publications focused on PV modules and inverters. Yield, which is assigned to LBD, and plant size, which is assigned to EOS (both based on [2]) are exceptions. Inverter ac power is assigned to R&D, LBD, and EOS. Array oversizing was mated by a combination of cheaper modules, making larger arrays affordable, and experimentation and learning by different PV actors. We assign variables that were affected by policies (e.g., sales taxes, PII fees) to the mechanism 'financial incentives', and variables that changed partially due to firm-level pricing decisions (e.g., inverter costs) to 'pricing strategy'.

As shown in Fig. 7A, R&D and EOS contributed more to BOS cost change through interactions of improved hardware with soft costs than through direct interactions of hardware with hardware costs. Even for PV systems (Fig. 7B), R&D and EOS contributed about half as much through hardware-soft cost interactons as compared to hardware-hardware

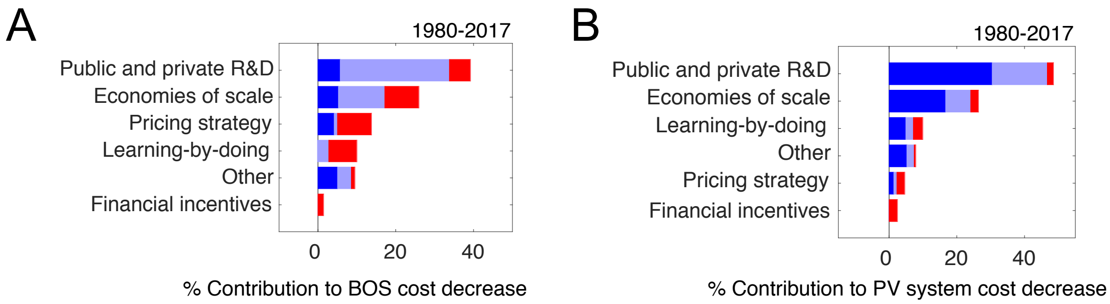


Figure 7: Contributions of high-level mechanisms to cost reduction in residential PV systems in the U.S. over the 1980-2017 period. Percentages give the estimated fraction of the net cost change over the 1980-2017 period (see Table 2) that was caused by each high-level mechanism for the chosen assignment between low- and high-level mechanisms. Contributions are negative when they act in the opposite direction to the net cost change over a period. In all periods above, the net change cost was negative, therefore positive contributions correspond to cost-reducing effects and negative contributions to cost-raising effects.

interactions. Since the significant contribution of hardware driven soft and hardware cost declines (e.g., inverter cost change) makes R&D and EOS are similarly important for BOS as for modules, the rankings of high-level mechanisms are similar for PV systems and modules [2] . Pricing strategy and financial incentives together contributed less than 10%. The larger contribution of LBD for PV systems is the main difference between the results for PV systems and BOS.

High-level mechanisms to reduce cost differces across countries. Next we use the assignment scheme introduced previously to relate low- to high-level mechanisms. Contributions of high-level mechanisms now indicate the potential of certain efforts (e.g. market expansion policies inducing scale economies) to reduce cost differences between countries in the future, based on the high-level mechanisms that have affected PV's features in the past. The results are speculative as future efforts affecting variables may differ from past efforts, but represents an improvement over a random guess due to historical evidence for the linkage of low- and high-level mechanisms. We find that—if past associations between low- and high-level mechanisms equal future associations—economies of scale, learning-by-doing, and financial incentives are most likely to reduce costs in the U.S. and Japan to the level in Germany. This picture differs from that shown in 7 for past cost change, where R&D plays a dominant role.

Conclusions from Task 1-Task 4. Summing contributions to hardware and soft cost improvement, hardware variables have caused 80-90% of PV system cost change across different countries. Features of processes and services to deploy PV systems ('soft technologies'), in contrast, contributed on average only 10-20% to cost change in the U.S., Japan, and Germany, for both residential and utility-scale systems. Importantly, our re-

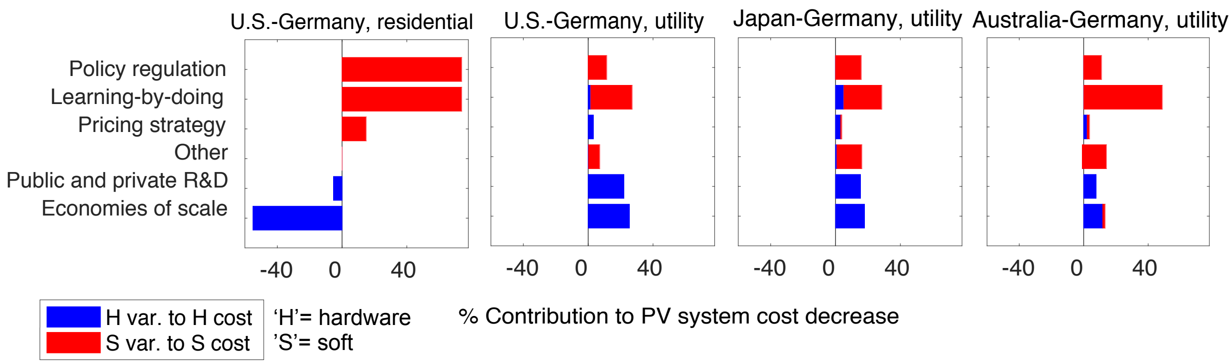


Figure 8: Comparisons of the high-level mechanisms that may explain differences in costs across countries. Cost differences are measured between higher-cost countries (U.S., Japan, Australia) and Germany. Bars show the percent contribution of high-level mechanisms that could help reduce the cost difference (i.e. contribute to a cost decrease) between a higher-cost country and Germany, under assignments of low- to high-level mechanisms detailed in the SI. These assignments are meant as plausible scenarios to explain past trends, and thus the results here should be treated as contingency scenarios to guide future efforts. A negative contribution of a low- or high-level mechanism means that a country with higher overall installed costs performs better than Germany in a specific area (one cost component, one variable). For instance, module and inverter costs are lower in the U.S. than they are in Germany [60], explaining the negative contribution of hardware variables to cost decrease. Note that contributions of hardware variables to soft cost differences (light blue bars in Fig. 3 and 4) are not shown here because the PV hardware features that affect soft costs tend to be similar across countries due to global trade of hardware.

sults differ from previous findings on progress made in soft costs (e.g. [8, 15]). Since these studies did not quantify the determinants of soft cost change, the observed decline soft costs may stem partially from hardware improvements, and should thus be interpreted with caution.

We also observe that features that improved slower in the past tend to cause cost differences between countries today. Scale economies and learning-by-doing emerge as the most likely mechanisms to reduce cost differences, if improvement mechanisms continue to influence the same PV cost components and variables as they have in the past. However, it is uncertain whether incentivizing learning to reduce soft costs, or investing in R&D efforts, is the more effective way to drive down costs. Studying the cost-effectiveness of different innovation pathways is thus an important area of future research.

Our results have several other implications for R&D and policy efforts to further reduce the costs of PV. Two basic approaches emerge from the insight that cost declines have been driven predominantly by hardware improvement: (1) Developing engineering design solutions to influence soft variables through hardware improvements, thereby building on what has proven successful in the past; (2) targeting soft variables directly through process innovations and policy support. Examples for (1) include higher module efficiencies to reduce module counts; automation and digitalization to make soft variables more hardware-like, e.g. by using automated construction systems and engineering review software to enable more robust task durations across different sites and locations; simpler, more standardized PV equipment to reduce the need for customization (e.g. plug-and-play PV systems, PV-integrated roofing materials). In all these solutions, soft costs, such as labor costs, are partially converted into additional hardware costs, such as the costs of a robot. Since one robot will likely build many PV systems, whereas human labor is required each time a system is built without a robot, per-unit cost reductions should nevertheless be possible. Future research could investigate tradeoffs between additional hardware costs and reduced soft costs.

Solutions for (2) may include process simulation tools to develop high-productivity workflow designs for installation processes, or the use of sensors to track inefficiencies. Based on these examples, flows of knowledge between PV and other technology sectors, both in terms of hardware and soft technologies, may become increasingly important to reduce costs.

For policy, incentivizing competition appears increasingly relevant. Marginal efficiency gains in installation and PV component supply may not be in the interest of PV companies due to lost revenues, but sustained efficiency gains could be if they increase demand. Near-term efficiency gains could be incentivized through awards for the fastest installers and permitting offices. Tools to enable streamlined soft cost data collection and sharing could support such programs.

Further research will also be needed to better understand the local conditions enabling consistently lower soft costs in some countries compared to others, so these conditions can be replicated elsewhere. Existing studies point to both hardware-related conditions (e.g., built environment not requiring roof penetrations in German PV installations [13]) and soft factors (e.g., absence of permit fees and permit requirements for residential systems in Germany [13]). Clear and consistent political goals behind the deployment of grid-connected systems (e.g., to support the phase-out of nuclear in Germany [61, 62]) as compared to a more diverse set of incentives and associated societal goals supporting both on- and off-grid systems in the early U.S. market, and competing goals of PV and nuclear innovation efforts in Japan [61], may also have contributed.

Task 5: Preliminary innovations classification and hypotheses

In this task, we developed a preliminary innovations table with the goal to help set up the much more extensive work to be carried out in Tasks 9 and 10. With this work we fully achieved Milestone 5.1: 'A classification scheme for innovations has been developed and used in the preliminary innovations table, and hypotheses about most important innovations have been generated.' Since the work was in preparation for Tasks 9 and 10, several concepts and definitions used in this section, such as the definition of an innovation, the method of collecting innovations, and innovation types are updated with new ones in Tasks 9 and 10. Below we report the work as it was performed during Task 5.

Our preliminary table of innovations is shown in Table 3. In this table, we outlined the major lines of innovations that were critical to PV's development. We also started to develop a framework for thinking about classifying innovations to facilitate systematic data collection planned for year 2. These efforts helped bring out some of the challenges of conceptualizing innovations in ways that are both intuitively meaningful and will function well with data.

Since patents are one of the major sources of data related to the innovation activity, we studied the corpus of patents, focusing on when patents for particular kinds of innovations occurred (Figures 9-10). To review our method, for each innovation we did a keyword search using the Google patent database, obtaining the 1000 most relevant patents according to Google's search engine. Figures 9-10 show histograms of years when these patents were published. For each innovation we search twice, once with the innovation name by itself and once with the innovation name and the term 'solar cell'. The goal of the latter search is to isolate patents for PV-specific applications of the innovation. Many innovations that were critical to PV's development originated in other industries and were later imported into the PV industry. Table 3 notes which innovations were imported. In these cases, we expect the PV-specific patents to tend to appear later in history than other patents related to the innovation, and our results confirm this intuition. As a robustness check, we also studied the results from using the alternate phrases 'solar', 'PV', and 'photovoltaic' to isolate PV-specific patents, finding the same qualitative patterns regardless of which phrase we use.

We noted several observations: First, patenting activity related to a given innovation takes place over long periods lasting decades, indicating that improvement to an initial invention can continue for a long time. Second, patenting activity may peak during particular periods, which vary from one innovation to another. Third, peak patenting periods differ depending on whether one looks at all patents or PV-focused ones. Not surprisingly PV-focused patenting activity surged during the PV boom. The results suggest that a reason why PV has undergone exceptionally rapid improvement among energy technologies was its ability to borrow from existing processes and technologies. Its relatedness to nearby technologies was sufficient to allow many existing process innovations to be adapted to PV over a relatively short period. These imported innovations, which were originally developed for other applications over a longer period of time, could be 'taken off the shelf' by PV.

In addition to noting which innovations were imported or native to the PV industry, we classified which innovations were primarily *process innovations*, primarily *product innovations*, or both. A process innovation alters the method for making a given good. For example, wafers were originally produced by cutting ingots with an inner diameter saw, which was later replaced by a wire saw. A product innovation results in a new good, or a good with significantly improved characteristics. For example, the Siemens process allows the production of 95-99% purity silicon, a distinct form of silicon with applications that are not possible for e.g. the metallurgical grade silicon used as feedstock to the process. A number of PV innovations (such as the Siemens process) are of both types. We expected that the coupling of process and product innovations is common in PV as compared with other technologies. For processes that involve fabricating special materials, such as semiconductors, it is common for innovations that are desired primarily for their process advantages (e.g. yield, throughput) to also affect product properties to some extent.

We developed hypotheses for what were the most important innovations for PV historically. We sharpen this question by distinguishing two notions of importance. Note that some innovations were critically necessarily to enable the technology. These include the Siemens process, the Czochralski process (as applied to high-purity silicon), and diffusion methods to dope wafers and form a p-n junction. Notably, these are all product (and process) innovations, which resulted in the creation of new goods that were essential for PV technology: high-purity silicon, large crystals of silicon, and doped silicon. We call these critical innovations, because it is clear that without them solar technology simply could not exist. Given this, we distinguish between innovations that were important because they enabled solar technology to exist at all from innovations that were important because they substantially improved or brought down the cost of solar technology. In the latter category, we suggest that the most important innovations were wire sawing and screenprinting, because they allowed high throughput, low-cost production of solar cells.

Table 3: Preliminary table of innovations.

Innovation	**Description**	**Process or artifact innovation?**	**PV area**	**Native to PV or imported?**
Silicon smelting with electric arc furnace	Reduction of silica into 95-99% pure silicon using an electric arc furnace.	process & product (metallurgical grade Si)	module fabrication	Imported
Siemen's process	Process for purifying silicon. A high-purity polysilicon rod is grown inside a chemical vapor deposition reactor from liquid trichlorosilane.	process & product (electronic grade Si)	module fabrication	Native
Si-purification with fluidized bed reactor	Process for purifying silicon. High-purity silicon granules are passed through a fluidized bed reactor and grown to a desired size.	process	module fabrication	Imported
Czrochalski process	Process for producing a single-crystal, cylindrical ingot of a semiconductor. A seed crystal is dipped into molten semiconductor and slowly extracted and spun simultaneously.	process & product (monocrystalline Si)	module fabrication	Imported
Wire sawing	Sawing using a wire drawn across a material at high speed.	process	module fabrication	Native
Tabbing and stringing	Process in which cells are arranged into an array and interconnected.	process	module fabrication	Native
Laminator	Machine to assemble a material with multiple layers.	process	module fabrication	Imported
In-line characterization	Testing of wafers as they move through stages of processing using automated detection tools (e.g. for cracks and other defects).	process	cell fabrication	Imported
Semiconductor texturing	Process for roughening a semiconductor surface. Typically this involves exposure to a caustic bath (e.g. sodium hydroxide) or an acid.	process & product (textured wafers)	cell fabrication	Native
Conveyor belt firing	Process for heating on a conveyor belt that passes through a tunnel-like furnace that is open at both ends.	process	cell fabrication	Imported (though significant PV-specific adaptation)
Tube diffusion	Process for doping a substrate to form an internal junction (such as a p-n junction). The substrate is exposed on one side to dopant which diffuses into the material.	process	cell fabrication	Imported
Ion implantation	Process for doping a substrate to form an internal junction (such as a p-n junction). Ions are accelerated onto one surface of the substrate.	process	cell fabrication	Imported
Plasma-enhanced chemical vapor deposition	Process for depositing thin layers of a material onto a substrate. The substrate is exposed to a chemical vapor of the material to be deposited, which binds to the substrate.	process	cell fabrication	Imported
Atomic layer deposition	A kind of chemical vapor deposition in which the substrate is exposed to two species of gas in alternation. Sequential exposures slowly build up the thickness of the deposited material.	process	cell fabrication	Being imported
Screen printing	Printing technique to apply conducting metal or other materials to a substrate in a desired pattern. A squeegee is moved across the screen, pushing the material through gaps in the screen.	process	cell fabrication	Imported
Silver paste	Conductive paste used for front metallization and rear busbars of a silicon-based PV cell. Must penetrate AR coating.	process & product (silver paste)	cell fabrication	Imported

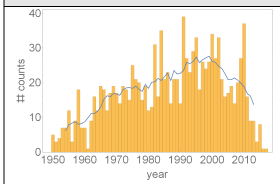
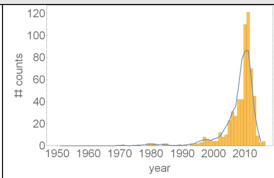
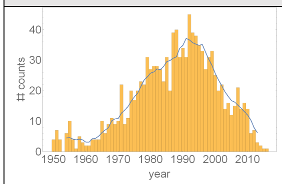
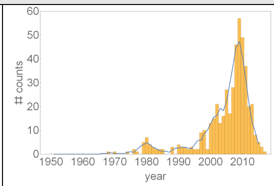
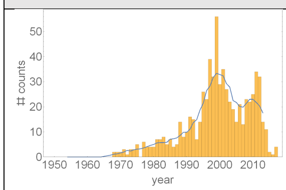
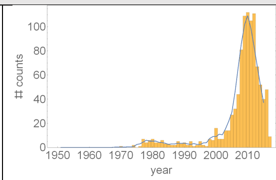
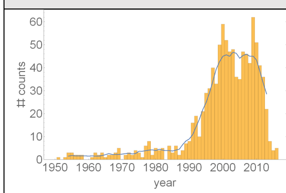
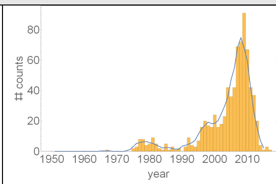
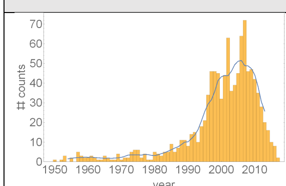
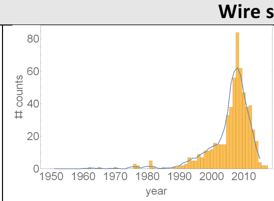
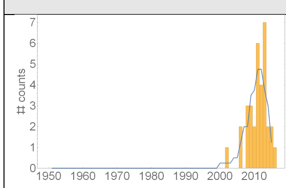
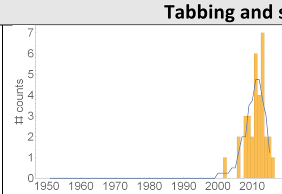
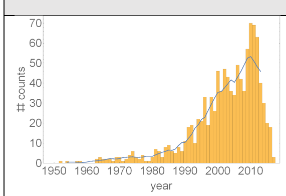
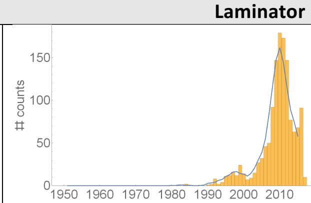
Innovation name	Innovation name + 'solar cell'	Comments
Electrode arc furnace		
		Earliest patents appear before 1950, peak in 1996. First mention in the context of solar in 1971, peak in 2011. Imported technology, ramping during solar boom.
Fluidized bed reactor		
		Earliest patents appear before 1950, peak in 1988. First mention in the context of solar in 1968, peak in 2009. Imported technology, ramping during solar boom.
Czrochalski process		
		Earliest patents appear in 1968, peak in 1996. First mention in the context of solar in 1970, peak in 2010. Imported technology, ramping during solar boom.
Silicon Ingot		
		Earliest patents appear around or before 1950, peak around 2000. First mention in the context of solar in 1967, peak in 2008. Imported technology, ramping during solar boom.
Wire saw		
		Earliest patents appear before 1950, peak around 2003. First mention in the context of solar in 1962, peak in 2008. Wire sawing is a technology with a particular development in solar. The problem of cutting ingots is very specific and offers limited opportunities to learn from other technologies. .
Tabbing and stringing		
		Earliest patents in 2002, peak at 2011. This is a genuine PV technology; there are no patents that don't mention solar cells.
Laminator		
		Earliest patents appear around or before 1950, peak around 2007. First mention in the context of solar in 1982, peak in 2010. Imported technology, ramping during solar boom.

Figure 9: Patent publication years for innovations important to PV module fabrication. First and second columns show histograms of publication years for patents found in the Google Patent database. First column shows results of searching for the innovation name by itself. Second column shows results of including the additional term 'solar cell'. Blue lines are smoothed distributions.

