Quantifying the Relationship Between Higher Photovoltaic Module Efficiency and the Adoption of Distributed Solar

Preprint

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National Renewable Energy Laboratory

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Quantifying the Relationship Between Higher Photovoltaic Module Efficiency and the Adoption of Distributed Solar

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Abstract — **The purpose of this study is understanding the relationship between module efficiency, system costs, and the economic and adoption potential of distributed rooftop solar. We use the dGen model to project the economic potential and adoption of high-efficiency photovoltaic (PV) modules across a range of efficiencies and cost scenarios in the continental United States. Our results reveal that high-efficiency modules can modestly increase the projected adoption of distributed solar, but system capital costs may play a larger role in changing the amount of projected adoption.**

Index Terms – **high efficiency modules, distributed solar, solar capital costs, distributed energy adoption modelling**

I. INTRODUCTION

Today, over 90% of solar panels are produced with single-junction crystalline silicon (c-Si) cells [1]. c-Si offers several benefits for cell manufacturers: affordability, abundancy, maturity, and relatively high efficiency compared to other mass-produced cell technologies [2]. Research and development activities led to gradual, steady improvement in silicon cell efficiency over time. Achieving higher-efficiency photovoltaic (PV) cells is an integral part of the quest to reduce solar system costs; with higher cell efficiencies, fewer panels are required per given energy output. To date, the record for most efficient single-junction c-Si cells stands at 26.7% without concentration [3], while the theoretical limit for c-Si cells is 29.8% [4]. The most efficient commercially produced c-Si cells today achieve 22-24% efficiency [5].

While single-junction c-Si cells are historically the most established, studied, and deployed type of PV cell, several other technologies have already outperformed c-Si in laboratory settings. III-V thin film single-junction cells without concentration have reached a confirmed efficiency of 29%, while multijunction III-V cells have accomplished upwards of 39% efficiency (Green 2018; NREL 2019). III-V, c-Si stacked multijunction cells have also exceeded 30% efficiency. Oxford PV has achieved an efficiency of 28% with a perovskite-silicon tandem cell (NREL 2019). While these technologies have achieved higher efficiencies in the laboratory, these devices are either not yet commercially available or are currently too expensive for mainstream PV markets. But with new technology revealing a path to higher efficiency, it is important to understand the relationship between increases in module efficiency and market demand, or the price premium higher efficiency modules could command.

Achieving higher-efficiency solar cells is of interest from a system perspective for several reasons. First, increased efficiency can drive reductions in solar installed system costs, as well as in the required area for the same system capacity due to the reduced number of panels [7]. Additionally, higher energy production per given area could enable adoption of solar on roofs that are currently space-constrained or even add value in nontraditional applications, such as portable devices and vehicles. However, the sensitivity of rooftop solar adoption to efficiency and total installed capital costs—including the costs of the module and the balance-of-systems (BOS)—has not yet been fully explore.

The purpose of this study is to understand the relationship between module efficiency, system costs, and the economic and adoption potential of distributed rooftop solar. Cell technology with higher efficiencies than single-junction silicon cells could allow customers who are currently limited by their rooftop area to offset a higher fraction of their electricity consumption with solar generation. However, high efficiency solar cells must still achieve a certain price to be competitive with existing c-Si technology. Our goal is to quantify the changes in rooftop solar adoption in the continental United States that could result from the use of higher-efficiency solar technologies and to understand the sensitivity of those results to total installed capital cost. This analysis will provide insights into the potential value of increasing PV efficiency and guide research and development efforts.

II. METHODS

We use the National Renewable Energy Laboratory (NREL) Distributed Generation Market Demand (dGen) model [8], an agent-based model of distributed energy resource (DER) adoption, to estimate the economic potential and projected adoption of behind-the-meter distributed rooftop solar throughout the United States. The dGen model relies on highly resolved geospatial datasets to simulate the load requirements, siting availability, electricity rates, resource strength, and other location-related conditions for each agent. For this analysis, we generate one agent per sector in each county, or 9,426 total agents for the entire United States. dGen also incorporates net metering policies at the state level and models these policies to expire as stated in state legislation; if no expiration date is stated in legislation, net metering is modelled to continue indefinitely.