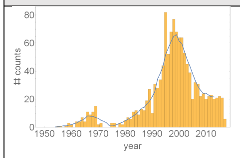
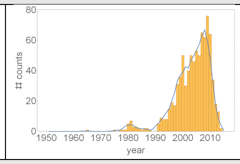
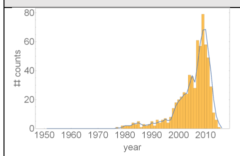
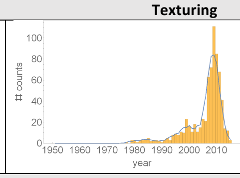
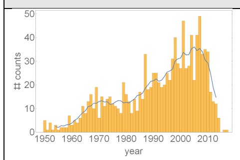
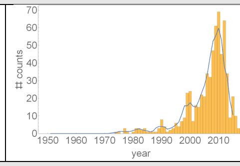
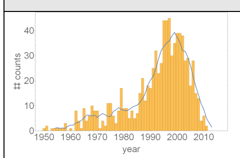
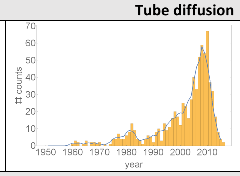
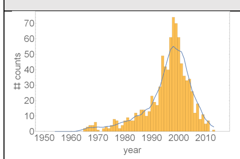
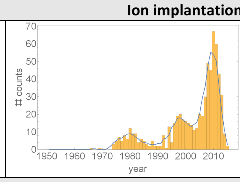
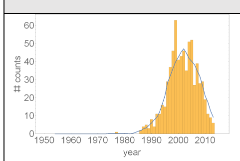
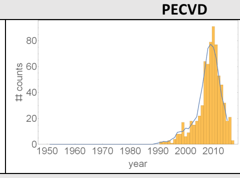
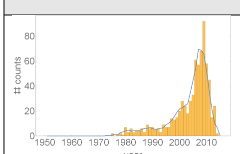
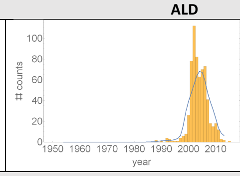
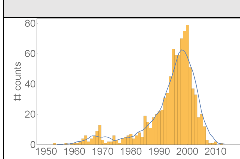
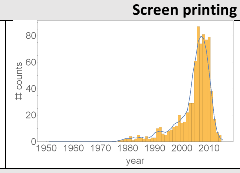
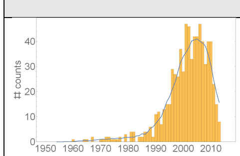
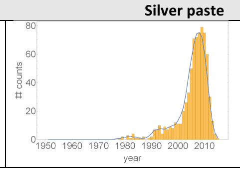
Innovation name	Innovation name + 'solar cell'	Comments
In-line Characterization		
		Earliest patents appear in 1955, peak in 1996. First mention in the context of solar in 1965, peak in 2008. Imported technology, ramping during solar boom.
Texturing		
		Earliest patents appear in 1977, peak in 2009. Texturing silicon is genuine innovation of the PV sector with only few applications outside.
Belt furnace		
		Earliest patents appear before 1950, peak in 2002 First mention in the context of solar in 1974, peak in 2010. Belt furnaces have been adapted for the need of silicon wafers. While the technology is imported there was some significant innovation.
Tube diffusion		
		Earliest patents appear before 1950, peak around 1996. First mention in the context of solar in 1960, peak in 2008. Imported technology, ramping during solar boom.
Ion implantation		
		First patents in 1965, just one year later one for solar. Ion implantation seems to have developed in parallel with solar but was until recently not considered in the PV industry. Peaks in 1995 and in 2009 for solar.
PECVD		
		First patent in 1977, peak in 1999. For solar, first mention in 1990, peak in 2009. PECVD method was adopted for PV and then integrated into industry.
ALD		
		First patents in 1975 and peak in 2001. First mention for solar in 1988, peak in 2007. ALD is not yet industrially adopted for PV and tools are currently under development.
Screen printing		
		Oldest patents from 1953, possibly earlier. Peak in 1995. For PV, first mention in 1977 peak in 2007. Technology adapted for use in PV.
Silver paste		
		Earliest patents in 1960, peak in 2002. For solar first mention in 1978, peak in 2008. Technology adopted from semiconductor industry.

Figure 10: Patent publication years for innovations important to PV cell fabrication. First and second columns show histograms of publication years for patents found in the Google Patent database. First column shows results of searching for the innovation name by itself. Second column shows results of including the additional term 'solar cell'. Blue lines are smoothed distributions.

Task 8: Preliminary policies classification and hypotheses

Preliminary policies table, classification scheme, and hypotheses (Subtasks 8.1 and 8.2, Milestone 8.1). In this task, we developed a preliminary policies table, Table 4, and a preliminary classification scheme for policies. This table outlines a few types of policies that have been used to expand deployment and improve the performance of PV systems and other technologies. Our preliminary policy classification scheme was based on a common framework, in which we divided policies into the two broad categories of demand-pull and technology-push types. Demand-pull policies attempt to increase demand for a technology, while technology-push policies attempt to improve a technology's performance to make it more attractive to marketplaces.

Within these two broad types we distinguish several sub-types. Technology push policies include direct government investment activities, in which government funds efforts to advance the state of a technology through universities, national labs, or cost-shares with industry. Technology push also includes several kinds of policies that incentivize, rather than directly fund, efforts to improve the technology. This includes tax incentives for R&D, or loans for pilot-stage production projects.

Similarly, demand pull policies split into several sub-types. First, government purchases of a technology (for use at e.g. a government facility or military base) directly add to demand for the technology. Second, technology usage tax policies have been developed, which create various tax incentives for businesses and consumers to purchase the technology. For example, investment tax credits give businesses tax credits for qualifying technology purchases, such as a solar installation. Another example is accelerated depreciation schedules, which allow businesses to reduce tax liability through faster deprecation of qualifying equipment. Third, regulatory mechanisms aim to improve market function by establishing market signals, setting up standards, or regulating particular kinds of contracts. This sub-type includes policies that affect retail electricity rates, such as net metering, value-of-solar tariffs, and time-of-use rates. This sub-type also includes mandates to consumers, business, or utilities to use particular technologies (e.g. energy-efficient building requirements, renewable portfolio standards). Fourth, other policies aim to improve markets through miscellaneous means, such as by enhancing access to technology information or fostering new businesses (e.g. training programs for local installers.)

Table 4: Preliminary table of technology policies.

Policy type	Policy sub-type	Policy	Description
Technology Push	Direct government investment	Public R&D	Publicly-funded research and development at national labs, universities (either at federal or state level in the US).
		Cost-shared R&D	Partially publicly-funded research and development in collaboration with industry, universities, labs.
		Testing centers	Support for national labs and other labs to perform testing of
		Standards development	Development of technology performance standards.
		Diagnostic tools & test methods	Development of diagnostic tools and test methods.
	R&D tax incentives, subsidies	R&D tax incentives	Tax incentives (credits, deductions) for conducting R&D.
		Loan guarantees, tax credits, or other incentives for new production	Incentives to build or scale up pilot production lines and new manufacturing facilities.
Demand Pull	Direct purchases	Direct government purchase	Government purchase of the technology (e.g. JPL block, PV systems for government facilities, military bases, etc.)
	Technology use tax incentives, subsidies	Investment tax credits (ITCs)	Tax credit to businesses for particular investment purchases (e.g. PV system).
		Production tax credits (PTCs)	Tax credit to businesses for generating electricity from qualified energy sources (e.g. Federal Renewable Electricity Production Tax Credit).
		Accelerated depreciation	Changes to depreciation schedule to enable greater tax deductions from faster depreciation (e.g. Modified Accelerated Cost Recovery System (MACRS))
		Purchaser rebates	Partial refund for purchasing technology (e.g. California Solar Initiative)
		Property tax exemptions	Exemption from property taxes for qualified energy systems (e.g. Indiana Renewable Energy Property Tax Exemption)
	Regulatory mechanisms	Loan programs	Programs to provide loans for specific technologies. May include income-qualified programs (e.g. Mass Solar Loan).
		Rate design: Feed-in tariffs (FITs)	Long-term contract offered to renewable energy producers based on the cost of generation of each technology rather than the price of electricity. Also known as standard offer contract, advanced renewable tariff, or renewable energy payments.
		Rate design: Net metering	Provision for distributed generation customers to sell excess electricity to a utility at the retail rate and receive credit on their utility bill.
		Rate design: Value-of-Solar (VOS) tariffs	Payment to customers with solar installations for electricity delivered to the grid, potentially at a different rate than the local retail rate.
		Rate design: Time-of-use (TOU) rates	Use of electricity rates that vary by time-of-day, day-of-week, or season.
		Government mandates	Statute or regulation requiring local governments or businesses to purchase or produce energy from particular sources.
		Streamlined permitting & interconnection	Streamlined processes to obtain permits to build and interconnect installations with the grid.
		Building requirements	Requirements on building efficiency (e.g. Zero-net energy home retrofitting, solar ready requirements in California)
		Technology access regulations	Regulations guaranteeing a technology cannot be denied to a willing consumer. (E.g. a home owner associated cannot deny solar installations to homeowners.)
		Consumer mandates	Requirements for businesses and consumers to purchase technologies.
		Renewable Portfolio Standard (RPS)	Regulations requiring utilities to increase production of energy from renewable energy sources. May require only a total on all renewables or have a separate solar carve out.
		PURPA energy purchase requirements	Requirement for utilities to purchase energy produced by qualified facilities that were developed at cost equal or below what the utility would have to pay at traditional plants.
		Regulations on wholesale markets and transmission	Changes to FERC rules on transmission and pricing of electricity in wholesale markets.
		Authorization of 3rd-party Power Purchase Agreements (PPAs)	Allowance or non-allowance by state governments for PPAs, which are financial agreements where a developer arranges for the design, permitting, financing and installation of a solar energy system on a customer's property at little to no cost. The developer sells the power generated to the host customer at a fixed rate that is typically lower than the local utiliy's retail rate.
	Miscellaneous demand pull	Improving market information	Information to improve market function (e.g. solarize campaigns, resource mapping).
		Seeding new businesses & business models	Assistance with establishing new business models such as quote platforms, third party ownership models, training for local installers, funding software development.

This work informed the next steps in study of policies and their influence on PV cost change, which we will discuss in Tasks 13 and 14. Based on this preliminary study of policies, we developed hypotheses for what were the most important policies for PV. This initial study suggested that the answer depends on the region and time in question. Across the globe, and before 2010, we think that feed-in tariffs were the most impactful policy. In the US after 2010, we think that investment tax credits were the most impactful. We expect each policy to benefit a technology at different stages of its development. Early on, when a technology's operating cost is too high to be supported at existing market prices, feed-in tariffs guarantee production of the technology at its current cost. In the hoped-for scenario where the technology improves and cost falls, this incentive will thus become weaker over time. Eventually the prospect of benefitting from investment tax credits, which let a developer monetize upfront capital costs, becomes a stronger incentive for deploying the technology.

Task 9: Develop table of innovations and low-level mechanisms

A. Methods

A.1. Identifying innovations affecting PV costs. In this work, we identify specific innovations and connect them to the determinants of technology costs. We employ this bottom-up approach to characterize in-depth the innovations and other factors affecting PV technology costs, building on a previously developed method of assigning the total cost change in a technology to different factors [2] that changed over time. Here we use the PV systems cost model shown in Equation 1 developed in our previous work (Task 1) [1] to guide our search for innovations that have affected PV system costs since the 1970s. We then develop a typology for the innovations identified in order to better characterize the sources of technological change. The typology classifies each innovation according to how it changed the variables in the cost model, including improvement processes such as automation, standardization, and digitalization. Based on the resulting table of cost variables, innovations and innovation types ('innovations table'), we draw conclusions on the prevalence of sources of technological change in PV modules and BOS. Finally, we investigate when and in which industry individual innovations originated.

We investigate innovations at both module and BOS levels. Unlike modules, which are mass-produced goods, BOS is an example of a custom-built, site-specific technology. Cost variables associated with BOS, such as installation time and labor rates, describe costs that are not hardwired into the technology and depend on local actors and site-specific conditions [1]. By examining the innovations at the BOS level as well as in modules, we begin to uncover innovation types that have been more prevalent in these two components of PV technology.

In this work we define an innovation as a successful commercial implementation of a new idea (including a first-of-a-kind idea as well as an existing idea that is rearranged or repurposed) that improves technology performance [63, 21, 64, 65]. Innovations represent significant changes in products or processes that often require deliberate efforts, such as research and development (R&D), to be developed and implemented. In the cost modeling framework used here, where we refer to changes in the cost equation variables as 'low-level mechanisms', innovations represent micro-level changes to one or multiple variables. We focus in detail on innovations in the PV system installation and project development processes as well as the hardware used.

Delineating one innovation from another is not straightforward, and we therefore include both narrower and broader innovations in our compilation. The main criterion we use to summarize a set of smaller modifications affecting one or more variables as one single innovation is that these modifications were implemented to achieve one specific overall improvement of PV technology (e.g., a new PV cell or inverter architecture). Often, these smaller scale modifications are performed simultaneously and/or are dependent on each other in pursuing a common goal to improve performance. Therefore, in such cases, we use the broader term for the innovation to reflect this commonality. For example, the development of the Czochralski method involved multiple distinct improvements (e.g., to the puller rod and the pulling method [66]), but we summarize these step-by-step improvements as one innovation ('Czochralski growth') because they all served the same high-level goal—growing single crystals by pulling a seed crystal out of molten silicon.

The number of innovations listed for each variable is not meant to be an indicator of the cost change that was achieved through that variable, since individual innovations do not necessarily affect costs equally and due to the inherent subjectivity in distinguishing one innovation from another. Instead, our innovations table is meant to provide a comprehensive view of the innovations that are regarded as important in the literature and can be investigated in further depth in future work. Individual innovations can also be analyzed for their cost effects, as we demonstrate under Task 10).

We first identify the innovations that improved PV's performance since 1970 by conducting a literature review. If an innovation affected any of our cost equation variables, no matter which performance metric an innovation aimed to improve (e.g. decrease cost, increase reliability, improve consumer experience), we include the innovation in our innovations table (Appendix). After the literature review, we sent our initial table of innovations to six experts in the PV industry. Through expert feedback, we confirmed that our innovations table is comprehensive and includes the key innovations.

In addition to specific innovations, there are also other factors that cause changes in variables in the PV cost model. These factors include micro- and macroeconomic developments and their effects on commodity prices and wages, firm-level pricing decisions, factory-level learning and scale effects, as well as changes in regulatory frameworks affecting the cost of PV. These factors do not fit into the innovation definition above. We therefore term these factors 'non-innovation drivers' of cost change. One example for non-innovation drivers is learning-by-doing. When narrowly defined as improvements in performance due to repeating routine tasks, learning-by-doing does not require new ideas in order to affect costs. Another example is material price changes due to bulk purchases or market forces that affect the total demand or supply for the material. In this work, we also identify such non-innovation drivers that change the variables in our cost model.

A.2. Innovation typology. We develop an innovation typology to explain how an innovation has induced change in one or more PV cost variables. We assign innovation types to each innovation by observing how a variable changed after an innovation was implemented. Often an innovation fits into multiple types. We identify ten different ways an innovation can affect a cost variable:

- Material quality improvement: Development of new materials or changes that enable existing materials to provide improved performance e.g. by reducing impurities and defects.
- Component design change: Functional changes of individual PV technology components.
- Component prefabrication and integration: Replacing on-site installation and manufacturing processes of individual PV components with previously designed and integrated components, often with the goal to enhance on-site or factory productivity and efficiency.
- Architectural change: Changes that affect the interaction of PV system components; often changes that focus on system performance (e.g., easier installation) in addition to component performance. Note that we define 'architectural' with respect to the architecture of the PV system as a whole. In the innovations table we also indicate when an innovation changed the architecture of a PV system component (e.g., a new PV cell or inverter architecture).
- Tool development: Development of new or improved hardware or software to complete a specific step in the processes required during module manufacturing, PV system design, or permitting.
- Process development: Conception of new manufacturing or deployment (e.g., system design, installation, permitting) methods.
- Automation: Use of technology or machinery in lieu of manual labor to control and monitor a manufacturing or installation process; often changes aimed at reducing the need for human assistance.
- Digitalization: Use of digital instead of analog technology for hardware design, planning, configuration, and for communication purposes between human actors and technology components.
- Standardization: Establishing a limited set of solutions that will be repeatedly used by a number of parties; includes codifying best practices as well as development of technical standards.
- Legal innovation: Recombination of different elements of a right, (e.g., the situations it applies to, the required burden of proof), or reinterpretation of a right, leading to a new law.

A.3. Innovation time stamps and industry origins. Our approach to assigning time stamps and industry origins to innovations follows five steps: (1) we select a set of keywords and phrases to describe each innovation in our list; the choice of keywords is based on the most common terminology used in papers and patents to describe the main functional novelty embodied in an innovation; (2) we conduct keyword searches on Google and Google Scholar to identify relevant sources; within these sources, we search for direct statements on the industry that first commercialized or broadly adopted an innovation, and the time period; (3) for relevant papers we conduct a backward citation search to confirm emergent hypotheses on innovation origins and time stamps, and to rule out contradictory statements in other references; (4) we confirm our findings from steps (2)-(3) using the same keywords to search for relevant patents; (5) for relevant patents we also conduct a backward citation search to rule out alternative industries of origin and time stamps. For innovations where we do not find relevant journal papers we jump directly to steps (4) and (5) and use evidence from patents instead.

Using the above approach, external industries are assigned as the industry of origin if patents and publications on the PV invention (which led to the innovation) cite patents and publications on the invention with the same functionality used in another industry. Functionality refers to the use of similar architectures, components and/or mechanisms as in the innovation described in the innovations table. For instance, for high-frequency inverter designs, the functionality is the use of MOSFETs, IGBTs, and other devices to increase switching frequencies of inverters. We also assign an external industry if non-academic sources indicate that this industry used the innovation before PV (e.g. if a company outside the PV industry was the first to commercially implement an innovation). The innovation origins in our set are listed in Table 5.

Table 5: List of industries and institutions ('innovation origins') assigned to PV innovations.

Origin	Description
Construction	Building design
	Structural stability testing
	Building materials
Electronics	Power electronics
	Microelectronics
	Energy wire manufacturing
Glass	Glass coatings
Semiconductors	Chips manufacturing
	Semiconductor device manufacturing
Metallurgy	Steel production
	Aluminum production
Photovoltaics	Module manufacturing
	System design
	Installation
	Equipment testing
Petroleum	Oil and gas drilling
	Oil and gas processing
Public institution	Energy commissions
	Professional associations

The data sources we use include academic literature (journal papers on specific inventions that led to innovations, review papers, history-focused sections in other scientific papers, government reports including reports submitted by research groups for review of their R&D grant) and gray literature (articles on company websites, market research reports, news media). Wherever possible we find multiple sources corroborating the time stamps and industry of origin information.

The time period of innovative activities studied here is defined by the goal of this work—to identify the time periods during which technical novelties were first commercialized, thereby being transformed from inventions into innovations. This focus allows us to draw a boundary around time periods that were significant for PV's commercial development, rather than going back to the scientific origins of photovoltaic systems such as the discovery of the photovoltaic effect in the 1800s.

B. Results

Results #1: General observations. Our innovations table shows 85 unique innovations[1] that affected PV system costs since 1970 (see the innovations table in the Appendix). Roughly half of these innovations influenced module-related variables, while the other half is linked to BOS-related variables.

We identify multiple innovations for all variables in the PV system cost equation. In particular, the variables causing a larger fraction of PV's cost decline, module efficiency and inverter costs [2, 1], are linked to a larger number of innovations. Although the number of innovations identified for a variable is not necessarily correlated with the variable's cost change impact, the multiplicity of innovations identified for these variables indicates the extent of R&D efforts devoted to these important variables. In addition, some of these innovations such as Czochralski growth are among the more broad innovations in the table, which include several smaller scale innovations, e.g. the use of seed crystals to define crystal orientation in Czochralski growth, liquid encapsulation techniques, or optical sensing to control crystal diameters [67]. This suggests that these variables were targeted by several simultaneous improvements that were coordinated and integrated to achieve higher performance.

Roughly one third of the innovations in our table influenced two or more variables, reflecting the coupling of variables through manufacturing processes or component designs (e.g. inverter designs). We observe such innovations mainly for the variables inverter costs and inverter efficiency, due to improvements that increased power density and thereby reduced materials needs for heat sinks and associated costs. Wafer thickness and silicon utilization also share a number of innovations (e.g. silicon carbide and diamond wire sawing).

Results #2: Innovation types. The most prevalent innovation types differ for modules and BOS, as indicated by the color differences between Fig. 11 and Fig. 12. Module innovations mainly led to new developments in materials, tools and processes (Fig. 11). Material quality is crucial for efficient operation. For example, growing higher quality single crystal silicon wafers without defects enables better absorption of light and increased conversion efficiency. Tools such as wire saws enabled cutting silicon ingots into thinner wafers, reduced material losses in the process, and greatly increased the speed of the wafer slicing process compared to the previous technology, inner diameter sawing. As

[1] The table has 133 entries. This includes (1) 85 innovations, some of which affect multiple variables and therefore are listed under multiple variables, and (2) 48 non-innovation factors.

an example of process development advances, screenprinting thin strips of metals on the silicon wafer to collect the electricity was important compared to previous processes, as it reduced equipment costs and increased throughput.

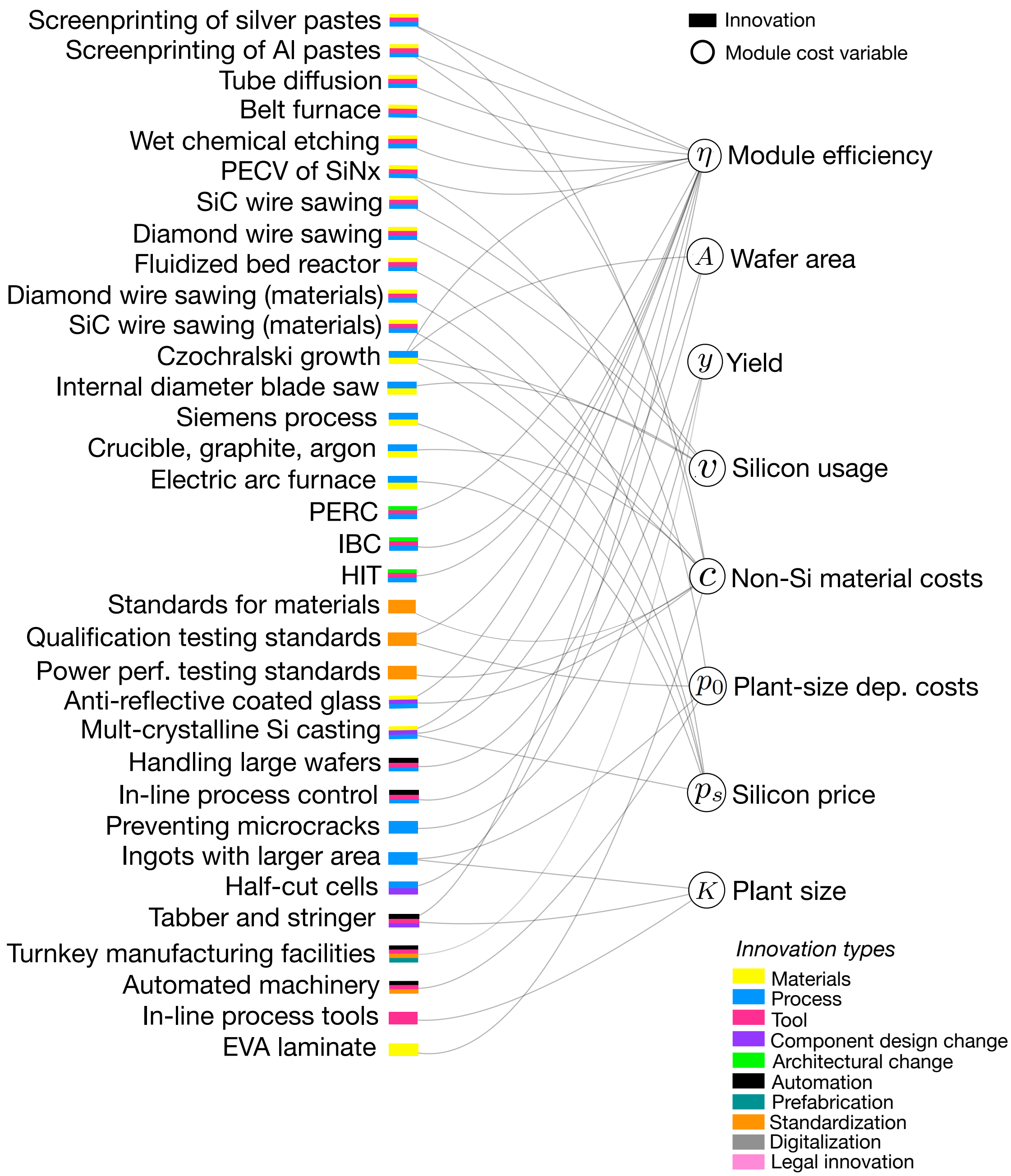


Figure 11: Module innovations (rectangles) and module cost variables (circles). Innovations are color-coded based on their types and plotted from most prevalent (top of left stack) to least prevalent type (bottom).