To quantify how efficiency could influence the markets for distributed solar, we estimate the nationwide economic potential and the projected adoption of these systems on a biennial basis from 2018 through 2030. Agents in dGen are attributed with a developable roof area, annual electricity consumption, and retail tariff. Each agent uniquely determines the PV system capacity, which could include non-adoption, that maximizes the net present value (NPV) of their investment. The economic potential in any given year is the total capacity in megawatts (MW) of all systems that are economically viable to install in that year; a system is determined to be economically viable if the project rate of return over a 30-year period exceeds a hurdle rate. In this case, that hurdle rate is the weighted average cost of capital (5.4%) from the 2018 NREL Annual Technology Baseline (ATB) [9].

The dGen model projects rooftop solar adoption using the Bass Diffusion Model (BM) [10] and estimates of customer willingness-to-pay (WTP) for new technologies. The BM is commonly used to project adoption of new technologies, where the basic premise is that technology adoption occurs via a mixture of “innovators” (early adopters) and “imitators” (follow-on adopters). Parameters for the BM were estimated by state and sector using panel data on historic solar adoption [11]. Whereas the Bass parameters govern the rate of adoption, the WTP parameters govern the achievable market size, or relationship between the payback period (year) of a PV system and the fraction of technically eligible consumers who eventually adopt the system. The WTP parameters were estimated from surveys of consumers [12][13]. The dGen model combines these two algorithms, and each year, agents recalculate the payback period of adopting rooftop solar, based on that year’s techno-economic characteristics, and proportionately adopt new systems as specified by the BM. The projected adoption in each year is represented by the MW of capacity installed by agents in the given year.

With the dGen model, we analyze adoption and economic potential with seven different module efficiencies of 25%-40% and compare that analysis to a baseline case intended to represent the possible progress of single-junction c-Si technology. The baseline c-Si scenario assumes the following efficiency schedule: 18% efficiency by 2020, 20% by 2025, 21.7% by 2030 [14] [15]. Our different high-efficiency scenarios assume the same efficiency for all years, as the purpose of these scenarios is not to represent the projected efficiency of a certain PV technology over time, but rather to understand the sensitivity of economic potential or adoption to efficiency. Table 1 presents these efficiencies.

TABLE I
EFFICIENCY SCENARIOS FOR HIGH EFFICIENCY MODULES

Efficiency Schedule	**Description**
Baseline Efficiency	Represents possible progress of single-junction c-Si modules; 18% by 2020, 20% by 2025, 21.7% by 2030
25%	A uniform 25% module efficiency held constant through 2030.
27%	A uniform 27% module efficiency held constant through 2030.
30%	A uniform 30% module efficiency held constant through 2030.
33%	A uniform 33% module efficiency held constant through 2030.
35%	A uniform 35% module efficiency held constant through 2030.
37%	A uniform 37% module efficiency held constant through 2030.
40%	A uniform 40% module efficiency held constant through 2030.

In addition to varying efficiency, we run each efficiency schedule at four different per watt (W) capital cost schedules, summarized in Table 1. Particularly interesting is the price premium that higher-efficiency systems can withstand over the baseline without having a negative effect on adoption, thus competing with the dominant incumbent technology. We use the ATB mid-cost projections for distributed solar as our baseline scenario cost schedule [9]. The remaining three cost schedules are listed in Table 2. The uniform $0.20/W reduction corresponds to a BOS cost reduction that might be expected for a 30% module with the same module price for residential rooftop systems in 2017 [16]. The other two cases are selected simply to examine the sensitivity of adoption to higher installed capital costs.

TABLE II
PV INSTALLED CAPITAL COST SCENARIOS ANALYZED FOR HIGH EFFICIENCY MODULES

Cost Schedule	**Description**
Baseline Cost	Priced per W; follows ATB Mid Cost schedule [9]
$0.20/W *Reduction*	A uniform $0.20/W reduction in the system installed capital cost compared to the baseline cost.
$0.20/W *Increase*	A uniform $0.20/W increase in the system installed capital cost compared to the baseline cost.
$0.50/W *Increase*	A uniform $0.50/W increase in the system installed capital cost compared to the baseline cost

With these cost and efficiency scenarios, we can estimate adoption and economic potential at eight different efficiency schedules and four different cost schedules per efficiency, allowing us to study the sensitivity between cost, efficiency, and adoption.