For BOS, the two most prevalent innovation types were ‘component design change’ and ‘prefabrication’ (Fig. 12). Examples for component design changes include transformerless inverters, modular inverters, and string inverters. These innovations aim at improve-

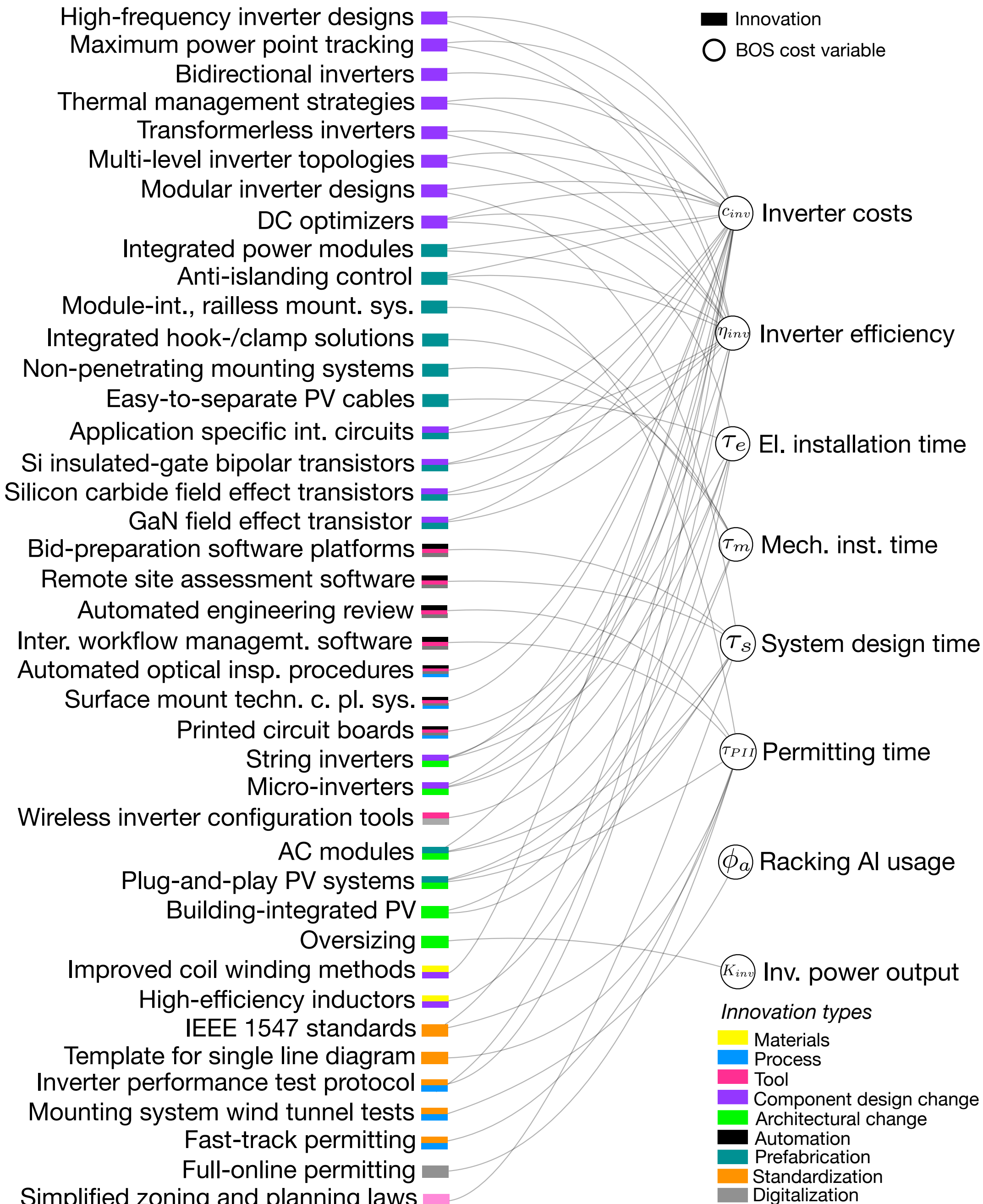


Figure 12: BOS innovations (rectangles) and BOS cost variables (circles). Innovations are color-coded based on their types and plotted from most prevalent (top of lect stack) to least prevalent type (bottom).

ments such as reducing material use (transformerless inverters), the need for customized manufacturing steps for different inverter applications and designs (modular inverter designs), and electrical losses (string inverters). Examples for component prefabrication include application specific integrated circuits or AC modules. Individual inverter or module mounting system components were combined into integrated pieces of equipment, making manufacturing and installation simpler.

Despite the diversity of innovation types affecting module and BOS variables, we also see patterns in the form of certain combinations of innovation types that appear more often than others. To improve materials, module-related innovations often required the development of new processes (color-coded yellow-blue in Fig. 11), or the combined development of new processes and tools (color-coded yellow-blue-pink in Fig. 11), indicating that PV materials required highly specialized production processes that could not be performed as effectively with existing tools. Examples for material-process-tool innovations include wet chemical etching for texturing, the use of belt furnaces, tube diffusion, and the development and screenprinting of silver and aluminum pastes. Innovations that increased automation in module manufacturing also involved the simultaneous development of new processes and tools (color-coded green-blue-pink in Fig. 11). With the exception of prefabrication and component design change coinciding several times (color-coded orange-grey in Fig. 12), we do not observe similar patterns in the list of BOS innovations. Combinations of innovation types are more diverse for BOS than for modules, with combinations of component design change and prefabrication, component design change and architectural change, and automation and digitization appearing several times.

Also noteworthy are the least prevalent innovation types: architectural changes, digitalization, standardization, and legal innovation. The scarcity of innovations falling into these categories may indicate a potential for improvement in these areas. Another interpretation is that these innovation types require non-traditional settings; standardization and architectural changes are often developed in cooperation of different institutions and component providers, rather than developed by individual companies in isolation).

Finally, we parsed the table in terms of innovations affecting physical or 'hardware' variables, and innovations targeting non-physical or 'soft' variables (see Fig. 13). We term the variables that characterize physical components such as module efficiency, area, and part counts 'hardware variables', while the variables characterizing processes and services are termed 'soft variables', and include variables such as task durations, wages, and fees [1]. Hardware innovations causing hardware changes can affect both hardware and soft variables, while soft innovations (e.g., streamlined deployment or permitting processes) are innovations that reduce soft costs without changing hardware [1].

The vast majority of PV innovations in our table are hardware innovations. Soft innovations (i.e., innovations targeting soft variables without changing hardware) such as fast-track permitting processes, standardized templates for single-line diagrams, and automated engineering reviews of grid interconnection applications were developed during the past decade and likely have not affected average PV system variables in the market yet. It is also noteworthy that most innovations target either hardware or soft variables, with few examples focusing on both (e.g. railless mounting systems). Note that the hardware vs soft variable distinction applies only to BOS cost variables in our model. This is due to the system boundary chosen in modeling the costs. In our cost model, the system boundary is drawn around a PV installation project, and includes project development and installation

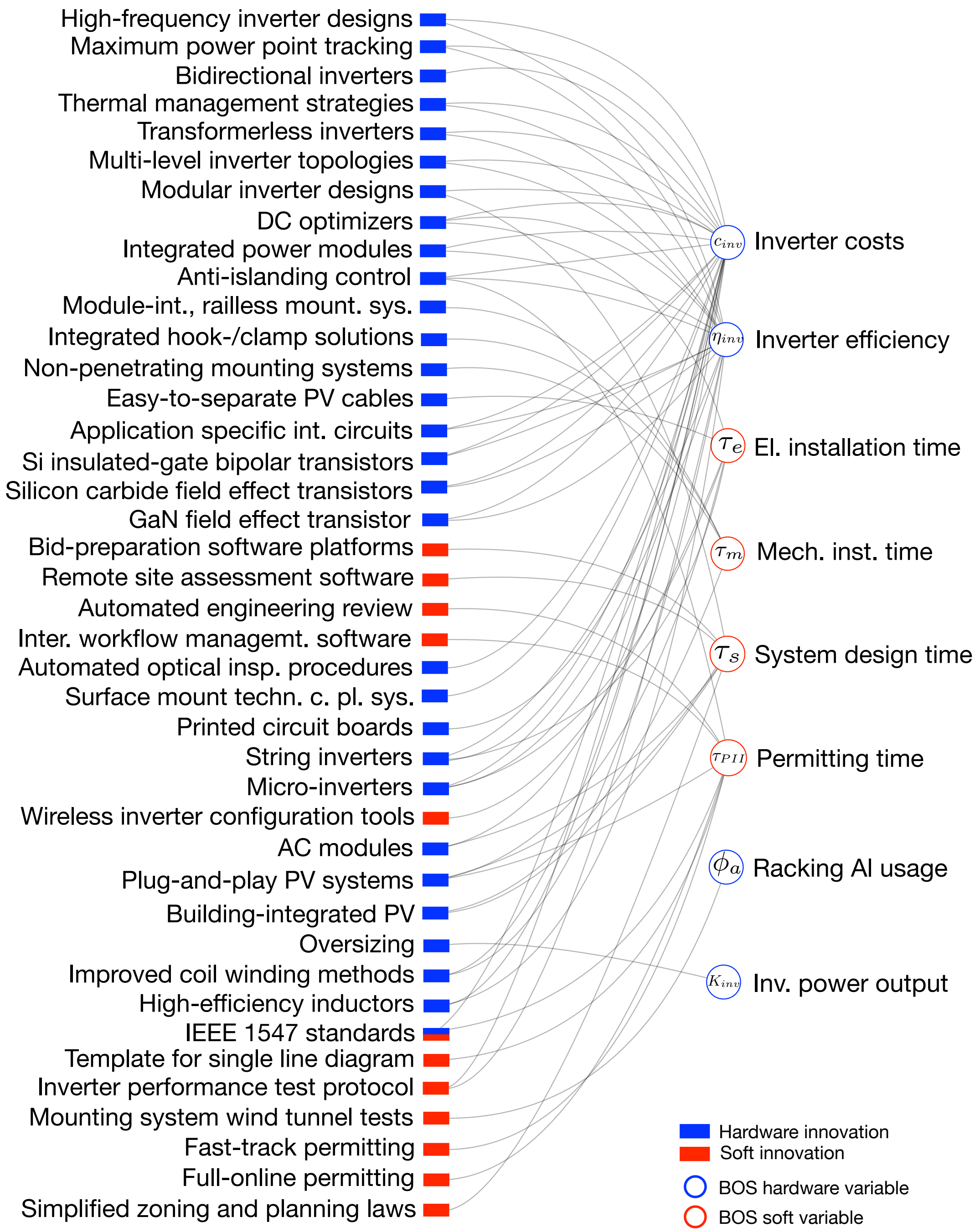


Figure 13: BOS innovations (rectangles) and BOS cost variables (circles). Innovations are color-coded based on whether they affect cost variables through changes in hardware (hardware innovation) or processes (soft innovation).

processes as well as the hardware used [1]. Hardware such as modules and inverters enter the system boundary with fixed features that do not change after they leave the factory gate. Therefore, we categorize all module- and inverter-related variables as hardware. A different system boundary choice could provide visibility into the soft costs in module manufacturing. For future cost reduction opportunities, understanding the evolution of the soft BOS variables is more important, since they are still determined by labor-intensive processes and disparate local regulations, while the production of hardware has been largely standardized and automated.

Results #3: Innovation origins. Looking across modules and BOS, the semiconductor and electronics industries had the largest impact on PV cost variables. Several important PV module innovations originated in the semiconductor industry (e.g. Czochralski growth, PECVD, belt furnace, tube diffusion, contactless soldering of ribbons. We also identified innovations with roots in metallurgy, electronics, and petroleum industries as well as the PV industry. Looking at BOS, inverter costs benefited from inventions in the semiconductor and electronics industries. Other BOS variables were influenced by innovations with roots in industries such as software engineering, electric utilities, PV, and electronics. Both module and BOS innovations origins show that PV was well-positioned within an ecosystem of technologies in many industries.

Consistent with the observed influence of external industries, only a limited number of innovations were designated as originating in the PV industry in the sense that the technical know-how was originally developed by the PV industry. These innovations include half-cut cells in modules, heterojunction with intrinsic thin layer cells, string inverters, maximum power point tracking (MPPT), AC modules, and remote site assessment software to support system design. However, the PV industry made contributions in adapting processes and tools from other industries. For example, using wind tunnel testing for the design of PV mounting structures required an adjustment of testing procedures to estimate and interpret aerodynamic loads for PV panels, which were not well described by the shapes tabulated in previously existing standards [68]. R&D efforts were therefore needed to determine how the results of individual tests of a given array on a particular roof structure could be generalized to derive design guidelines for an entire class of roof-mounted solar arrays. Anti-reflective coatings for glass provide another example for an external innovation that PV contributed to. Although extensive research has been done outside the PV domain to reduce the reflectivity of glasses used in optical equipment, ensuring the durability of coatings under outdoor weather conditions faced by PV panels required the development of additional coating characteristics, as well as performance testing to document energy gains and soiling behaviors of new coatings [69, 70]. Overall, PV industry-based innovations were about equally prevalent for modules and BOS. This might indicate that both component-level and system-level innovations required inputs from the PV industry as well as other industries. In terms of the actors and institutions involved in the invention and innovation process, we see a larger diversity for BOS as compared to modules. While most module innovations originated in research organizations or in industry, several BOS innovations were developed by city governments, states, or PV industry associations (e.g. State of Colorado, IEEE, U.S. municipalities).

Results #4: Timeline of innovations. Our analysis shows that cost improvement in PV was a continuous process, with inventions spread relatively evenly over the years since the 1920s (Fig. 14). For module innovations, the 1960s, '70s and '80s were particularly important; several module-related inventions were commercially implemented in the PV industry during that time period (e.g. wire sawing, development and screenprinting of aluminum and silver pastes).

Figure 14 indicates that not all but a group of innovation types (e.g. architectural change, digitalization, component prefabrication and integration) are concentrated in certain time periods, after 1990s, in particular. Module innovations (purple markers) are more prevalent in the earlier periods, and are concentrated in a group of industries (i.e., PV, metallurgy, semiconductors, electronics. On the other hand, BOS innovations (orange markers) appear more frequently in the later periods and are spread across the industries except for mining, metallurgy, and glass.

Results #5: Non-innovation drivers. Non-innovation drivers that changed the cost variables show some differences across modules and BOS. For modules, non-innovation drivers have been mainly related to cheaper materials and equipment (e.g. material discounts due to bulk purchases, easy access to materials and equipment due to a maturing PV industry) as well as learning-by-doing. For BOS, non-innovation drivers such as regulations and standards were important, since BOS encompasses components that connect modules to legacy infrastructure, namely the grid.

We also identified non-innovation drivers common to both modules and BOS. One such driver that was assigned to several variables for both modules and BOS was learning-by-doing. This assignment relies mainly on the assumption that repetition leads to learning and improvement, but it is difficult to prove this effect with data. Although there may be innovations that enable factory-level or installer-level learning-by-doing, we did not find evidence for such innovations. Other non-innovation drivers that are common to BOS and modules come from changes determined outside the PV industry, such as wages and material price changes due to demand from other markets.

Task 10: Study factors conditioning innovations

For this task we conducted both historical and prospective analyses. Section A below discusses the historical analysis which focused on quantifying the cost impacts of specific innovations that affected particular cost variables in the past. Section B discusses the prospective analysis which investigated potential cost changes via new design approaches that emphasize automation and standardization through a case study of plug-and-play PV systems. The work performed under this task achieves the Milestones 10.1 and 10.2 by quantitatively relate innovations and low-level mechanisms.

A. Historical analysis: Estimating the cost impacts of past innovations

Task 9 focused mainly on a qualitative assessment of the innovations affecting PV cost variables. However, one can also analyze the cost impacts of individual innovations quantitatively by using a cost model and an innovations table which lists innovations affecting

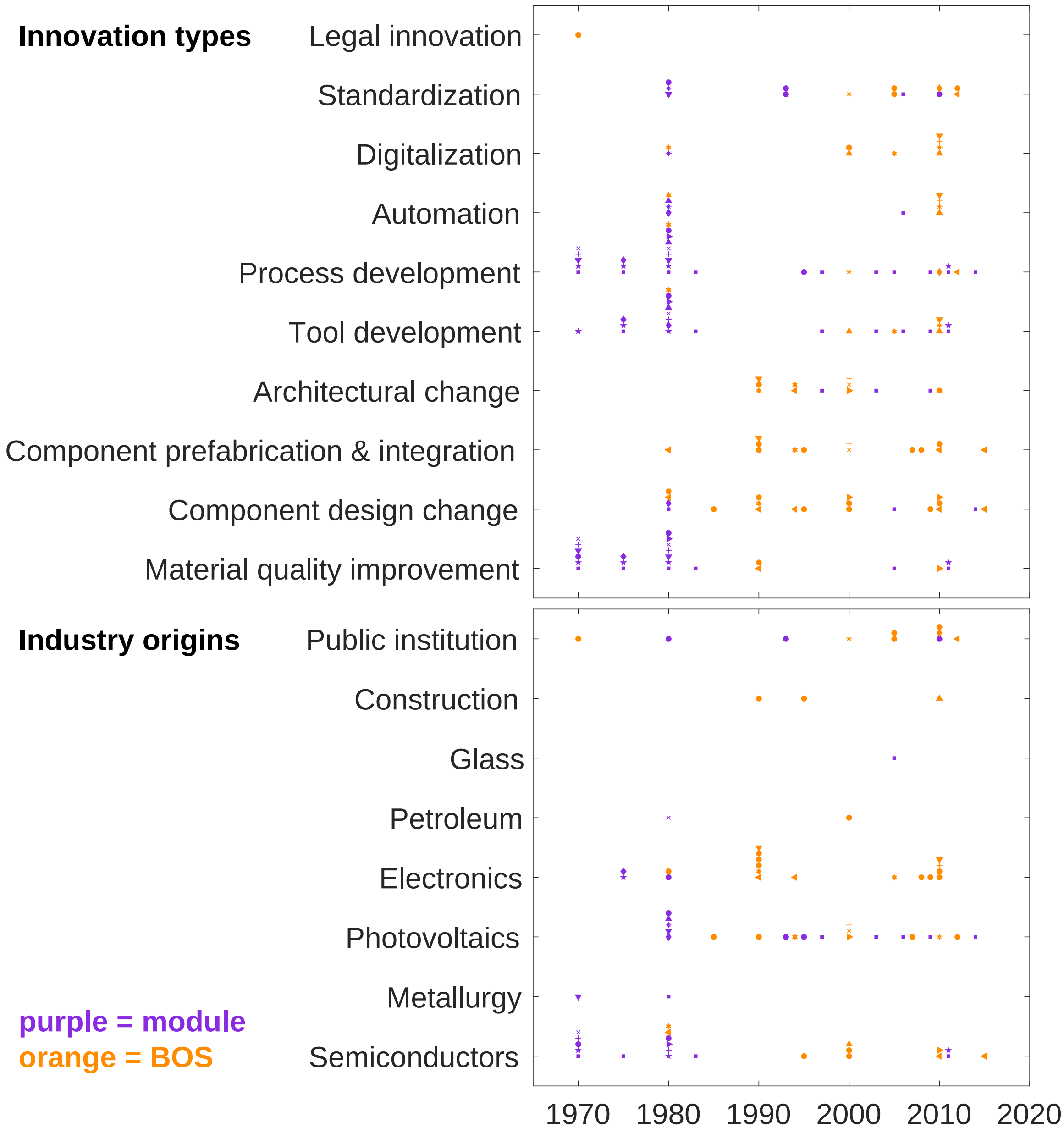


Figure 14: Innovations are categorized based on innovation types (top panel) and industry origins (bottom panel), and plotted over time based on approximate innovation years. Each marker represents an innovation. Purple markers show innovations that affect module variables; orange markers show innovations that affect BOS variables. For a given year, if an innovation is assigned to one innovation type, then it is plotted as a circle. If an innovation is assigned to multiple innovation types, then it is depicted with another marker type and the same marker type is used across all these innovation types (top panel) and the industry origin of the innovation (bottom panel).

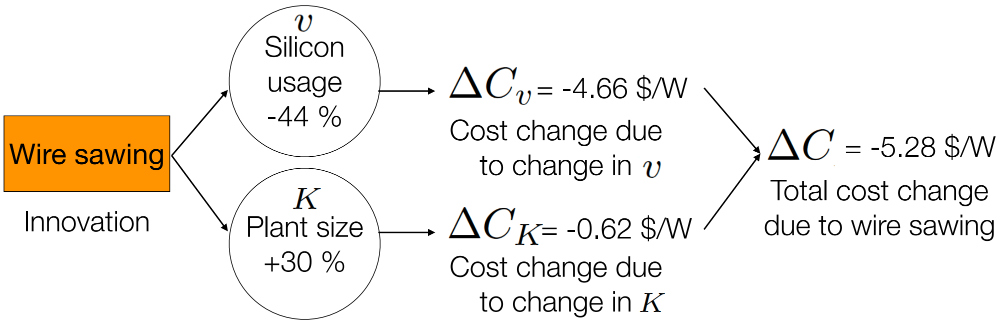


Figure 15: Example 1: The effect of wire sawing on cost variables and the resulting cost change around 1980 (2015 USD). Overall, these changes lead to a cost decrease from 29 $/W in 1980 to 24 $/W (2015 USD). Silicon usage reduction contributed 88% of this cost change, while increased throughput contributed 12%. The cost change due a change in a variable is calculated by using the cost change method developed in [2].

the cost variables. In the first example below, we demonstrate an approach for estimating the cost impact of an individual innovation based on how it changes the cost variables after it is implemented. In the second example, we attribute the total cost change due a change in a variable to all of the innovations affecting that variable. The approaches can be used to estimate the cost effects of other innovations of interest.

Example 1: Estimating the cost impact of an individual innovation In this example, we estimate the cost impact of switching to wire saws from ID saws. Since wire sawing was introduced in the 1980s [25, 71], we model its cost impacts based on the state of the technology around that time. We first populate our module cost equation with data for 1980 (see Table 6). We then identify which variables of the PV module cost model were affected by the switch to wire saws. Based on a literature review, we determine that mainly silicon usage (v) and throughput, i.e. plant size (K), were impacted by the introduction of wire sawing [72, 73]. We then change the silicon utilization and throughput variables by the amounts indicated by the literature. We estimate the impact of these changes on module cost by using the cost change method developed in [2].

Figure 15 illustrates the approach and shows the effect of wire sawing on cost variables and the resulting cost change. Reducing the silicon losses during wafering by 30%, wire sawing reduces the module cost by 4.66 $/W (2015 USD). By increasing the throughput by 30%, it reduces the module cost by an additional 0.62 $/W (2015 USD). Overall, these changes lead to a cost decrease from 29 $/W in 1980 to 24 $/W (2015 USD). Silicon usage reduction contributed 88% of this cost change, while increased throughput contributed 12%.

In this example, we focused on two variables, silicon utilization and throughput, that improved due to wire sawing. However, an innovation may initially change certain variables such as yield in a direction that increases cost. For example, cutting thinner wafers reduced throughput in earlier versions of wire sawing machines due to reduced silicon ingot load and cutting speeds [74]. Thinner wafers were also harder to handle in subsequent

Table 6: Data for cost equation before wire sawing (1980 values) and after wire sawing. Data have been collected from multiple sources; only the mean values used to populate the equation are shown in this table. c and p_0 are calculated using various other data. Note that the scaling factor, b, in the equation is 0.27.

Variable	**Unit**	**Before wire sawing (1980 values)**	**After wire sawing**
Plant size (throughput) (K)	modules/year	1 MW/year = about 17200 modules/year	30% increase: 1.3 MW = about 22,300 modules/year. "30% increase in production volume owing to more wafers per inch of ingot" [73]. Assuming that efficiency and thickness are the same as before, this translates into an overall throughput increase of 30%.
Silicon thickness (t)	μm	500 μm	same as before
Silicon utilization (U)	unitless	20%. Losses during ingot growth and cutting (30%), and wafering (50% for ID saws [71]) are accounted for.	35%. Wafering losses are reduced by about 30% due to wire saws [72], from 50% to 35%. Ingot growth and shaping losses are assumed to be the same as before.
Silicon usage ($v = t/U$)	cm	0.25	0.14
Module efficiency (η)	unitless	8%	same as before
Polysilicon price (p_s)	2015 $/kg	126	same as before
Wafer area (A)	cm^2	90	same as before
Yield (y)	unitless	75%	same as before
Non-Si materials costs per wafer area (c)	2015 $/cm^2	0.062	same as before
Capital, labor, O&M, electricity costs (p_0)	2015 $	1.32	same as before

processing steps such as demounting, signaling, and cleaning [74], and therefore reduced yield [75]. Also, the cost of consumables used in wire sawing (e.g. wires, slurry, glue) was still higher than that of the ID saw until mid-1990s [76]. To achieve higher yields and higher wafer quality, the wire sawing process was optimized by controlling wire speed, wire tension, cutting speed, the composition and properties of the abrasive SiC powders and the carrier fluids, and various other machine parameters [77]. This indicates that the cost effect of an innovation likely evolves as the processes are optimized over time, as exemplified by the historical account of wire sawing above. The approach presented here can be used to capture the intermediate or final cost impacts of an innovation.

Example 2: Attributing total cost change to innovations This section demonstrates an approach to quantitatively assign cost reductions to innovations associated with a given PV cost variable. In this demonstration, we will focus on the innovations affecting a module-related variable, non-silicon materials costs, c, in the module cost equation in [2].

In the case of an aggregate variable like non-silicon materials costs, we first disaggregate it into its constituents in order to obtain a fine-grained picture of the specific innovations affecting them. The constituent material categories include materials needed to produce silicon ingots such as crucibles and argon, SiC or diamond wire sawing materials, silver and aluminum pastes and associated screenprinting materials, anti-reflective coated glass, and other cell and module materials. However, such disaggregation is not a mandatory step for all variables and may not be necessary for other variables that are more specific, e.g. thickness of silicon.

For this example, we are using a cost equation only for PV modules rather than PV systems. The module cost equation from [2] is as follows. Variable definitions are provided under Task 9.

$$C\left(\frac{\$}{W}\right) = \frac{\alpha}{\sigma A \eta y}\left[Av\rho p_s + cA + p_0\left(\frac{K}{K_0}\right)^{-b}\right]. \tag{7}$$

We obtain the data on these material costs are for years 2010 and 2018 [78][79]. However, the cost of glass in 2010 could not be determined so we will use the cost data for glass in 2012 in [80] as an approximation. However, these models report costs in \$/W, rather than the unit for c, which is \$/cm^2, referring to non-silicon material costs per wafer area. Therefore, in order to report non-silicon material costs in \$/W, c must be multiplied by the term $\alpha/(\sigma\eta y)$, the variables for which have already been defined in the previous case study. For the purposes of this analysis we will create a new variable c_W as defined below:

$$c_W = c\frac{\alpha}{\sigma\eta y} \tag{8}$$

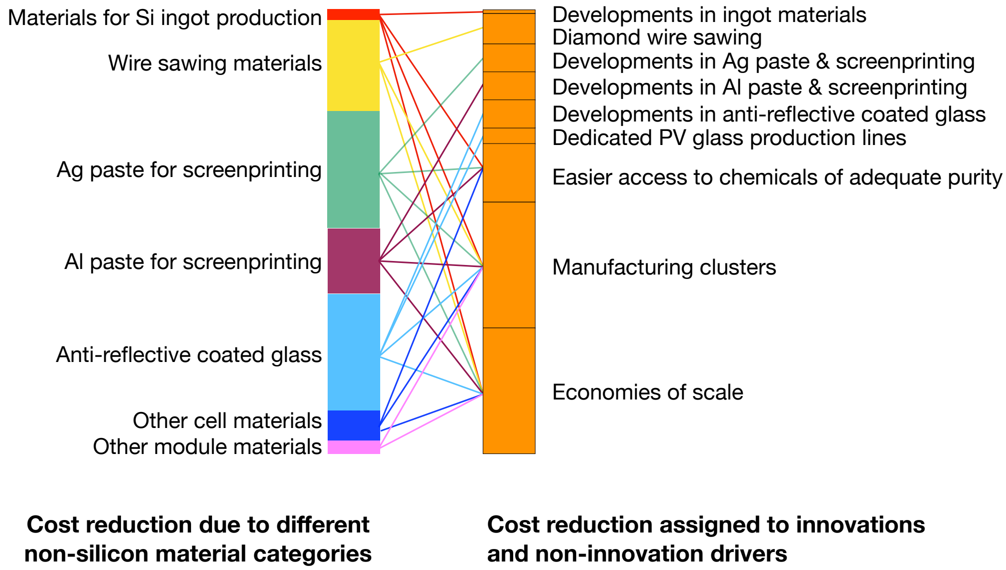


Figure 16: Example 2: Left: Cost reduction due to a change in a cost variable, c (non-silicon materials costs), is broken down into contributions of different material types between 2010 and 2018. Cost change due to each material type is proportional to the height of each box. Material types are matched with the innovations (developments in ingot materials, wire sawing, Ag and Al pastes and screenprinting, anti-reflective coated glass) and non-innovation drivers (easier access to chemicals of adequate purity, manufacturing clusters, economies of scale) affecting them. Right: Cost reduction due to the assigned innovations and non-innovation drivers is proportional to the height of each box.

If we want to identify the proportion of these cost changes which can be attributed to reductions in material costs themselves (rather than just efficiency improvements), any changes in the $\alpha/(\sigma\eta y)$ term over this period must first be evaluated and removed. We assume that α remains constant over the 2010-2018 period [2]. Changes in efficiency (η) are documented in [78][79]. For y, we assume a 2010 value of 94% based on 2012 data in [2], and extrapolate a value of 97% for 2018. This results in a 20% reduction in the $\alpha/(\sigma\eta y)$ term over the 2010-2018 time period, whereas all non-silicon material costs decreased by 72% over the same time period. Therefore, we can assume that innovations specific to non-silicon materials account for 73% of the cost reductions observed in non-silicon material costs over 2010-2018.

The next step is to assign cost reductions to the innovations and non-innovation drivers associated with variable c. We first obtain the cost reduction in the material categories between 2010 and 2018 using data from the literature [78, 79, 80] and our cost model for PV modules [2].

We then take the innovations and non-innovation drivers affecting variable c from our innovations table (Appendix) and match them with the material categories of c as shown in Figure 16. For demonstration purposes, here we assume that the cost reduction caused by each material category is equally distributed across the innovations affecting that category.

We find that the largest overall contributors to cost reductions in the 2010-2018 period were economies of scale, manufacturing clusters, and easier access to high purity chemicals as shown in the right column on Figure 16, where cost change is proportional to the height of each box. These are all non-innovation drivers, which we assumed affected many or all material categories and therefore had a large cost impact due to our equal distribution of cost effects across innovations or non-innovations. In future work, cost impacts could be distributed in a non-equal way depending on data availability. Note that the example shown here is intended as a demonstration rather than a definitive quantitative assessment of cost impacts. In this example we estimated the effects of innovations through changing the non-silicon materials costs (c) variable only. Some of these innovations also affect other variables and lead to cost changes through changing these variables as well. These other variables also would need to be taken into account in order to estimate the total cost impacts of an innovation.

B. Prospective analysis: Cost reduction through innovative system design

In this work we explore how design approaches that emphasize standardization and automation, such as plug-and-play PV systems, can create cost reduction opportunities by reducing interactions and speeding up activities with high process costs. Plug-and-play systems employ an array of innovations intended to simplify and standardize PV projects, enabling individuals without specialized training to deploy them. One technology commonly used in plug-and-play system are AC modules—PV modules with an AC microinverter directly mounted to the module and capable of producing AC power with no external DC power [81]. The use of AC modules simplifies wiring and reduces the hardware needed to demonstrate compliance with electrical codes [82]. Touch-safe electrical connection ports, integrated grounding wires, and module frame grounding are designed to simplify, standardize, and improve the safety of electrical wiring. Modules can be quickly deployed using pre-manufactured racking systems, integrated hook and clamp connections, or module-integrated railless systems. Pre-attached sealing putty reduces or eliminates the need for flashing or other waterproofing measures. System permitting, inspection, and interconnection (PII) is standardized and automated with the help of a PV utility interface device in some designs, while others use a simple power cord for interconnection at an electrical outlet.

B.1. Methods

B.1.1. Analysis of photovoltaic projects using design structure matrices Cost decline in PV systems can be linked to changes in the inputs to PV projects and how those inputs interact with each other [83]. We call these inputs *elements*, which are the physical items and people involved in the project—PV hardware (e.g. modules, racking, inverters), infrastructure at the project site (e.g. roof, grounding, electrical distribution equipment), human actors (e.g. electricians, system designers, permitting personnel), and their tools and equipment. When two elements interface with each other in the process of creating a working PV system—whether through a material connection, spatial adjacency, an electricity flow, or an information transfer—we call this an *interaction*. Elements are typically items of cost, while interactions can affect the cost intensity of elements. Groupings of elements and interactions together form *cost components*, the major categories of costs for installations.[2]

We evaluate opportunities for cost improvement by modeling plug-and-play projects using design structure matrices, connecting elements of PV projects and their interactions to cost, and evaluating the impact of design changes on key cost components.

To study the effect of plug-and-play systems on cost, we consider a range of design options that explore different degrees of automation and standardization. We prepare design structure matrices (DSM) for three different PV systems:

1. A conventional small-scale PV system representative of the current U.S. residential market. This is the benchmark design for comparison.
2. A plug-and-play system of similar scale, requiring owner assembly, and interconnected using a smart PV utility interface.
3. A comparatively smaller plug-and-play system, substantially pre-assembled, and interconnected through a power cord and standard electrical outlet.

We call these systems *conventional*, *plug-and-play large*, and *plug-and-play small*. The conventional system design is based upon the prevailing system architecture currently used in the U.S. [83]. The two plug-and-play system designs are based upon the dominant architectures discussed in literature and expected in the U.S. market [82, 27, 84].

The three designs we model cover a range of design choices. While the plug-and-play small system is similar in design to household appliances, the plug-and-play large system has more likeness to conventional PV systems. Although the two plug-and-play systems that we model diverge in design, in reality, future designs may incorporate strategies from both, and our results may provide insights for those too.

The system boundary for this analysis is the local project level, capturing downstream effects of plug-and-play design changes where most costs are incurred. Excluded are supply chain, manufacturing firm, and certain aspects of the installation firm; however, the costs of these excluded elements and interactions are proportionate to or reflected within the costs of other items in the DSM.

B.1.2. Cost change potential in photovoltaic systems We define a combined metric for latent cost reduction potential, κ_i, for BOS cost components. We compute this metric as a scaled product of these two cost ratios. To the second ratio we apply a power factor, b_i, which takes a value of zero if the technical minimum of cost component i is approximately zero and takes a value of one if technical minimum is significantly greater

[2] There are eleven primary cost components for small-scale PV installations: modules, inverter system, structural balance of system, electrical balance of system, supply chain, sales tax, installation labor, PII (permitting, inspection, and interconnection), customer acquisition, overhead, and profit.

than zero. This product is scaled by a constant α such that the values of κ_i to sum to 1. Equation 9 depicts the computation of the latent cost reduction potential:

$$\kappa_i = \alpha\left(\frac{C_{i,2}}{\sum_{i=1}^{11} C_{i,2}}\right)\left(\frac{C_{i,2}}{C_{i,1}}\right)^{b_i} \tag{9}$$

This metric assumes there is always cost reduction potential until a cost component hits its minimum. Based on a literature survey of technical minima, we select values of b_i equal to zero for the following cost components:

1. Installation labor costs, which can be entirely eliminated if system hardware is substantially pre-assembled, designed for touch-safe electrical features, and interconnected using standard plugs [82, 27]
2. PII, which is precluded if the item 1 above is met, the system is tested and listed Nationally Recognized Testing Laboratory for conformity to code (e.g. [82], and the AHJ and utility policies allow (e.g. [85])
3. Structural BOS, which can be reduced to an adhesive layer pre-affixed to PV modules which would eliminate all module racking, racking fasteners, module fasteners, roof penetrations, and the associated waterproofing [28]

We use a value of one for b_i for the remaining components. The values of κ_i are influenced by the selection of the time period (2010 to 2018), and we expect that cost components which have experienced variable cost change over time would yield somewhat different results if an alternate period were studied. Further, while this approach is adequate for ranking cost components according to their importance for future cost change, these estimates should not be construed as a detailed evaluation of economic or technical cost reduction potential.

B.1.4. Prospective cost change in the balance of system We conclude our analysis by comparing the designs of conventional projects to plug-and-play projects and study the changes in elements and interactions that comprise each cost component, evaluating which components are likely to improve. We first decompose each cost component into its constituent parts (elements and interactions). Next, we compare the results of this decomposition across the three modeled systems, using the latent cost change potential of each component to evaluate if plug-and-play designs can significantly improve key cost components.

As the inputs to cost components, elements and interactions carry cost significance. Elements are physical items and people involved in the project; the former may have to be purchased, incurring costs to a component through the purchase and other means (e.g. supply chain and profit), and the latter may earn wages and accrue other costs (e.g. payroll) in association with cost components. Although not all elements will have equal cost, eliminating an element will generally reduce cost, ceteris paribus. The cost intensity of the elements in a cost component is affected by interactions, and, all else equal, eliminating interactions will typically decrease cost. For example, reducing interactions can result in:

B.1.5. Data Our analysis of the sources of cost reduction potential in plug-and-play systems uses two datasets: (1) equipment and project-level data on PV system design and installation, including technical and process information and (2) historical cost data for residential PV systems in the U.S.

To model project design and installation, we draw from an array of recent literature and project-related documents including technology handbooks (e.g. [86, 87]), national codes (e.g. [88, 89]), technical reports (e.g. [28, 90]), local permitting guidelines (e.g. [91, 92]), utility interconnection policies (e.g. [85, 93]), design standards (e.g. [94, 95]), system diagrams (e.g. [96, 97]), research publications (e.g. [29, 82]), national solar benchmark reports (e.g. [83], installer surveys (e.g. [98]), product specifications (e.g. [99, 100]), installation manuals (e.g. [101, 102]), and visual documentation of system installation processes (e.g. [103, 104]). We capture common practices and specifications in conventional residential PV system design and installation, while acknowledging that current industry practice and system design are not only diverse, but continuously evolving. Where heterogeneity exists and there is adequate data on frequency of use, we use system information that is most representative of the industry. Where rates of occurrence are not readily available, we make selections in accordance with best practices in engineering and project management. Our research identifies two dominant plug-and-play system designs, and we collect information for both, while recognizing that there are other configurations and approaches to deployment.

For our analysis of cost reduction potential, we use historical data from previously published studies, disaggregated into cost components according to the most important categories of expense. We draw upon previously published studies performed by national laboratories [98, 83]. We use gross domestic product (GDP) price indices from the U.S. Bureau of Economic Analysis to adjust for the effects of inflation [105].

Results Figures 17 to 19 show that plug-and-play designs change the BOS architecture and project flow significantly. To evaluate the effect, we quantify the elements and interactions according to the relevant typologies (element pre-assembly, interface type, degree of standardization, degree of automation, and domain) and compare the play-and-play installations to the conventional.

Table 7 presents each components' latent cost reduction potential, inflation-adjusted cost data for years 2010 and 2018, share of 2018 system cost, and residual share of 2018 cost relative to 2010 value. The table provides definitions of each cost component and listings of elements and interactions that are included in each component. We find that installation labor (18%) and firm overhead and profit (14% and 21%) account for the largest shares of latent cost reduction potential, followed by electrical BOS (11%) and customer acquisition (8%). Three cost components have very little latent potential: sales tax (1%), PII (4%), and the inverter system (4%). The remaining three components–structural BOS, supply chain, and modules—have modest latent potential (6% to 7%). Thus, profit, installation labor, overhead, electrical BOS, and customer acquisition present the largest opportunity for future cost reduction strategies focusing on costly components that have been slow to improve through other innovations.