Thus far, this analysis makes the previously mentioned estimations in a market vacuum, in which the only PV technology available to each agent is the module of the given efficiency schedule. To more thoroughly understand how higher-efficiency modules can impact adoption, we project the adoption of current c-Si modules and the higher-efficiency modules when they are in direct competition with each other. To simulate this competition, each agent is presented with three options: adopting a c-Si system, adopting a higher-efficiency module system, or continuing to purchase grid-sourced electricity without adopting any PV system. For consistency and comparability, agents with identical attributes are used to evaluate each technology. The agent adopts the technology with a higher 20-year net present value (NPV), and the amount of capacity installed with that technology is calculated based on the factors mentioned previously. The agent adopts neither technology if the NPV is below zero for either system. When the technology options are equal in NPV, the resulting projected adoption is categorized as a tie. Note that we do not model consumer preference for higher-efficiency panels as a proxy for premium products; the comparison is purely techno-economic.

We simulate this competition across the efficiencies listed in Table 1 and under the four different cost schedules. Using relative NPV as our criteria for adoption, results from this competition reveal how often our representative agents select higher-efficiency modules over c-Si modules, and vice versa, represented by the total projected adoption by technology.

Note that besides our baseline scenario, our model creates a counterfactual situation, in which a scenario's high-efficiency module is commercially available for adoption starting in 2018. The amount of adoption that our model projects in a given timestamp is based on the cumulative adoption up to that point. Thus, the projected adoption in a given timestamp assumes that agents have been able to adopt the same high-efficiency module from 2018 to the timestamp in question.

III. RESULTS

A. Economic Potential and Projected Adoption of High Efficiency Modules

The results from our analysis demonstrate that high-efficiency cells can improve the economic potential and projected adoption of distributed rooftop solar, but only within a certain range of costs. In our baseline scenario, which assumes our baseline efficiency and baseline cost schedule, our model projects an economic potential of roughly 493 GW and projects 11.3 GW of adoption in the 2029 to 2030 time frame in the continental United States. In the scenario where high-efficiency modules have the same system cost per W as the baseline c-Si case, we estimate that an average module efficiency of 30% would increase the economic potential of distributed solar by over 26 GW, or roughly 5.4%, from 2029 to 2030 (Figure 1). 25%-efficient modules with baseline costs could increase economic potential by 7 GW over the baseline scenario in that time period, and 40%-efficient modules could add 58 GW. The economic potential relative to the baseline converges at 21.7% efficiency, which is the baseline efficiency in 2030.

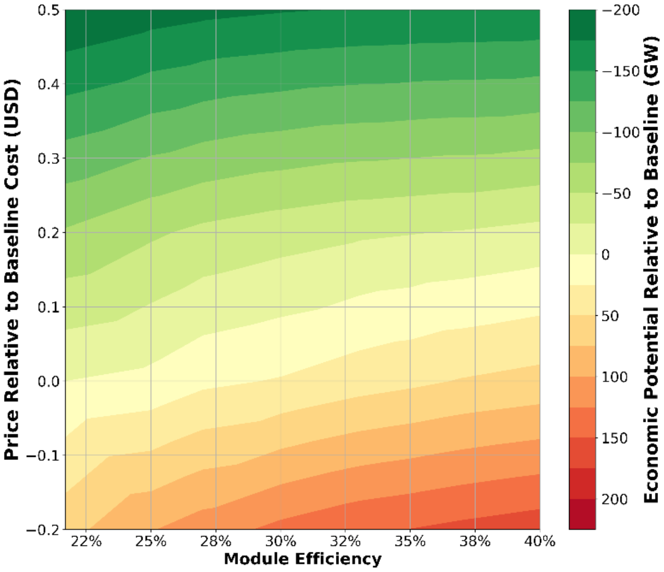

Fig. 1. Contour map of economic potential, module efficiency, and cost relative to baseline in years 2029 and 2030

In terms of adoption, an average module efficiency of 30% at baseline costs could improve distributed solar adoption by just over 400 MW, or about 3.5%, from 2029 to 2030. That number climbs to 860 MW, or 7.6%, with 40%-efficient panels (Figure 5). Furthermore, Figure 2 shows the delta in cumulative projected adoption between the baseline scenario and 30%-efficient modules at our four cost schedules. By 2030, with 30%-efficient modules at baseline costs, roughly 4 GW more of cumulative capacity could be adopted than in our baseline scenario, representing a 7.8% increase in adoption; systems with 40%-efficient modules could increase cumulative projected adoption by 5.4 GW over the baseline (Figure 3). For reference, the cumulative projected adoption from 2018 to 2030 in our baseline scenario is 50.8 GW.