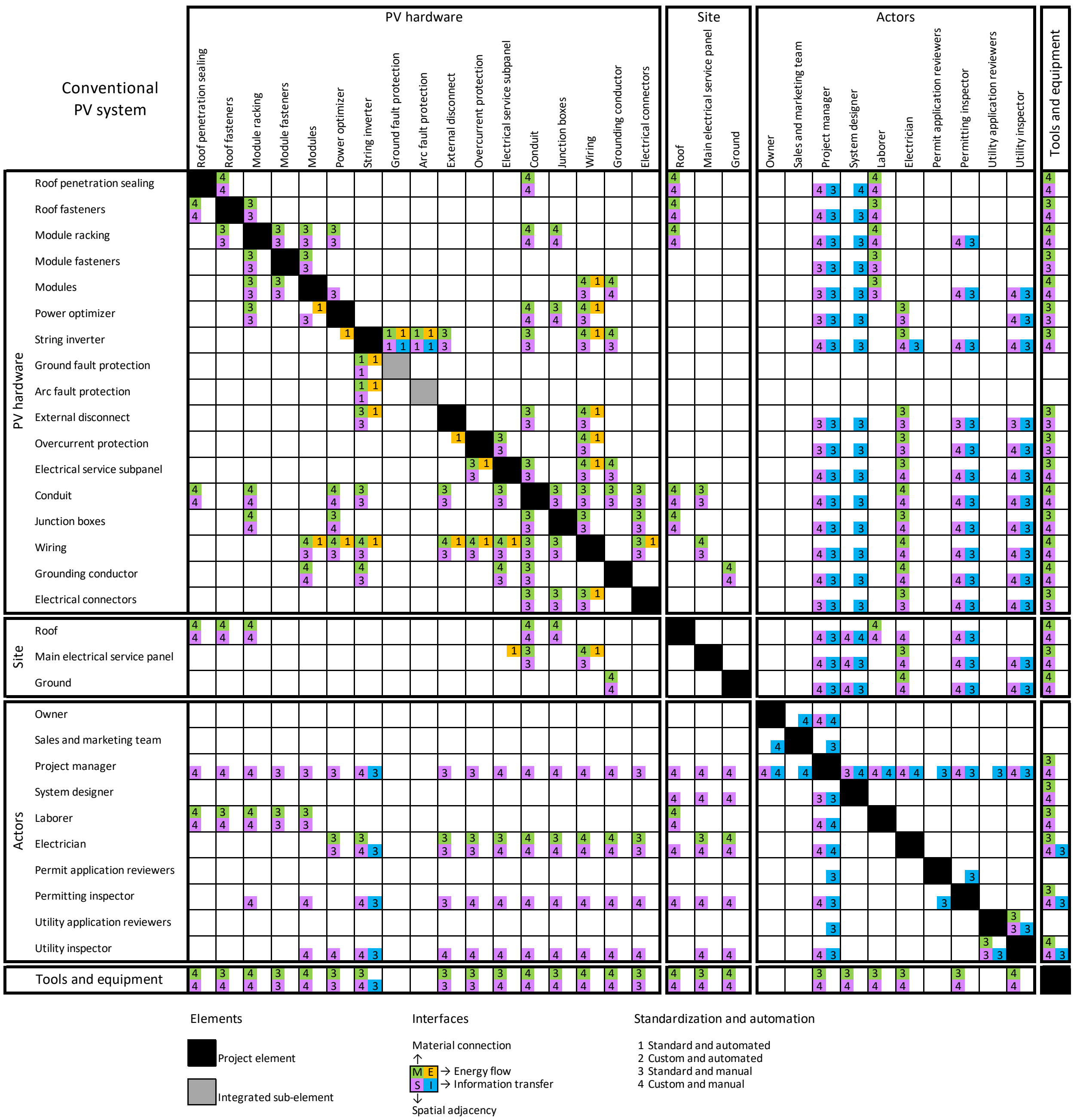


Figure 17: Design structure matrix for a conventional small-scale PV system.

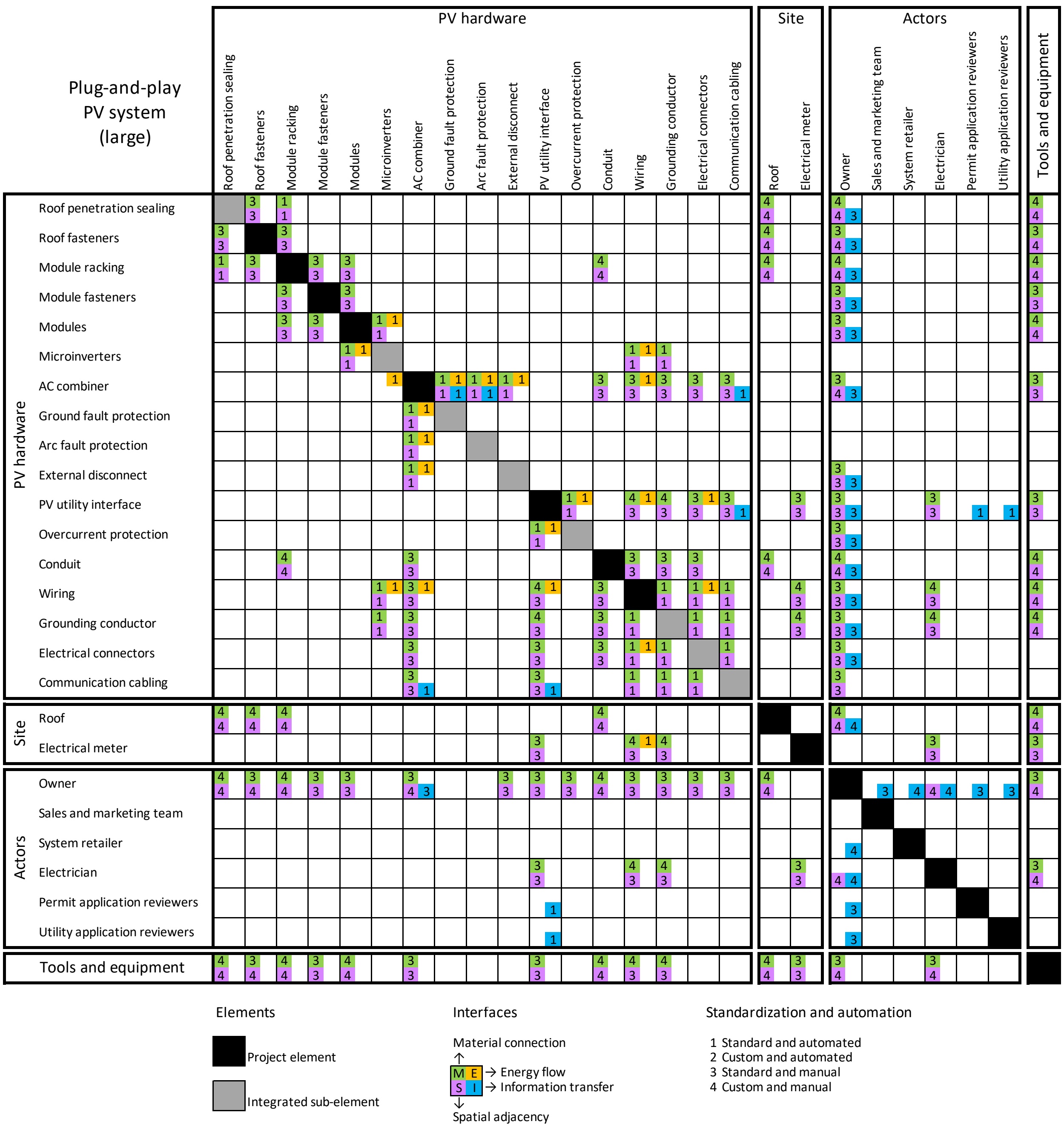


Figure 18: Design structure matrix for a large plug-and-play PV system.

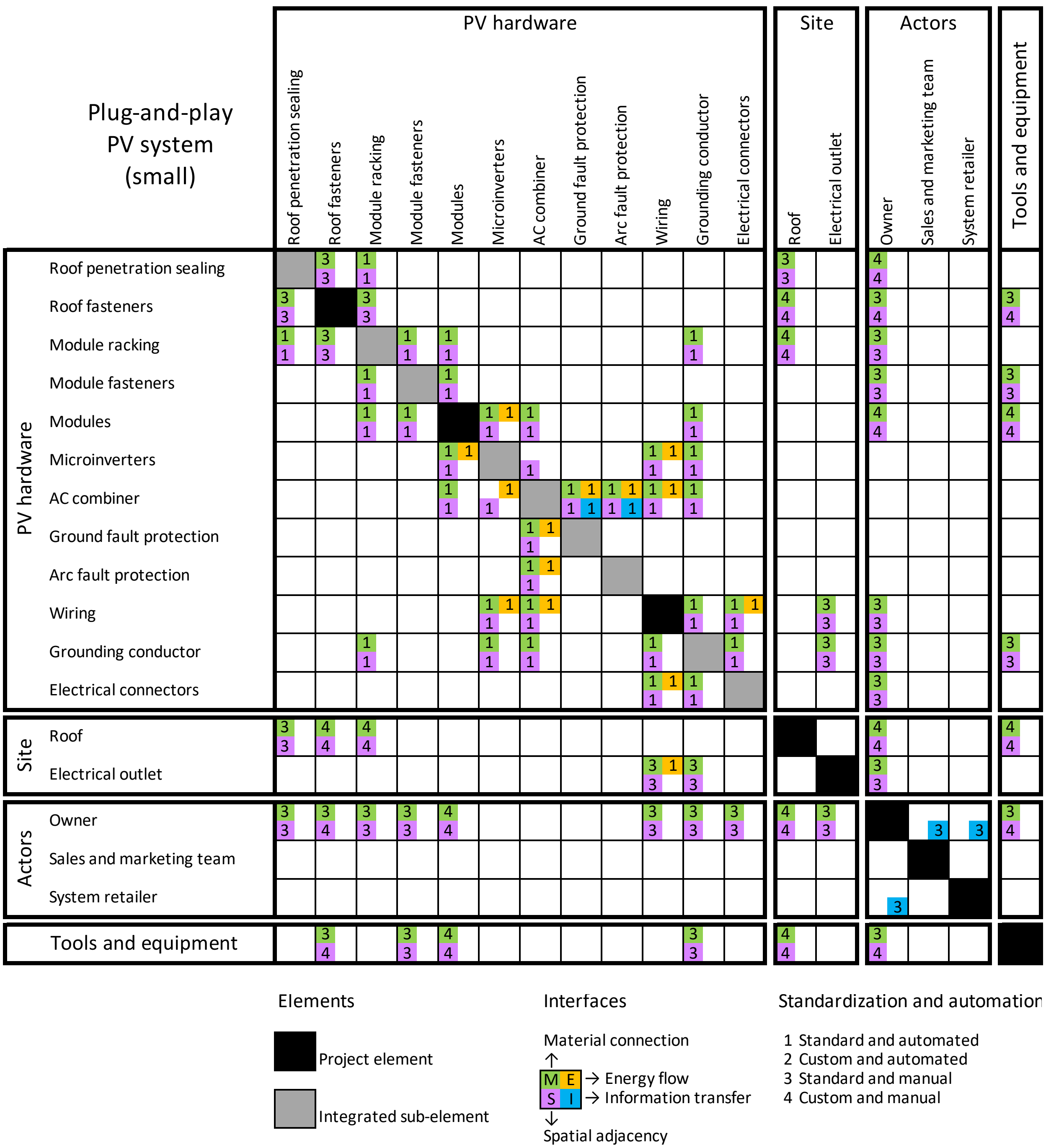


Figure 19: Design structure matrix for a small plug-and-play PV system.

Cost Component	2010 cost	2018 cost	Share of 2018 system cost	Residual cost share[1]	Latent cost reduction potential	Definition	Included elements	Included interactions
Modules	$2.47	$0.47	18.0%	19.0%	5.8%	Price of DC module to first buyer.	Modules.	N/A
Inverter system	$0.48	$0.18	6.9%	37.3%	4.4%	Price of inverter and its integrated hardware to first buyer. Historical cost change analysis and conventional DSM uses string inverter, PnP DSMs use microinverters with AC combiner.	String inverter (conventional), microinverters and AC combiner (PnP) with integrated disconnect (PnP large), integrated ground and arc fault protection (all).	Interaction cells with automated material connections with the string inverter (conventional) or microinverter and AC combiner (PnP)—excluding wiring and grounding.
Structural BOS	$0.36	$0.10	3.8%	27.5%	6.5%	Price of module racking, module fasteners, roof fasteners, and roof penetration sealing to first buyer.	Module racking, module fasteners, roof fasteners, and roof penetration sealing.	Interaction cells with automated material connections with the module racking, fasteners, or roof sealing.
Electrical BOS	$0.22	$0.19	7.3%	88.0%	10.8%	Price of all non-inverter and non-module electrical hardware to first buyer.	Power optimizers (conventional), external disconnect (conventional), wiring, conduit, electrical connectors, overcurrent protection, service panels, grounding conductor, communication wiring (PnP large), PV utility interface (PnP large).	Interaction cells with automated material connections with the electrical BOS elements.
Supply chain	$1.11	$0.35	13.4%	31.5%	7.2%	Added cost for shipping and handling of equipment (e.g. 16% in 2018). Additional supply chain costs for modules and inverters (e.g. 35% and 20%, respectively in 2018).	All PV hardware.	None. Supply chain interactions are beyond the system boundary.
Sales tax	$0.33	$0.06	2.5%	19.8%	0.8%	Sales tax on equipment weighted by state installed capacity (9% in 2010, 7% in 2018 when weighted by state).	All PV hardware.	N/A
Installation labor	$0.75	$0.28	10.7%	37.5%	18.1%	Direct hourly cost of electrician and laborer wages plus indirect labor burden (e.g. FICA, workers compensation)	Laborer (conventional) and electrician (conventional and PnP large). Owner's labor (PnP) is excluded as a cost component.	Interactions with laborer and electrician.
PII	$0.20	$0.06	2.3%	30.5%	3.9%	Applications and labor for permitting (AHJ) and interconnection (utility) as well as associated staff time for paperwork and inspection. Typical permit fee is $200 in 2018 and $490 in 2010.	Permit and utility application reviewers, permit and utility inspectors, project manager.	Interactions with permit and utility application reviewers, permit and utility inspectors.
Customer acquisition	$0.77	$0.30	11.5%	39.0%	7.6%	Cost of marketing, advertising, sales calls, sales-related site visits, preparing bids, and contract negotiation.	Conventional: sales and marketing, project manager, system designer. PnP: sales and marketing.	Conventional: interactions with sales and marketing, system designer, and project manager (with owner and site only). PnP: interactions with sales and marketing.
Overhead	$0.39	$0.29	11.1%	74.3%	14.0%	Cost of administration and buisness overhead. Includes payroll, facilities, information technology, office expenses and staff for administration, legal, finance, and business management.	Conventional: sales and marketing, project manager, system designer, laborer, electrician, tools and equipment. PnP: sales and marketing, system retailer, electrician (large), tools and equipment. Many elements are beyond the system boundary.	Conventional: interactions with sales and marketing, project manager, system designer, laborer, electrician, tools and equipment (except permitting and utility). PnP: interactions with sales and marketing, system retailer, electrician (PnP large), tools and equipment. Many interactions are beyond the system boundary.
Profit	$0.33	$0.33	12.6%	98.6%	21.0%	Fixed profit margin applied to all direct expenses incurred by firms: 17% (system retailer and electrician for PnP, PV installer for conventional).	All PV hardware. Conventional: sales and marketing, project manager, laborer, electrician, permitting and inspection elements. PnP: electrician (PnP large), sales and marketing.	Interaction cells with automated material connections. Conventional: Interactions with sales and marketing, system designer, project manager, laborer, electrician, permitting and inspection elements. PnP: Interactions with electrician (PnP large), sales and marketing.
Total	$7.41	$2.61	100%	35.3%	100%			

Cost data are reported in 2018$/$W_{DC}$ and are derived from [98, 83] for U.S. residential PV installations. Note 1: relative to 2010 component cost.

Table 7: Solar PV cost components.

Table 7 and Figures 20 and 21 show that plug-and-play designs have significant potential to improve the five cost components with the most latent opportunity for cost change: profit, installation labor, overhead, electrical BOS, and customer acquisition. Several mechanisms are responsible:

1. Eliminating various project tasks or shifting their responsibility to the consumer removes the associated overhead and profit of installation firms
2. Pre-assembly of system hardware and standardization of project tasks eliminates installation labor costs
3. Reduction and simplification of BOS electrical hardware lowers equipment costs
4. Standardization of system design precludes many custom and manual tasks which comprise customer acquisition

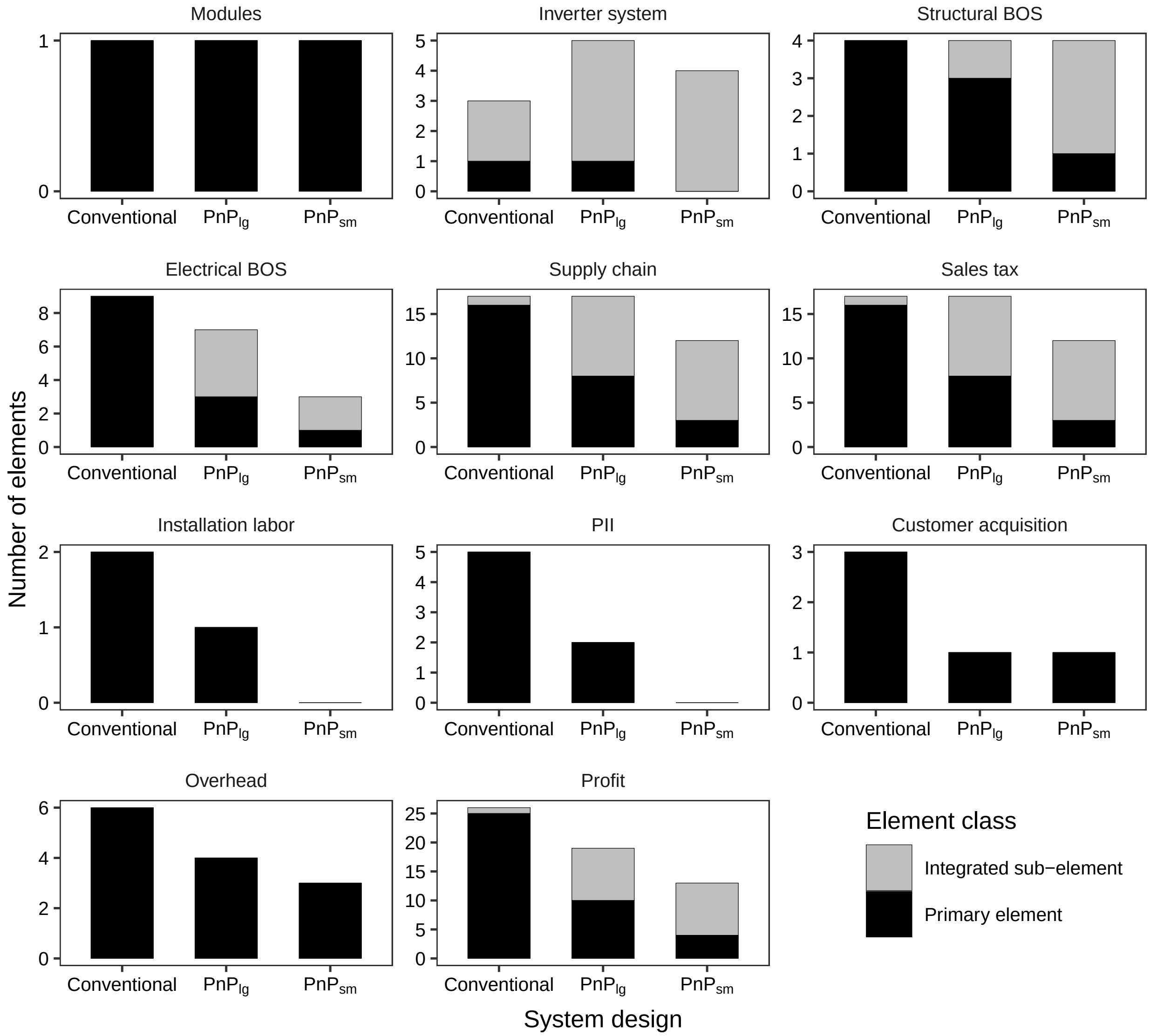


Figure 20: Elements by cost component in PV systems. Plug-and-play designs reduce the number of elements in many PV system cost components and pre-assemble much of the hardware. Four trends are evident for cost components in plug-and-play large and small systems relative to conventional: the number of elements in BOS components is reduced (-16% or -43% on average), the share of pre-assembly is increased (eightfold and twelvefold on average), or both; the small system has a more pronounced effect and eliminates installation labor and PII entirely; time-intensive components such as installation labor, PII, and customer acquisition see the greatest decrease in relative share (60% and 90%); the majority of BOS hardware is pre-assembled (53% and 75%, a fourfold and fivefold increase). Abbreviations: PnP = play-and-play; conv = conventional; lg = large; sm = small. ‘Integrated sub-elements’ are hardware elements which are pre-assembled and connected to other hardware. ‘Primary elements’ are the main inputs to the project.

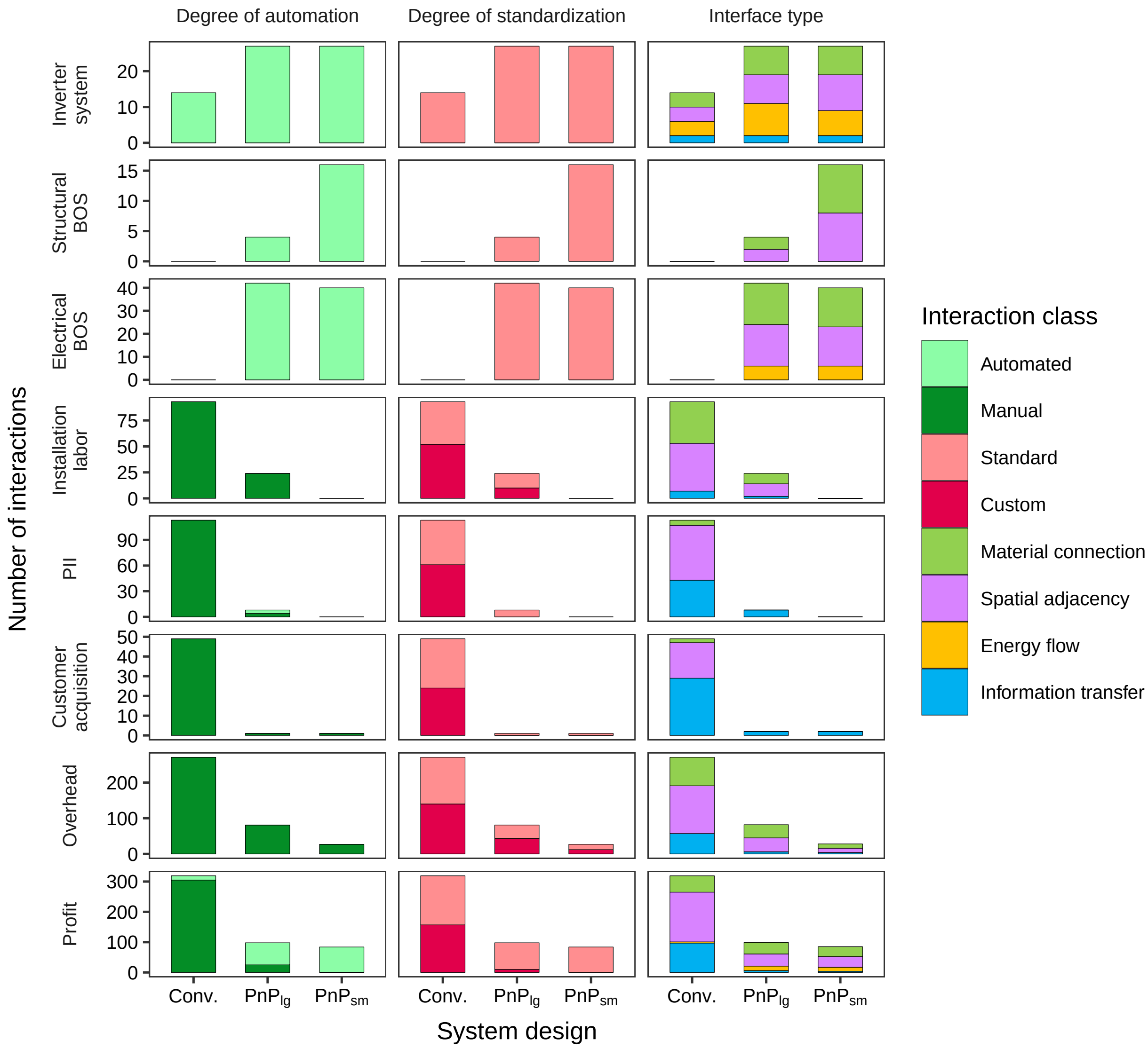


Figure 21: Interactions by cost component in PV systems. Plug-and-play designs standardize, automate, and reduce the number of interactions in many PV system cost components. Five trends are evident for cost components in plug-and-play large and small systems relative to conventional: the number of interactions in BOS components is reduced (-67% or -77% on average), although interaction increase in BOS hardware (fourfold and fivefold on average); the share of automation is increased (fourfold and fivefold on average); the share of standardization is increased (52% and 43% on average); the small system has a more pronounced effect and eliminates installation labor and PII entirely; the number of information transfers decreases the most (-89% and -95%), followed by spatial adjacency and material connections, while number of energy flows increases (275% and 225%). Abbreviations: PnP = play-and-play; conv = conventional; lg = large; sm = small. 'Automated' interactions proceed in part or in whole without human involvement. 'Manual' interactions require human action. 'Standard' interactions are fixed or pre-defined and do not vary across project sites. 'Custom' interactions are unique or project-specific in design or implementation.

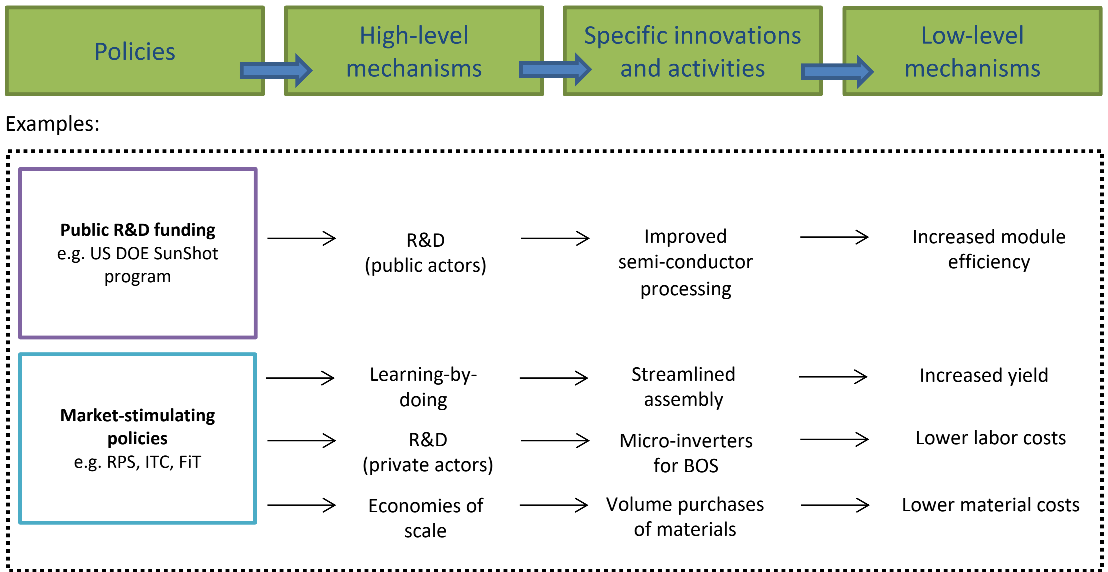


Figure 22: Framework tracing the influence of policies supporting PV deployment and R&D. Policies contributed to PV's cost improvement by enabling 'high-level mechanisms', specific innovations, and ultimately 'low-level mechanisms' of cost reduction.

Task 13: Develop table of PV policies

Policies table. This task was completed in earlier work, shown in Table 4.

Task 14: Model the effects of policies

Government policies have played a crucial role in PV market growth and cost reduction by supporting research and development (R&D) to improve the PV technology and by stimulating market expansion and private sector activity [106, 107, 2]. In this work, we describe a framework for studying the effects of policies on cost change.

A. Framework In this work, we describe the framework that we developed to analyze policy influence on cost change mechanisms, a classification scheme for policy instruments,[3] a method of estimating the cost of market-stimulating policies, and the data used in this analysis.

A.1. Framework for tracing the effects of policies on technology costs.

Our framework involves tracing how various policies supporting PV deployment and R&D contributed to PV's cost improvement by enabling 'high-level mechanisms', specific innovations, and ultimately 'low-level mechanisms' of cost reduction (Fig. 22). Due to its hierarchical structure, this framework allows low- and high-level explanations of the

[3] Here, we use terms 'policy' and 'policy instrument' interchangeably, with the same meaning.[GK: I think we should use them to mean different things.]

reasons of cost change. This way we can link specific policy types to quantifiable low-level mechanisms of cost change. Below we explain the relationships between each level of the hierarchy in more detail.

Low-level mechanisms of cost change. Our method (explained in Tasks 1-4) starts with developing a bottom-up cost model which decomposes the total cost of a technology into cost components (such as materials costs, labor costs) which can be written in terms of key cost variables (such as conversion efficiency, plant size, material prices). Low-level mechanisms represent changes in the cost variables, which in turn change the overall technology cost. Using 'cost change equations' [2], we were able to identify which low-level mechanisms were more impactful in changing PV costs.

High-level mechanisms of cost change. In our framework, high-level mechanisms include public and private R&D, economies of scale (EOS), and learning-by-doing (LBD). These are induced by policies, and in turn stimulate one or more low-level mechanisms described above. In our previous work [2, 1], low-level mechanisms are assigned to the high-level mechanisms that were most responsible for their change by using a mapping scheme. This way the contributions of individual high-level mechanisms to the overall PV cost change are estimated. For example, R&D was the most important high-level mechanism which contributed to 60% of the module cost reduction in 1980-2012. Next, we described each high-level mechanism.

R&D includes activities some of which lead to specific innovations [108, 3] that stimulate one or more low-level mechanisms. For example, R&D activities that targeted improving the Czochralski process for growing monocrystalline silicon crystals led to innovations that enabled larger crystals. These innovations affected several low-level mechanisms, including changes in module efficiency, wafer area, silicon utilization, and silicon price [2, 3]. R&D activities are funded by governments or private sector and are performed by universities, government-run research institutes, or private-sector enterprises.

Learning-by-doing (LBD) includes reduction of costs as a result of increased efficiency at manufacturing or installation tasks through repetition [2]. Here we use a narrow definition of LBD which relies on the idea that as workers repeat the same tasks, they take less time for the same task and make fewer mistakes. This leads to cost reduction by reducing labor costs and improving manufacturing yield.

Economies of scale (EOS) is an emergent phenomenon where a larger factory, company, or a larger industry will have lower costs per unit output as the input costs are shared across a larger output [2, 109]. At the factory level, when a factory increases its equipment and labor, certain costs, such as land and electricity costs, get shared across a larger quantity of production output, thus, reducing these costs incurred per product. Similarly, at the company level, when a company increases the number of its facilities to increase its annual production, the costs of certain administrative processes that are handled centrally are shared among more factories and thus scale slower than the company's annual production. At the industry level, as the industry grows, costs such as lobbying by industry associations, which the companies pass on to consumers by adjusting their profit margins, are shared among more companies. Thus, costs incurred per unit manufactured increase slower than the annual production of the entire industry.

A.2. Policy typology

Policies are a set of techniques by which governmental authorities attempt to affect social change [110, 111]. In our framework policies influence costs by leading to high-level mechanisms, which in turn contribute to low-level mechanisms. Policies have been classified using different classification schemes in the policy analysis literature and the environmental and climate policy literature [24, 112, 110, 113, 111]. In this work, we structure our discussion of policies based on the primary purpose of policies and the primary policy instruments used to achieve the purpose.

Along the first dimension, we categorize policies into two broad categories, R&D funding policies and market-stimulating policies, based on their primary purpose [2]. The purpose of R&D funding policies is to support development of innovations to improve a technology. Market-stimulating policies aim at expanding the market for the technology by targeting different supply-side or demand-side actors. Policies targeting supply-side actors, e.g., PV system components manufacturers and system installers, are often referred to in the literature as 'supply-push' policies [113], for example, regulations to ensure worker safety in factories of PV system components. Policies targeting demand-side actors, which include technology consumers – e.g., PV system owners or renters along with buyers and consumers of PV electricity – are categorized in the literature as 'demand-pull' policies [113], for example, subsidies for PV system owners and feed-in-tariffs.

Other market-stimulating policies that target actors outside the technology's industry may still influence the market or technological change. Examples include consulting initiatives of national governments that provide support to state governments in formulating state-level technology-specific policies. Another example is import tariffs on PV system components, which aim not necessarily at increasing supply or demand of PV but at changing the geography of PV supply chain by increasing the cost of imported components relative to the domestically manufactured ones.

The second dimension of our policy classification is based on the type of policy instruments used. While all government R&D-funding programs are fiscal policy instruments, market-stimulating policies can be classified in three categories [110, 111]:

- *Fiscal instruments* involve transfer of funds (to or from the government) or provision of economic incentives or disincentives, or support specific economic activities. These instruments try to restrict choices of individuals and organizations, not by prohibiting certain choices, but by altering costs of making specific choices. E.g. R&D funding, tax exemptions, and support for venture capital investments. (In the policies table in the previous section, this category was called "Economic instruments", which are of two types: fiscal policies which relate to government expenditures and revenue, and monetary policies which target valuation of a country's currency or target inflation rate or interest rates. However, only fiscal instruments are relevant for our study as monetary policies do not target a specific technology or a specific group of technologies. We therefore relabelled this category as "Fiscal instruments".)

- *Regulatory instruments* are measures undertaken by the government to mandate certain choices and behaviors. These are formulated in the form of rules and directives that often restrict the choices that can be made by individuals and organizations. E.g. intellectual property rights, mandatory emission standards, and competition policies.
- *Information & knowledge dissemination instruments* are policy initiatives that attempt to influence society through the transfer of knowledge and information, the communication of a reasoned argument, and persuasion. They do not involve coercion, like regulations, or provide economic incentives, like fiscal instruments. These instruments include, among others, voluntary agreements, education and training programs, climate mitigation targets, and public campaigns. (In the table in the previous section under Task 13, this category is labelled as "soft instruments". We renamed this category so that it is not confused with "soft costs" in cost modelling.)

A.3. Conceptual model of policy influence on cost change mechanisms.

Based on the characteristics of each policy type, policies might influence high-level mechanisms differently. Demand-pull policies aim at increasing PV demand, which in turn motivates PV manufacturers to invest in R&D, production, and scaling up factories or building new factories, or for entrepreneurs to set up new manufacturing companies. These activities are part of private R&D, LBD, and EOS high-level mechanisms. In contrast, supply-push policies target supply-side actors. For example, subsidies to PV manufacturers directly contribute to private R&D, LBD, and EOS. Other policies such as government funding for collaborative R&D between public-sector research institutions and PV industry mainly affect public and private R&D, whereas federal policy consulting initiatives to help state governments formulate their PV subsidies can affect private R&D, LBD, and EOS by promoting demand increase in the state's jurisdiction.

Significant Accomplishments and Conclusions

In this work we used the case of PV systems to advance ideas on the role of physical and non-physical improvement for a technology's cost evolution and spatial patterns therein. We find that improvements in physical features of PV systems ('hardware variables') have not only reduced hardware costs, but have also caused a large fraction of the changes in soft costs. We also connect historical cost changes to cost differences between countries today and identify soft costs and locally constructed hardware as major drivers of cost differences.

These results suggest more general ideas for how the cost structure of a technology affects its improvement rate. The large initial share of hardware costs (70% in 1980), paired with improvement efforts targeted primarily at hardware features, created a fertile ground for hardware-driven cost reductions. Component-level improvements translated into system-level (e.g. installation) efficiency gains and reduced costs. This successful combination of cost structure and innovation efforts may partially explain why PV improved in cost so rapidly. Nuclear power plants, which increased rapidly in cost in several countries, started out as a technology with a relatively high share of soft costs, yet nuclear R&D has prioritized the design of hardware (e.g. reactors), not construction processes.

The lack of 'soft technological change' in PV also points to broader challenges in clean energy innovation and beyond. The cost of several major carbon free technologies, including wind and nuclear, is now determined to a substantial degree by soft costs [60, 55]; achieving rapid adoption to decarbonize energy systems will likely require that these costs come down quicker than they have in the past. Our paper outlines a technology-agnostic framework to disentangle the physical and non-physical drivers of costs.

In this work we also conducted a comprehensive analysis of innovations affecting both PV module and BOS costs. Using our PV system cost equation as an organizing framework, we were able to connect specific innovations to cost variables. We found that the innovation types that affected module cost variables were mainly centered around material, tool and process improvements, while BOS innovations focused on reducing the complexity of system installation and design processes through component integration and standardization. This is a significant result because it shows that these two components of the PV technology required different innovation pathways to achieve higher performance and reduce costs. This analysis also revealed that despite these differences, both module and BOS innovations targeted hardware variables, rather than soft variables. As the share of soft costs is increasing, the innovation efforts may lean towards soft variables going forward. This result has implications for the stakeholders undertaking the innovations efforts, as this shift in the innovation patterns will require collaboration with a more diverse set of stakeholders such as local governments, and streamlining and standardizing processes across different locations.

Another key observation is related to the effects of policies on PV's improvement and cost reduction. With our framework connecting policies to quantifiable mechanisms of cost reduction, we find that market-stimulating policies and public R&D are complementary, and not substitutable in their cost reducing effects. Our studies of cost drivers at different levels, i.e. low-level and high-level mechanisms [2, 1, 4], reveal how different technology features respond to R&D and market-stimulating policies. We see that public R&D funding leads to innovations that target a certain group of cost variables (e.g. module efficiency) that are important for the technology performance and cost, but hard to improve without directed efforts and resources such as basic research [3]. Market-stimulating policies, on the other hand, send a crucial signal to encourage the adoption of the technology and the expansion of its supply chain. These policies tend to affect cost variables (e.g. material costs, yield, labor cost) that can be changed in a cost-reducing direction by increasing the scale, by repetition, or with applied R&D in a commercial setting. Our framework provides a parsimonious structure for observing the evidence for the differing effects of policies to technology costs.

There were two pivot points in the project. The first one is related to quantifying the cost effects of innovations, which was initially proposed in our grant proposal. We developed approaches to quantify the cost effects of innovations such as wire sawing (Task 10). However, as the project progressed, we decided to de-emphasize this quantitative analysis, and instead conduct a qualitative analysis that would be comprehensive in terms of the types and number of innovations studied. As a result, we developed our innovations table which includes a large set of innovations and were able focus on the bigger picture of the differing innovation types affecting modules and BOS.

Another pivot in scope occurred as we conducted our prospective analysis of innovations. Although our plan for the prospective analysis was not extensively detailed in our grant proposal, we expanded on this work second and third years of the project. This work culminated in a fourth journal article from this project, exceeding our initial proposal of three articles. In this work, we investigated the effects of certain innovation types, i.e., automation and standardization in system design, in the context of plug-and-play PV systems. A significant accomplishment emerging from this work is the development of detailed design structure matrices to study the cost-incurring processes and interactions in PV projects. We find that standardization and automation reduce the complexity of BOS processes, reducing or simplifying the interactions between hardware components and human actors, and therefore have potential for future cost reduction.

Inventions, Patents, Publications, and Other Results

Journal publications under this award:

- Magdalena M. Klemun, Goksin Kavlak, James McNerney, and Jessika E. Trancik. Evolution of hard and soft costs in technologies and the case of photovoltaic systems, tbd, 2020. [1]
- Goksin Kavlak*, Magdalena M Klemun*, Ajinkya S. Kamat, Brittany Smith, Robert M. Margolis, and Jessika E. Trancik. On the nature of innovations affecting photovoltaic system costs, tbd, 2020. *contributed equally. [3]
- Philip Eash-Gates, Ajinkya S. Kamat, Goksin Kavlak, Magdalena M. Klemun, and Jessika E. Trancik. Effects of plug-and-play photovoltaic designs on balance-ofsystem costs, tbd, 2020. [4]
- Ajinkya S. Kamat*, Goksin Kavlak*, Magdalena M Klemun, and Jessika E. Trancik. Policy drivers of cost decline and market expansion in photovoltaic systems, tbd, 2020. *contributed equally. [5]

Theses partially funded by this award:

- Magdalena M. Klemun. Ph.D. Thesis: Effects of hardware and soft features on the performance evolution of low-carbon technologies. MIT Institute for Data, Systems, and Society. November 2019.
- Philip Eash-Gates. M.S. Thesis: Modeling barriers to cost change in solar and nuclear energy technologies. MIT Technology and Policy Program. June 2019.
- Goksin Kavlak. Ph.D. Thesis: Drivers of photovoltaics cost evolution. MIT Institute for Data, Systems, and Society. September 2017.