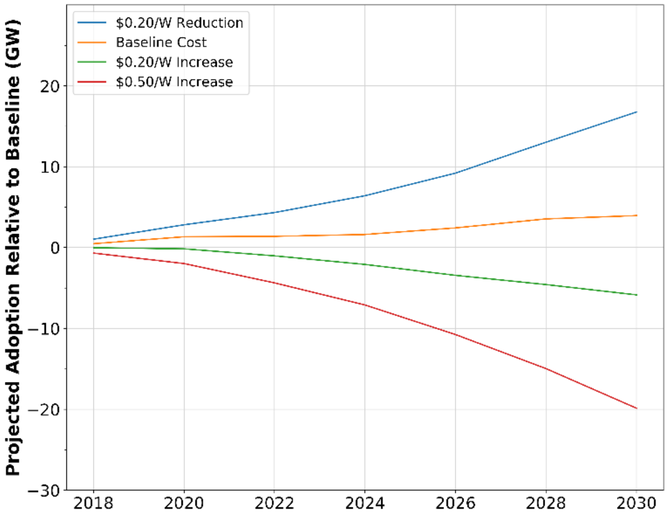

Fig. 2. Cumulative projected adoption of 30%-efficient modules relative to the baseline scenario from 2018 to 2030

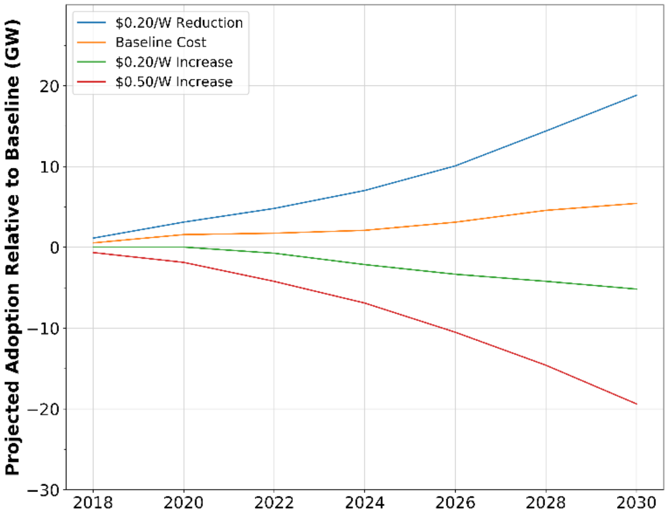

Fig. 3. Cumulative projected adoption of 40%-efficient modules relative to the baseline scenario from 2018 to 2030

B. Sensitivity of Projected Adoption to Installed Capital Cost

The previous discussion of results focused on economic potential and projected adoption of high-efficiency modules at baseline system capital costs. When system capital costs decrease below the baseline, however, our results suggest an even faster rate of installations. At $0.20/W below the baseline cost schedule, a 30%-efficient module could increase cumulative adoption by just over 16.8 GW by 2030, while 40%-efficient modules could increase cumulative adoption by over 18.8 GW (Figure 3). From 2029 to 2030, $0.20/W cheaper modules at 30% efficiency would increase projected adoption by 3.7 GW, well over the 400 MW for the same efficiency at baseline costs (Figure 5). Figure 5 reveals the full relationship between module efficiency, system capital costs relative to the baseline, and projected adoption relative to the baseline in 2030.

Next, we solve for the price premium that high-efficiency panels could withstand over the c-Si baseline to result in no net loss in demand. Earlier years are more forgiving to system cost increases than later years due to lower projected c-Si efficiency. From 2019 to 2020, a 30%- and 40%-efficient module system could endure roughly a $0.17/W and $0.20/W increase in costs, respectively, while still being as attractive as c-Si systems (Figure 4). For reference, the baseline cost schedule projects capital costs of $2.31/W for residential systems and $1.63/W for commercial and industrial systems from 2019 to 2020, and our baseline scenario projects 5 GW of adoption.