Conference papers, and other public releases of results:

- Podcast by Goksin Kavlak and Jessika Trancik, MIT Energy Initiative, `http://energy.mit.edu/podcast/energy-technology-evolution/`, April 2, 2020
- Podcast by Magdalena Klemun, MIT Environmental Solutions Initiative, `https://climate.mit.edu/podcasts/til-about-wind-and-solar-power`, April 2, 2020
- Workshop organized by Jessika Trancik: Pathways to Deep Decarbonization, Santa Fe Institute, Santa Fe, NM, February 26-28, 2020
- Presentation by Goksin Kavlak: Drivers of innovation in energy technologies and the case of photovoltaics, Santa Fe Institute, Santa Fe, NM, February 28, 2020
- Talk by Goksin Kavlak: Modeling the drivers of cost evolution in solar photovoltaics, United States Geological Survey, Reston VA, January 30, 2020
- Course taught by Jessika Trancik: Evaluating technologies for a clean energy transition, Vale and the MIT Environmental Solutions Initiative, Brazil, January 6-7, 2020
- Talk by Jessika Trancik: Modeling Photovoltaics Innovation and Deployment Dynamics, DOE SETO Washington, D.C., December 17, 2019
- Presentation by Magdalena Klemun: Evolution of hardware costs and soft costs in photovoltaic systems. 37th U.S. Association for Energy Economics/International Association for Energy Economics North American Conference, Denver, CO, November 6, 2019

- Poster presentation by Goksin Kavlak: Evaluating the causes of cost reduction in photovoltaics, MIT Materials Day, Cambridge, MA, October 9, 2019
- Presentation by Magdalena Klemun: Technology cost evolution modeling: Lessons learned from photovoltaics and nuclear, Workshop on Methods for R&D Portfolio Analysis and Evaluation, National Renewable Energy Laboratory, Golden, CO, July 19, 2019
- Invited talk by Goksin Kavlak: Evaluating the enabling factors of and constraints to cost reduction in photovoltaics, Institute of Urban Environment, Chinese Academy of Sciences Xiamen, China, July 15, 2019
- Presentation by Goksin Kavlak: On the nature of innovations affecting the cost of photovoltaics systems, International Society of Industrial Ecology, Beijing, China, July 11, 2019
- Presentation by Magdalena Klemun: On the nature of innovations affecting the cost of photovoltaics systems, International Symposium of Sustainable Systems and Technology, Oregon, USA, June 26, 2019
- Presentation by Magdalena Klemun: Soft and hard factors affecting the cost evolution of low-carbon energy technologies, Technology, Management, and Policy Consortium, George Washington University, Washington, D.C., June 17, 2019
- Guest lecture by Magdalena Klemun: Measuring the impact of low-carbon technology investment, The New School for Social Research, Economics of the Environment class, April 11, 2019
- Research on photovoltaics cost declines mentioned in Bloomberg.com article, `https://www.bloomberg.com/opinion/articles/2019-04-05/capitalism-is-more-likely-to-limit-climate-change-than-socialism`, April 5, 2019
- Research on photovoltaics cost declines featured in Energy Policy Article Digests `https://www.journals.elsevier.com/energy-policy/article-digests/explaining-the-plummeting-cost-of-solar-modules`, April 1, 2019
- Talk by Philip Eash-Gates: Evaluating determinants of cost change in clean energy technologies, MIT Institute for Data, Systems, and Society community and the Technology and Policy Program, March 6, 2019
- Goksin Kavlak interviewed by CleanTechnica about the paper on causes of cost reduction in photovoltaic modules, `https://cleantechnica.com/2019/01/31/solar-power-research-study-investigates-rapidly-declining-costs/`, January 31, 2019
- Talk by Jessika Trancik: Drivers of technological change in energy systems, MIT-Japan 2019, January 24, 2019
- Seminar by Jessika Trancik: Answering core questions about technological innovation, Santa Fe Insitute, January 11, 2019
- Paper on the reasons for cost decline in PV modules got featured in Vox `https://www.vox.com/energy-and-environment/2018/11/20/18104206/solar-panels-cost-cheap-mit-clean-energy-policy`
- Paper on the reasons for cost decline in PV modules was featured in the New york Times `https://www.nytimes.com/2018/11/28/climate/climate-fwd-smartphones-solar.html`
- Paper on the reasons for cost decline in PV modules was featured in Ars Technica `https://arstechnica.com/science/2018/11/how-the-falling-cost-of-solar-panels-`

can-teach-us-to-make-new-tech-affordable/

- Paper on the reasons for cost decline in PV modules was featured in Financial Times https://www.ft.com/content/b47b5f06-ef54-11e8-89c8-d36339d835c0
- Paper on the reasons for cost decline in PV modules was featured in MIT News http://news.mit.edu/2018/explaining-dropping-solar-cost-1120
- MIT Energy Night poster presentation by Goksin Kavlak, October 19, 2018; Evaluating the drivers of cost reduction in photovoltaics.
- Boston College guest lecture by Goksin Kavlak, October 2, 2018; Material requirements of PV and implications for PV costs.
- Kellogg School of Management, Northwestern University, July 9, 2018; Connecting technology improvement to bottom-up structure.
- Industrial Ecology Gordon Research Conference, Switzerland, May 22, 2018; Evaluating the drivers of cost reduction in PV systems (w/ Goksin Kavlak and Magdalena Klemun).
- Yale School of Forestry and Environmental Science, April 24, 2018; Drivers of technological improvement in clean energy.
- CompleNet'18 Keynote speech, March 8, 2018; Understanding the drivers of technological progress.
- Solar Energy Technologies Office Portfolio Review, February 2018 (w/ Magdalena Klemun).
- Announcement of research through university news outlet (http://news.mit.edu/2016/why-have-solar-energy-costs-fallen-1026)
- LCA XVII Conference, October 3, 2017; Evaluating Changing Technologies: The Case of Photovoltaics Costs
- Swiss Re/ IDSS Meeting, September 11, 2017; Measuring and accelerating progress in clean energy using data-informed models
- TEDx Cambridge, July 26, 2017
- C3E Ambassadors Meeting, July 18, 2017; Drivers of technological improvement in clean energy
- ISIE Conference, June 28, 2017; Evaluating the changing causes of photovoltaics cost reduction (w/ Goksin Kavlak and James McNerney).
- DOE seminar, May 22, 2017; Evaluating the causes of photovoltaics cost reduction.
- ALJ/MIT Meeting, February 24, 2017; Measuring and accelerating progress in clean energy using data-informed models.
- IDSS, MIT Energy Systems Workshop, March 20, 2017; Modeling technological progress toward decarbonization
- NSF-sponsored Production Function Workshop, February 28, 2017; Determinants of the rate of technological innovation.
- AAAS Annual Meeting, February 18, 2017; Modeling technology innovation to accelerate clean energy development.

Awards:

- Magdalena Klemun receives her Ph.D. degree from MIT Institute for Data, Systems, and Society. Thesis title: Effects of hardware and soft features on the performance evolution of low-carbon technologies, November 2019.

- Magdalena Klemun receives MIT Research and Policy Engagement Fellowship, MIT Technology and Policy Program, Fall 2019.
- Philip Eash-Gates receives his Master's of Science degree from MIT Technology and Policy Program. Thesis Title: Modeling barriers to cost change in solar and nuclear energy technologies, June 2019.
- Best presentation award received by Magdalena Klemun, Technology, Management, and Policy Consortium, June 17, 2019.
- Austrian Marshall Plan Foundation poster award received by Magdalena Klemun, December 8, 2018.
- Goksin Kavlak receives her Ph.D. degree from MIT Institute for Data, Systems, and Society. Thesis title: Drivers of photovoltaics cost evolution. September 2017.

Path Forward

Plans for future research. The findings of our project suggest several directions for future research. Three of these directions are discussed below.

First, future work may examine the determinants of individual soft cost components to close knowledge and data gaps and tailor future cost reduction efforts to individual locations. Such work may involve the collection of region-, site-, and location-specific soft cost data to better characterize the variability in installation, permitting, and supply chain costs across the U.S. and other countries. A key goal of this research is to quantify the difference between best-in-class performance (i.e. cost) levels in individual system scales and locations, and realized costs, in order to recommend cost reduction strategies tailored to individual sites and locations. As described in 'Opportunities for commercialization' below, such research may result in the development of a commercial software product that provides data-driven guidance for local decision makers on PV system cost components to target for cost reduction.

Second, our work on the role of hardware and soft PV technology evolution in reducing PV costs [1] suggests several avenues for future cost reduction, either by pursuing hardware-driven soft cost reductions or by investing in efforts to streamline deployment processes and facilitate learning across locations. Future research may develop new models to study the cost effectiveness of these different approaches. For example, the benefits of automation in PV deployment will depend on the cost and development timeline for automated installation systems, the number of jobs created and displaced, and opportunities to share costs and equipment among multiple actors and institutions in a location. Conversely, the return on investments in soft technologies will be affected by how quickly and effectively these locations can be transferred across locations.

Third, while our work estimates the cost of market-expansion policies that drove down the cost of PV [5], future work may develop new concepts and metrics to capture systemic effects of market-expansion policies, and compare these effects to those of public support for R&D. For example, while our estimate includes policy costs incurred through fiscal instruments and through the implementation of regulations, it does not account for the environmental and other benefits of clean energy market benefits.

Opportunities for commercialization. Software products to support cost reduction efforts by installers may comprise an interactive user interface and a model to analyze cost components, variables, and processes in PV system design, installation, permitting, and inspection in the context specific to individual projects (site-level) and locations (neighborhood-, city- or state-level). The software could provide recommendations by screening cost data provided by the user, and comparing realized cost levels to benchmarks for cost components like installation costs, supply chain costs, and permitting costs. The software could then identify and rank 'interactions' to be targeted by installers, and suggest design strategies tailored to the project and location, as well as steps in installation and permitting to achieve cost reduction. Interactions represent points of physical contact between individual hardware components, between hardware components and installers, as well as instances of information exchange between actors. Past research has identified interactions that can present barriers to cost reduction. Proposed design strategies may involve reduction, elimination, standardization, or automation of the project inputs. The software will output modeling results at two levels: (1) specific changes to variables determining PV cost at the engineering design and project management level; (2) and investments in learning, R&D, and economies of scale to enable continuous and sharp declines in cost over longer periods of time.

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Appendix

Innovations table (Task 9)

Please see the innovations table below.

Number	Variable	Variable_moduleOrBOS	Innovation_name	Innovation_description	Innovation_type	Industry	Time_innovation
1	eta	module	Czochralski growth for mono-crystalline Si	Produces Si ingots. Improvements: Better control of crystal growth process through improved hot zone design, magnetic fields, recharging, computer simulations, preventing crucible contamination leading to higher quality crystals, larger ingots, and reduced material losses from cropping and shaping the ingot.	Material quality improvement; Process development	Semiconductors	1970
2	eta	module	Multi-crystalline Si casting	Produces Si ingots. Improvements: Crucible coatings, seeding of silicon to obtain optimum grain sizes, gettering leading to higher quality and larger ingots, and reduced material losses from cropping and shaping the ingot.	Material quality improvement; Component design change; Process development	Metallurgy	1980
3	eta	module	Wet-chemical etching for texturing	Improving optical performance, and reducing wire saw damage. Improvements: Etch solutions with reduced impurities, in-line etch process, limiting surface damage	Material quality improvement; Process development; Tool development	Semiconductors	1975
4	eta	module	Belt furnace	Junction formation process. Improvements: Spin-on, CVD, spray-on, screenprint deposition methods, process optimization (e.g. to match tube diffusion \eta, for newer cell structures like PERC,…), automation, laser doping instead of IR lamps	Material quality improvement; Process development; Tool development	Semiconductors	1980
5	eta	module	Tube diffusion	Junction formation process. Improvements: P2O5 to liquid POCl3, Larger furnaces, longer tubes, 2-step instead of 1-step process, low-pressure version, process optimization (e.g. of oxygen flow, for shallow junction, with new Ag pastes, for newer cell structures…), automation. Many versions of process are in use.	Material quality improvement; Process development; Tool development	Semiconductors	1970
6	eta	module	PECVD of SiNx for surface passivation	Depositing layer(s) for surface passivation and antireflective coating. PECVD of SiNx is a key innovation due to simplification of process by replacing multiple steps for passivation, AR coating, and paste control. Rear surface passivation is now emerging in PERC.	Material quality improvement; Process development; Tool development	Semiconductors	1983
7	eta	module	Development and use of screenprinting of silver pastes	Silver paste forms metal contacts; allowed less doping with less capital intensive (screenprinting) equipment and increased throughput. Development of silver paste compositions and development of screenprinting process were key innovations.	Material quality improvement; Process development; Tool development	Electronics	1975
8	eta	module	Development and use of screenprinting of aluminum pastes	Aluminum paste forms metal contacts at the back of the cell and creates back surface field (Al-BSF) architecture. Development of paste compositions and development of screenprinting process, especially the Al-BSF formation, were key innovations.	Material quality improvement; Process development; Tool development	Electronics	1975
9	eta	module	Passivated emitter cell architectures: Passivated emitter solar cell (PESC), Passivated Emitter Rear Locally diffused cell (PERL), and Passivated emitter and rear cell (PERC)	Surface passivation to reduce recombination. PERC: higher rear surface reflection	Architectural change; Process development; Tool development	Photovoltaics	2009
10	eta	module	Interdigitated back contact cell (IBC)	Reduced shading losses, simpler interconnection, higher packing density, lower resistive losses, but several costly high temperature processes	Architectural change; Process development; Tool development	Photovoltaics	2003
11	eta	module	Heterojunction with intrinsic thin layer cell (HIT)	a-Si:H and c-Si create the pn-junction; higher efficiency at high temperatures, low process temperatures	Architectural change; Process development; Tool development	Photovoltaics	1997
12	eta	module	Tabber and stringer	Connecting solar cells. Key innovations include: Automation of stringing which reduced operation time and energy; machine vision for optical alignment of cells allowing narrower and more busbars reducing interconnect resistance, and detecting defects.	Component design change; Automation; Tool development	Photovoltaics	1980

13	**eta**	**module**	Anti-reflective coated glass	Helps with light trapping improving power output. Innovation for PV was AR coating with reliability and durability needed for outdoor PV	Component design change; Process development; Material quality improvement	Glass	2005
14	**eta**	**module**	Developments in wafer shapes and sizes	Quasi-square or rectangular shaped wafers and reduction in wafer size variability allowed the gap between cells to be reduced, increasing the packing factor of the module. Enabled by improvements in crystal growth and other wafer processes.	Material quality improvement; Process development; standardization	Photovoltaics	1980
15	**eta**	**module**	Half-cut cells in modules	Reducing resistive losses	Component design change; Process development	Photovoltaics	2014
16	**eta**	**module**	Qualification testing standards	IEC 61215 standards outline test procedures for design qualification mainly aiming for production quality control. Enabled balancing rigid quality requirements and allowed the development of low-cost modules. IEC 61730 outline PV module safety standards consistent with IEC 61215.	Standardization	Photovoltaics	1993
17	**eta**	**module**	LBD	Improvements through learning-by-doing; in other words, by repetition of routine tasks	Non-innovation		
18	**t_Si**	**module**	Internal diameter blade saw	Cutting ingots into wafers. Allowed flat and parallel cuts with little wafer breakage.	Material quality improvement	Semiconductors	1970
19	**t_Si**	**module**	SiC wire sawing	Cutting ingots into wafers. Wire diameter, type, and cutting speed determine the material usage. Improvements: Increased speed compared to internal diameter blade saw, thinner and stronger wires over time, reduced kerfloss	Material quality improvement; Process development; Tool development	Semiconductors	1980
20	**t_Si**	**module**	Diamond wire sawing	Cutting ingots into wafers using wires coated with diamond particles. Mainly used for monocrystalline wafers as of yet. Improvements: Ability to reduce wafer thickness and further reduce kerfloss.	Material quality improvement; Process development; Tool development	Semiconductors	2011
21	**t_Si**	**module**	Contactless soldering of ribbons	Prevents microcracks by creating homogeneous temperature field within the cell, reducing thermal and mechanical stress; helped overcome limitations in handling and processing thinner wafers. Types include IR soldering, laser soldering.	Process development; Tool development	Semiconductors	
8	**t_Si**	**module**	Development and use of screenprinting of aluminum pastes	Aluminum paste forms metal contacts at the back of the cell and creates back surface field (Al-BSF) architecture. Development of paste compositions and development of screenprinting process, especially the Al-BSF formation, were key innovations. New Al paste formulation that reduce wafer bow (warpage) after firing enabled thinner cells.	Material quality improvement; Process development; Tool development	Electronics	1975
22	**t_Si**	**module**	LBD	Improvements through learning-by-doing; in other words, by repetition of routine tasks	Non-innovation		
18	**U_Si**	**module**	Internal diameter blade saw	Cutting ingots into wafers. Allowed flat and parallel cuts with little wafer breakage.	Material quality improvement	Semiconductors	1970
19	**U_Si**	**module**	SiC wire sawing	Cutting ingots into wafers using wires coated with diamond particles. Wire diameter, type, and cutting speed determine the material usage. Improvements: Increased speed compared to internal diameter blade saw, thinner and stronger wires over time, reduced kerfloss	Material quality improvement; Process development; Tool development	Semiconductors	1980
20	**U_Si**	**module**	Diamond wire sawing	Cutting ingots into wafers, mainly used for monocrystalline wafers as of yet. Improvements: Ability to reduce wafer thickness and further reduce kerfloss.	Material quality improvement; Process development; Tool development	Semiconductors	2011

1	U_Si	module	Czochralski growth for mono-crystalline Si	Produces Si ingots. Improvements: Better control of crystal growth process through improved hot zone design, magnetic fields, recharging, computer simulations, preventing crucible contamination leading to higher quality crystals, larger ingots, and reduced material losses from cropping and shaping the ingot.	Material quality improvement; Process development	Semiconductors	1970	
2	eta	module	Multi-crystalline Si casting	Produces Si ingots. Improvements: Crucible coatings, seeding of silicon, gettering leading to higher quality and larger ingots, and reduced material losses from cropping and shaping the ingot.	Material quality improvement; Component design change; Process development	Metallurgy	1980	
23	U_Si	module	LBD	Improvements through learning-by-doing; in other words, by repetition of routine tasks	Non-innovation			
24	p_Si	module	Electric arc furnace	Produces ~98% pure metallurgical grade-Si (MG-Si) from silica. Improvements: Larger furnaces and improved energy efficiency.	Material quality improvement; Process development	Metallurgy	1970	
25	p_Si	module	Siemens process	Produces electronic grade silicon (polysilicon). Improvements: Increasing batch size, energy efficiency, improved handling	Material quality improvement; Process development	Semiconductors	1970	
26	p_Si	module	Fluidized Bed Reactor (FBR)	Produces electronic or solar grade silicon (polysilicon). More energy efficient than Siemens process, but hard to scale and more difficult to achieve electronic grade Si.	Material quality improvement; Process development; Tool development	Petroleum	1980	
1	p_Si	module	Czochralski growth for mono-crystalline Si	Produces Si ingots. Improvements: Better control of crystal growth process through improved hot zone design, magnetic fields, recharging, computer simulations, preventing crucible contamination leading to higher quality crystals, larger ingots, and reduced material losses from cropping and shaping the ingot.	Material quality improvement; Process development	Semiconductors	1970	
2	p_Si	module	Multi-crystalline Si casting	Produces Si ingots. Improvements: Crucible coatings, seeding of silicon, gettering leading to higher quality and larger ingots, and reduced material losses from cropping and shaping the ingot.	Material quality improvement; Component design change; Process development	Metallurgy	1980	
27	p_Si	module	LBD	Improvements through learning-by-doing; in other words, by repetition of routine tasks	Non-innovation			
28	p_Si	module	EOS	Increased polysilicon plant scaling leading to lower unit manufacturing cost.	Non-innovation			
29	p_Si	module	Other	Long-term contracts stabilizing prices	Non-innovation			
30	p_Si	module	Other	Supply-demand imbalances in the market (e.g. overcapacity and overproduction) change polysilicon price even though production cost remain the same.	Non-innovation			
31	p_Si	module	Other	Shifting production to locations with different electricity rates, labor rates, raw material costs, and capital expenditures, which leads to lower production costs	Non-innovation			
32	y	module	Automated machinery	Processing steps (cell aligning, soldering, stringing, module assembly), loading/unloading between steps, and testing and inspection have been increasingly automated. Enabled by robotic material handling equipment, optical sensors, software to control/monitor devices and allow flexible operation. Reducing labor costs, while increasing yield, as thinner cells and heavy large items are handled more easily with automated machinery.	Automation; Tool developmen; Digitalization; Standardization	Photovoltaics	1980	
33	y	module	Preventing wafer edge and surface microcracks due to wafering	Fewer microcracks reduce wafer breakage - this was achieved by using finer, more uniform SiC particles, and then when switching to diamond wire saws, optimizing the sawing parameters such as speed and wire re-use.	Process development	Photovoltaics	1995	

34	**y**	**module**	In-line process control	Optical inspection of incoming wafers for cracks and other defects using automated detection tools to reduce wafer breakage and ensure high quality cells. Electroluminescence imaging of cells and modules. Automatic optical inspection of cells in stringer.	Automation; Process development; Tool development	Photovoltaics	1980
35	**y**	**module**	LBD	Improvements through learning-by-doing; in other words, by repetition of routine tasks	Non-innovation		
1	**A**	**module**	Czochralski growth for mono-crystalline Si	Produces Si ingots. Improvements: Better control of crystal growth process through improved hot zone design, magnetic fields, recharging, computer simulations, preventing crucible contamination leading to higher quality crystals, larger ingots, and reduced material losses from cropping and shaping the ingot.	Material quality improvement; Process development	Semiconductors	1970
2	**A**	**module**	Multi-crystalline Si casting	Produces Si ingots. Improvements: Crucible coatings, seeding of silicon to obtain optimum grain sizes, gettering leading to higher quality and larger ingots, and reduced material losses from cropping and shaping the ingot.	Material quality improvement; Component design change; Process development	Metallurgy	1980
36	**A**	**module**	Overcoming limitations in handling large wafers	Overcoming handling limitations by automation, redesigning processing and handling equipment, and standardization allowed increased wafer area while maintaining higher yield; reducing cell and module manufacturing costs that show little area dependence.	Automation; Process development; Tool development	Semiconductors	
37	**A**	**module**	LBD	Improvements through learning-by-doing; in other words, by repetition of routine tasks	Non-innovation		
38	**c**	**module**	Developments in silicon ingot manufacturing materials: crucible, graphite, argon	Crucibles with lower cost and longer life, crucible coatings; Cz hot zone designs that reduce argon and graphite consumption. These reduced cost per kg Si processed	Material quality improvement; Process development	Semiconductors	1970
39	**c**	**module**	Developments in SiC wire sawing materials: slurry, wires, coolant, fixturing	Wires are used for cutting the ingots into wafers, and slurry facilitates the process. Slurry recycling was a key innovation, where the abrasive SiC particles and silicon debris are separated from polyethylene glycol.	Material quality improvement; Process development; Tool development	Semiconductors	1980
40	**c**	**module**	Developments in diamond wire sawing materials: wires, fixturing	Wires coated with diamond particles cut ingots into wafers. Compared to SiC slurry wire sawing, thinner and stronger wires, higher productivity and ease of recycling the kerf material	Material quality improvement; Process development; Tool development	Semiconductors	2011
7	**c**	**module**	Development and use of screenprinting of silver pastes	Silver paste forms metal contacts; allowed less doping with less capital intensive screenprinting equipment and increased throughput. Development of silver paste compositions and development of screenprinting process were key innovations.	Material quality improvement; Process development; Tool development	Electronics	1975
8	**c**	**module**	Development and use of screenprinting of aluminum pastes	Aluminum paste forms metal contacts at the back of the cell and creates back surface field (Al-BSF) architecture. Development of paste compositions and development of screenprinting process, especially the Al-BSF formation, were key innovations.	Material quality improvement; Process development; Tool development	Electronics	1975
13	**c**	**module**	Anti-reflective coated glass	Helps with light trapping improving power output. Innovation for PV was AR coating with reliability and durability needed for outdoor PV	Component design change; Process development; Material quality improvement	Glass	2005
41	**c**	**module**	EVA laminate	Encapsulating the connected cells with low reflectivity allowing transfer of light. Over time the durability of PV EVA was improved Improvements to the additive formulation increased durability by preventing yellowing. There are other encapsulant materials, but EVA remains in widespread use mainly because of its good cost–performance ratio.	Material quality improvement	Electronics	1980