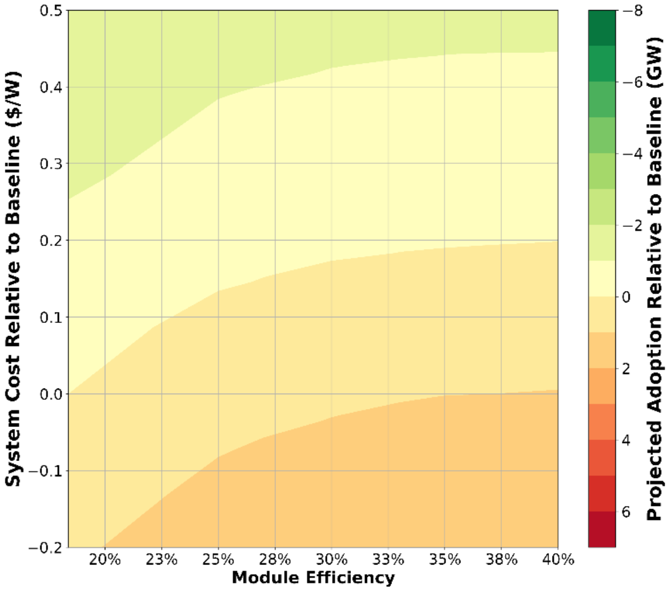

Fig. 4. Contour map of projected adoption, module efficiency, and cost, relative to baseline in years 2019 and 2020

But as the efficiency of c-Si cells improves over time, high-efficiency systems have less leeway in costs. From 2029 to 2030, a 30%-efficient module system can only exceed c-Si system costs by roughly $0.05/W before adoption falls below c-Si levels, while a 40% efficient module system can withstand a $0.09/W premium (Figure 5). For reference, the baseline scenario project costs $1.49/W for residential systems and $1.12/W for commercial and industrial systems in 2030. With a price premium, agents are inclined to adopt a smaller system; however, agents who are limited by their roof size rather than cost can adopt larger systems with high-efficiency modules, which offsets the loss of capacity from the price premium.

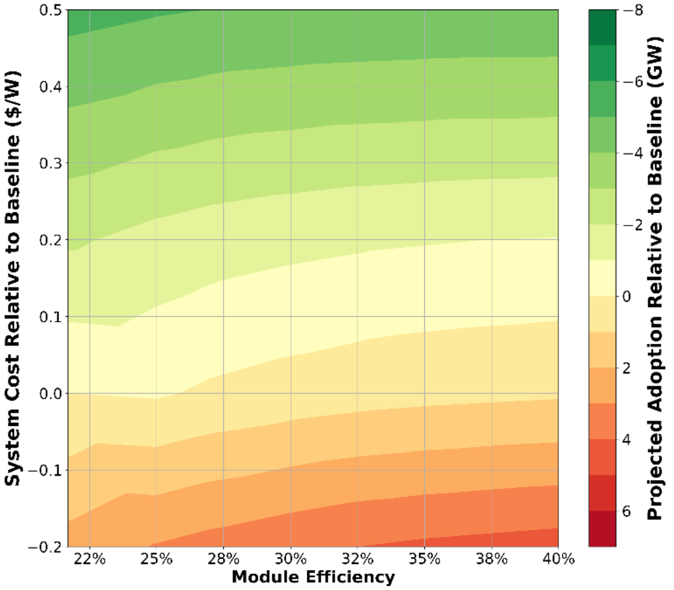

Fig. 5. Contour map of projected adoption, module efficiency, and cost relative to baseline in years 2029 and 2030

As shown in Figure 5, a c-Si module with $0.1/W cheaper system costs than the baseline would increase projected adoption by just over 2 GW from 2029 to 2030. At the same time, a 40%-efficient module at baseline costs would only increase projected adoption by 0.9 GW. The results from our sensitivity analysis suggest that changes in system costs could drive changes in projected adoption more than changes in efficiency, and that high-efficiency modules could potentially have more impact if they can reduce balance of system costs, rather than if they alleviate roof area constraints.

According to our model, a dip in relative adoption emerges around 25% efficiency. This dip is because the PV market is more saturated in 2030 for a 25%-efficient module than for a baseline c-Si Module. Our method for predicting adoption dictates that adoption will grow slower in more saturated markets, and thus, relative to the baseline, adoption for a 25%-efficient module dips. Other efficiencies do not experience this dip in 2030 because either their market potential remains proportionally higher than their projected adoption, or because their projected adoption is higher even with market saturation.