42	**c**	**module**	Qualification testing standards	IEC 61215 standards outline test procedures for design qualification mainly aiming for production quality control. Enabled balancing rigid quality requirements and allowed the development of low-cost modules. IEC 61730 outline PV module safety standards consistent with IEC 61215.	Standardization	Public institution	1993
43	**c**	**module**	Standards for module materials	IEC 62775, 62788, 62805 standards address polymeric packaging materials such as encapsulants, EVA, and TCO.	Standardization	Public institution	2010
44	**c**	**module**	Other	Easier access to adequate purity and low-cost chemicals used in cell manufacturing (e.g. HF, HNO3, HCl)	Non-innovation		
45	**c**	**module**	Other	Dedicated PV glass production lines enabled lower glass cost	Non-innovation		
46	**c**	**module**	EOS	Bulk purchasing discounts	Non-innovation		
47	**c**	**module**	Other	Facilities located near clusters of specialized material suppliers obtain cheaper materials	Non-innovation		
48	**K**	**module**	In-line processes	Tools with higher throughput due to higher speed; minimum handling, and lower breakage rate compared to batch processes. Conveyor belt length, width, speed, and the number of parallel lines can affect throughput.	Tool development	Photovoltaics	1980
12	**K**	**module**	Tabber and stringer	Connecting solar cells. Key innovations include: Automation of stringing which reduced operation time and energy; machine vision for optical alignment of cells allowing narrower and more busbars reducing interconnect resistance, and detecting defects.	Component design change; Automation; Tool development	Photovoltaics	1980
22	**K**	**module**	Production of Si ingots with larger cross-sectional area	Improvements in Cz process enabled better control of pull rate and temperature leading to larger diameters. Mc-Si ingots increased in size due faster crystal growth and other process improvements. These led to higher throughput and reduced power consumption.	Process development	Semiconductors	1980
49	**K**	**module**	Other	Duplication of the same equipment to increase overall throughput	Non-innovation		
22	**p_0**	**module**	Production of Si ingots with larger cross-sectional area	Improvements in Cz process enabled better control of pull rate and temperature leading to larger diameters. Mc-Si ingots increased in size due faster crystal growth and other process improvements. These led to higher throughput and reduced power consumption.	Process development	Semiconductors	1980
6	**p_0**	**module**	PECVD of SiNx for surface passivation	Depositing layer(s) for surface passivation and antireflective coating. PECVD of SiNx is a key innovation due to simplification of process by replacing multiple steps for passivation, AR coating, and paste control. Rear surface passivation is now emerging in PERC.	Material quality improvement; Process development; Tool development	Semiconductors	1983
32	**p_0**	**module**	Automated machinery	Processing steps (cell aligning, soldering, stringing, module assembly), loading/unloading between steps, and testing and inspection have been increasingly automated. Enabled by robotic material handling equipment, optical sensors, software to control/monitor devices and allow flexible operation. Reducing labor costs, while increasing yield, as thinner cells and heavy large items are handled more easily with automated machinery.	Automation; Tool developmen; Digitalization; Standardization	Photovoltaics	1980
50	**p_0**	**module**	Turnkey manufacturing facilities	Includes equipment, process technology, and factory control. Enables fast entry to the market without much R&D experience. Often smaller factories and have higher capital costs	Automation; Tool development; standardization	Photovoltaics	2006
51	**p_0**	**module**	Standards for power performance testing	IEC 60904 series, IEC 60891, IEC 61853 focus on evaluating PV module power performance, increase the known reliability of the product and therefore decrease the cost of capital which the module manufacturer or a project developer is able to obtain.	Standardization	Public institution	1980

52	**p_0**	**module**	Other	Over time production has shifted to locations with different electricity rates, labor rates and capital expenditures	Non-innovation		
53	**p_0**	**module**	LBD	Employee churning across facilities enables learning-by-doing and reduces labor costs	Non-innovation		
54	**p_0**	**module**	Other	Clustering of PV manufacturing supply chain in China	Non-innovation		
55	**c_inv_eta_inv**	**BOS**	Application specific integrated circuits (ASICs)	Microchips designed and optimized for specific applications (e.g. specific control strategies), reducing component counts (fewer individual devices, control cards)	Prefabrication/integration, Design change	Semiconductors	1980
56	**c_inv_eta_inv**	**BOS**	High-frequency inverter designs	Combination of system architecture, circuit design changes and device innovations (use of MOSFETs, IGBTs) to increase inverter switching frequencies	Design change	Semiconductors	2000
57	**c_inv_eta_inv**	**BOS**	Maximum power point tracking (MPPT)	Electric circuit designs and control strategies that adapt inverter resistance to maximize efficiency of power extraction from PV array (i.e. MPPT is the electronic equivalent to a tracker)	Design change	Photovoltaics	1985
58	**c_inv_eta_inv**	**BOS**	Bi-directional inverters	Designs where all or most devices (e.g. switching elements) operate in both directions, enabling battery charging and discharging	Design change	Semiconductors	1995
59	**c_inv_eta_inv**	**BOS**	Silicon insulated-gate bipolar transistors (Si IGBTs)	Semiconductor switching devices with increased switching frequencies	Design Change, Prefabrication/Integration		
60	**c_inv_eta_inv**	**BOS**	Silicon carbide (SiC) field effect transistors	Reduced losses (due to wide-bandgap material) allow for higher switching frequencies compared to Si IGBTs, which reduces the need for passive components like coils and capacitors, or allows smaller components. These effects reduce raw material usage and thus costs	Design Change, Prefabrication/Integration	Semiconductors	2010
61	**c_inv_eta_inv**	**BOS**	Gallium nitride (GaN) field effect transistors	Similar cost-reducing mechanisms as SiC devices; additional advantage is lateral structure which reduces stray inductances and parasitic resistances and therefore simplifies component packaging	Design Change, Prefabrication/Integration	Semiconductors	2015
62	**c_inv_eta_inv**	**BOS**	Thermal management strategies	Improved component layouts to increase heat dissipation into environment. Air cooling	Design change	Semiconductors	2000
63	**c_inv_eta_inv**	**BOS**	Transformerless inverters	Change in national electric code (NEC) in 2010 that allowed transformerless inverters, which require less raw material (due to electronic instead of mechanical switching) and are therefore less costly	Design change	Electronics	2010
64	**c_inv**	**BOS**	Automated optical inspection procedures	Automated circuit board inspection after every manufacturing step. Machine compares photograph of circuit board to reference data	Automation, Digitalization, Process development, tool development	Semiconductors	
65	**c_inv**	**BOS**	Soldering machines	Circuit board is moved through liquid solder paste to bond wire connections to circuit board	Automation, process development, tool development	Semiconductors	
66	**c_inv**	**BOS**	Printed circuit boards	Automated manufacturing of circuit boards instead of point-to-point construction	Automation, Digitalization, Process development, tool development	Electronics	1950
67	**c_inv**	**BOS**	Surface mount technology (SMT) component placement systems (also called pick-and-place or PNP machines)	Machines for placement of capacitors, coils, transistors, and other surface mounted devices on printed circuit boards	Automation, Digitalization, Process development, tool development	Semiconductors	1980
68	**c_inv_eta_inv**	**BOS**	String inverters	Reduced power losses due to centralized MPPT, reduced mismatch losses between modules, reduced string diode losses	Design change, Architectural change	Photovoltaics	2000
69	**c_inv_eta_inv**	**BOS**	Microinverters	Simpler, faster installation. No extra installation for rapid shutdown requirement established by national electric code (NEC)	Design change, Architectural change	Electronics	1994
70	**c_inv_eta_inv**	**BOS**	AC modules	Higher total per-Watt inverter costs	Prefabrication/integration, Architectural change	Photovoltaics	1994
71	**c_inv_eta_inv**	**BOS**	Multi-level inverter topologies	Increased range of inverter output voltages; allows smoother output waveforms, reducing harmonic distortions and voltage stress	Design change	Electronics	1980

72	c_inv_eta_inv	BOS	Improved coil winding methods	Increased volume fraction used by windings to cut per-Watt material and space usage	Material quality, Design change	Electronics	1990
73	c_inv_eta_inv	BOS	High-efficiency inductors	Use of novel magnetic materials for inductor core (amorphous cores, ferrites, metal alloy powders) to reduce energy losses	Material quality, Design change	Semiconductors	2010
74	c_inv_eta_inv	BOS	Performance evaluation software	Simulations of thermal and electrical inverter behaviour instead of physical prototyping	Tool development, Digitalization	Semiconductors	2000
75	c_inv_eta_inv	BOS	IEEE 1547 standards	Series of standards that specify a set of universal criteria for the technically sound interconnection of distributed energy sources to the distribution grid; Consists of mandatory functional technical requirements (e.g. for equipment testing, as well as monitoring and control) and compliance options for equipment and equipment operation	Standardization	Public institution	2005
76	c_inv_eta_inv	BOS	Inverter performance test protocols	Series of standards for measuring inverter output characteristics (in particular inverter efficiency as a function of AC output power and DC voltage); one example is the California Energy Comissions's protocol; any inverter used in a CEC approved PV system must be tested by an independent lab to this protocol	Standardization, process development	Public institution	2000
77	c_inv	BOS	Modular inverter designs	Standardized smaller inverter units that can be assembled into larger inverters through series and parallel circuits; goal is to reduce the costs of customization for different PV applications, and to support the scale-up of the production of smaller units	Design change, Architectural change	Electronics	1990
78	c_inv_eta_inv	BOS	Anti-islanding control	Circuit designs and control strategies to prevent power supply from PV system to grid during an outage; Innovations in early 2000s enabled pre-certification and low-cost implementation of anti-islanding controls (e.g. through software codes), thereby reducing inverter and interconnection costs	Prefabrication/Integration	Electronics	1990
79	c_inv_eta_inv	BOS	Integrated power modules	Replacement of multiple discrete components (conductors, transformer, filters) by one integrated module; an example is the AC filter-transformer module used in 2nd generation SMA inverters	Prefabrication/Integration	Electronics	2008
80	c_inv_eta_inv	BOS	Aluminum die-cast housing	Replacement of stainless steel housing with aluminum housing to improve specific heat capacity while reducing weight	Material quality improvement		1990
81	c_inv_eta_inv	BOS	Printed circuit board (PCB) layout changes to enable large-scale manufacturing	Improvements in the choice of reference points (e.g. for component pick and place machines) to suit the manufacturing process	Non-innovation		
82	c_inv_eta_inv	BOS	Review of National Electric Code Article 690 (Solar Photovoltaic Systems)	Industry taskforce recommendations leading to review of code specifiying performance and installation (e.g. circuit design) requirements for PV systems; goal was simplification of code, adjustment to recent industry development;	Non-innovation		
83	c_inv_eta_inv	BOS	EOS in inverter factories	Reduced per-unit capex and opex due to larger output	Non-innovation		
84	c_inv_eta_inv	BOS	LBD in inverter factories	Manufacturing cost reductions due to incremental improvements in manufacturing steps resulting from repetition	Non-innovation		
85	phi_a	BOS	Wind tunnel testing of mounting systems	Experimentally testing structural stability of installer equipment allows for novel, reduced-material designs compared to previous, more conservative building codes and standards	Standardization, process development	Public institution	2012
86	phi_a	BOS	Module-integrated, railless mounting systems	Rails integrated into modules such that modules can be mounted directly to the roof	Prefabrication/integration	Photovoltaics	2007

87	**tau_s**	**BOS**	Bid preparation software platforms	Automated design of engineering and sales proposal, including financial analysis, system layout diagram, single-line drawing, contract preparation (e.g. PVBid); more comprehensive than remote shading analysis software (see below)	Tool development, Digitalization, automation	Construction	2010
88	**tau_s**	**BOS**	Remote site assessment software	Software for remote analysis site-specific conditions (shading, roof obstructions). An example is the use of satellite image instead of on-site measurements to create 2D image of building. Use of algorithm to construct 3D model and simulate shading. The result is a heat map of site-specific, shading-adjusted irradiance values	Tool development, Digitalization, automation	Photovoltaics	2010
89	**tau_s**	**BOS**	Building-integrated PV installation	PV integrated into building design from the beginning of design process to reduce time needed for PV-specific adjustments	Architectural change	Photovoltaics	1990
90	**tau_s**	**BOS**	Simplified zoning and planning laws	Simplify design requirements, thereby reducing design time	Legal innovation	Public institution	1970
70	**tau_s**	**BOS**	AC modules	Eliminating DC circuit reduces design time	Prefabrication/integration, Architectural change	Photovoltaics	1994
91	**tau_s**	**BOS**	Modular inverter designs	Standardized smaller inverter units that can be assembled into larger inverters through series and parallel circuits; goal is to reduce the costs of customization for different PV applications, and to support the scale-up of the production of smaller units	Design change	Electronics	1990
92	**tau_s**	**BOS**	Plug-and-play PV systems	Pre-configured electrical connections that require no manual field wiring and reduce overall number of connections that need to be made on-site. System standardization will likely also reduce system design time (particularly in extreme forms of 'off-the-shelf' plug-and-play designs).	Prefabrication/integration, Architectural change	Photovoltaics, Public institution	2000
93	**tau_s**	**BOS**	LBD	Faster system design through incremental improvements resulting from repetition of design tasks	Non-innovation		
94	**tau_mec**	**BOS**	Integrated mounting systems ("plug-and-play" mounting, "solar platforms")	Prefabricated mounting systems reduce component count and need for tools, thereby reducing on-site installation time (fewer and simpler steps)	Prefabrication/integration, Architectural change	Photovoltaics	2000
86	**tau_mec**	**BOS**	Module-integrated, railless mounting systems	Rails integrated into modules such that modules can be mounted directly to the roof	Prefabrication/integration	Photovoltaics	2007
95	**tau_mec**	**BOS**	Integrated hook and clamp solutions (direct attachment mounting)	Integrate standard grounding features in clamp. No need to install grounding separately	Prefabrication/integration	Construction	1995
89	**tau_mec**	**BOS**	Building-integrated PV installation	PV integrated into building design from the beginning of design process to reduce time needed for PV-specific installation	Architectural change	Photovoltaics	1990
96	**tau_mec**	**BOS**	Non-penetrating mounting systems	Ballasted support system for fixing PV panels on roof using strategically placed weights (e.g. cinder blocks) to achieve stability without bolting rails down by penetrating roof membrane (often used for low-tilt roofs, or when roof too old to be penetrated; not suitable in high-wind areas)	Prefabrication/integration	Construction	1990
97	**tau_mec**	**BOS**	LBD	Faster installation through incremental process efficiency improvements resulting from repetition of installation tasks; LBD can result in lower idle time of workers on-site, better organization of crew schedules etc.	Non-innovation		
69	**tau_ele**	**BOS**	Microinverters	Simpler, faster installation. No extra installation for rapid shutdown requirement established by national electric code (NEC)	Design change, Architectural change	Electronics	1994
70	**tau_ele**	**BOS**	AC modules	Simpler, faster installation because microinverter (AC modules) or DC optimizer (smart modules) already integrated into module. No extra installation for NEC rapid shutdown requirement (see above)	Prefabrication/integration, Architectural change	Photovoltaics	1994

98	**tau_ele**	**BOS**	Easy-to-separate PV cables	Faster, safer installation because co-extruded cables can be separated using fingers instead of cutter. Positive and negative conductor can nevertheless be transported on single spool	Prefabrication/integration	Electronics	2010
99	**tau_ele**	**BOS**	Y-connectors	Connectors with one input and two outputs allow simplified ("ready-to-plug") parallel circuit connections	Non-innovation		
92	**tau_ele**	**BOS**	Plug-and-play PV systems	Pre-configured electrical connections that require no manual field wiring and reduce overall number of connections that need to be made on-site	Prefabrication/integration, Architectural change	Photovoltaics, Public institution	2000
100	**tau_ele**	**BOS**	Wireless inverter configuration tools	Apps for simplified inverter activation and broadcasting of firmware updates through Wifi/Bluetooth	Digitalization, tool development	Electronics	2005
101	**tau_ele**	**BOS**	DC optimizers	DC-DC-converters installed with each individual module; converters adjust their output voltage to match module output current to string current, thereby maximizing conversion efficiency through adjustment of (i.e. maximum-power-point tracking at the module level)	Design Change	Electronics	2009
102	**tau_ele**	**BOS**	LBD	Faster installation through incremental improvements resulting from repetition of installation tasks	Non-innovation		
103	**tau_PII**	**BOS**	Full online permitting	Enables completion of all aspects of the permit process (application submittal, plan review, fee payment, delivery of approved permits via email or a website) online, often faster than before	Digitalization	Petroleum	2000
104	**tau_PII**	**BOS**	Template for single line diagram	Template for single line diagram that replaced customized single line diagrams	Standardization	Photovoltaics	2012
105	**tau_PII**	**BOS**	Cross-training programs for permit staff	Cross-training programs for electrical and building inspectors (goal: one site visit instead of two)	Non-innovation	Public institution	2010
106	**tau_PII**	**BOS**	Automated engineering review of grid interconnection	Automated screening system aggregates equipment information and site specifications provided via application portal, distribution-feeder information, and billing information. This information is then linked to built-in calculations to automatically complete initial review screens (e.g. whether interconnection will exceed acceptable transformer loads)	Tool, Digitalization, Automation	Electronics	2010
107	**tau_PII**	**BOS**	Solar permit application checklist	Compact summary of technical requirements for homeowners (the innovation is to translate experiences from previous questions into effective information)	Non-innovation	Electronics	2000
108	**tau_PII**	**BOS**	Software applications to improve interconnection workflow management for utility	Software that consolidates internal management and processing of interconnections under different interconnection rules. Simplifies document retention and retrieval by enabling departments within a company to interact with a common database	Automation, Digitalization, tool development	Electronics	2010
109	**tau_PII**	**BOS**	Fast track permitting	Expedited permitting for small-scale, standard systems	Standardization, process development	Public institution	2010
110	**tau_PII**	**BOS**	IEEE 1547 standards	Series of standards that specify a set of universal criteria for the technically sound interconnection of distributed energy sources to the distribution grid; Consists of mandatory functional technical requirements (e.g. for equipment testing, as well as monitoring and control) and compliance options for equipment and equipment operation	Standardization	Public institution	2005
111	**tau_PII**	**BOS**	Anti-islanding control	Circuit designs and control strategies to prevent power supply from PV system to grid during an outage; Innovations in early 2000s enabled pre-certification and low-cost implementation of anti-islanding controls (e.g. through software codes), thereby reducing inverter and interconnection costs	Prefabrication/integration, Architectural change	Electronics	1990
92	**tau_PII**	**BOS**	Plug-and-play PV systems	Pre-configured electrical connections that require no manual field wiring and reduce overall number of connections that need to be made on-site	Prefabrication/integration, Architectural change	Photovoltaics, Public institution	2000

76	tau_PII	BOS	Inverter performance test protocols	Series of standards for measuring inverter output characteristics (in particular inverter efficiency as a function of AC output power and DC voltage); one example is the California Energy Comissions's protocol; any inverter used in a CEC approved PV system must be tested by an independent lab to this protocol	Standardization	Public institution	2000
112	tau_PII	BOS	Policy regulation	New building codes that made it easier to install and permit PV (e.g. California solar PV guidebook)	Non-innovation		
113	tau_PII	BOS	Transparent permitting and interconnection requirements	Improved public access (e.g. online access) to information on requirements for PV permits	Non-innovation		
114	tau_PII	BOS	Online interconnection application and submission	One single point of entry for applications that previously came via mail, email, fax	Non-innovation		
115	tau_PII	BOS	LBD	Faster permitting due to repetition and accumulating experience in permitting office, electrical inspection etc.	Non-innovation		
116	c_sc	BOS	E-commerce marketplaces	Enables smaller firms to gain centralized access to a larger pool of products. Could in future allow aggregating orders by multiple small installers to benefit from bulk purchase prices	Non-innovation		
117	K_inv	BOS	Oversizing	Increasing the ratio of module dc power to inverter ac power to a number larger than one to increase energy yield	Architectural change	Public institution	2010
118	K_inv	BOS	LBD in module factories	Inherited from module because lower cost modules encouraged oversizing	Non-innovation		
119	K_inv	BOS	EOS in module factories	Inherited from module because lower cost modules encouraged oversizing	Non-innovation		
120	eta_w	BOS	LBD	Incremental improvements in wire and cable layouts resulting from repeated system design	Non-innovation		
121	p_w	BOS	EOS	Bulk purchases of wires and cables to reduce per-unit costs	Non-innovation		
122	p_w	BOS	Other	Drivers of changes in cable and wire prices inside or outside the boundary of the PV industry - uncertain drivers from perspective of PV industry	Non-innovation		
123	p_a	BOS	Other	Drivers of changes in commodity prices inside or outside the boundary of the PV industry - uncertain drivers from perspective of PV industry	Non-innovation		
124	w_ele	BOS	Other	Drivers of wage changes inside or outside the boundary of the PV industry - uncertain drivers from perspective of PV industry	Non-innovation		
125	w_mec	BOS	Other	Drivers of wage changes inside or outside the boundary of the PV industry - uncertain drivers from perspective of PV industry	Non-innovation		
126	w_s	BOS	Other	Drivers of wage changes inside or outside the boundary of the PV industry - uncertain drivers from perspective of PV industry	Non-innovation		
127	w_PII	BOS	Other	Drivers of wage changes inside or outside the boundary of the PV industry - uncertain drivers from perspective of PV industry	Non-innovation		
128	c_r	BOS	EOS	Bulk purchases of racking systems by installers to reduce per-unit costs	Non-innovation		
129	c_r	BOS	Pricing strategy	Firm-level pricing decisions	Non-innovation		
130	c_oe	BOS	EOS	Bulk purchases of non-inverter electrical hardware (meters, monitors) to reduce per-unit costs	Non-innovation		
131	c_oe	BOS	Other	Drivers of hardware cost change outside the PV industry	Non-innovation		
132	c_PII	BOS	Policy regulation	Lowering permitting fees	Non-innovation		
133	p_op	BOS	EOS	Economies of scale at the firm level reducing overhead per Watt installed	Non-innovation		