C. *Projected Adoption by Module Type with Competition*

The previous results and figures project adoption when agents only had one choice of PV technology. As discussed in Section II, to better understand the value that higher-efficiency modules can offer, we project adoption by technology when agents are presented with the choice between a high-efficiency module, a c-Si module, or no module. From 2029 to 2030, when agents have the option between the baseline c-Si module or a 30%-efficient module, both at baseline system capital costs, total projected adoption reaches 12.4 GW. Of that 12.4 GW, the 30%-efficient module would have a higher NPV than c-Si modules for roughly 5.9 GW worth of adoption. The c-Si modules would still provide more value for 2.2 GW of projected adoption. For 4.4 GW out of the 12.4 GW, the value between the c-Si module and the 30%-efficient module was equal. If this projected adoption were to be split evenly between the two modules, it would result in a projected adoption of 8.1 GW for the 30%-efficient module, or 65.0% of the distributed PV market share when competing with a c-Si module.

Figure 6 breaks down the results from competing a module with a c-Si module at each efficiency. The results do not vary too drastically between efficiencies; from 25% to 40% efficiency, the high-efficiency module increases from 65.0% of market share to 67.5% out of the total projected adoption, which increases from 11.9 to 12.9 GW.

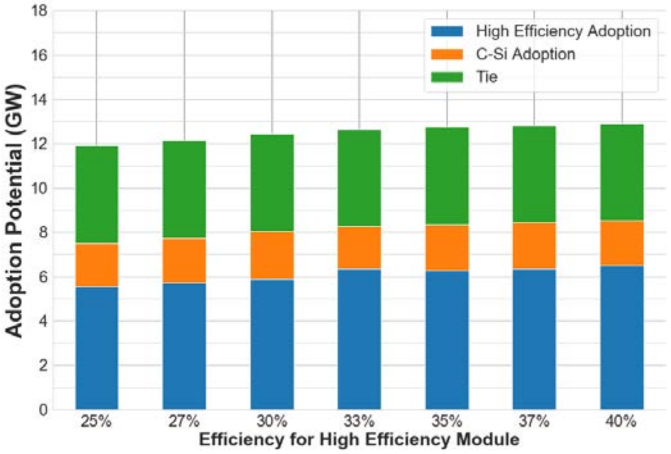

Fig. 6. Projected adoption by module technology at baseline system costs with competition in years 2029 and 2030

As shown in Figure 6, our model still projects adoption for single-junction c-Si modules, even when competing against a higher-efficiency module at the same system capital costs per W. An explanation for this result is that, even though system capital costs per W are equal between the two technologies, total system capital costs are still higher for the higher-efficiency module. A higher-efficiency module would allow an agent to install a higher-capacity system per given roof size, and because our system costs are priced per W, a higher-capacity system would result in a higher total installation cost. Figure 7 illustrates the average system sizes in kilowatts (kW) at each efficiency and at baseline costs per W across all sectors. As efficiency rises, the average installed system size increases, demonstrating that agents are installing larger systems with higher-efficiency modules, and suggesting that agents with space-constrained roofs can install larger systems. Therefore, the total system capital costs will be higher, and a c-Si system could have a higher NPV with its lower installation costs.

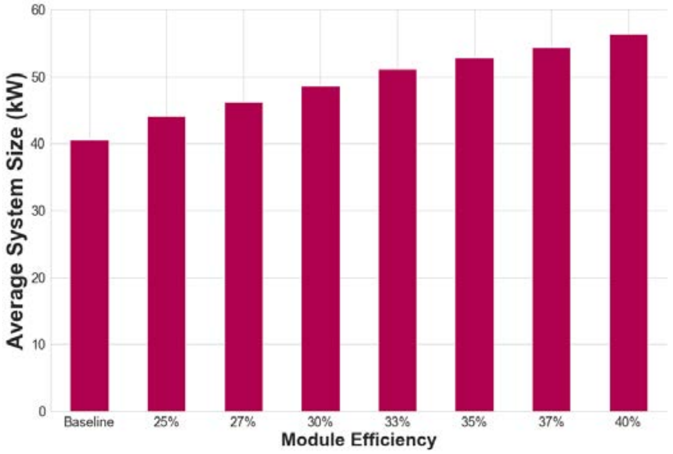

Fig. 7. Average adopted system size by efficiency at baseline costs in years 2029 and 2030 across all sectors

The largest growth in average system size is observed in the industrial sector (Figure 8). With baseline c-Si modules, industrial customers are installing, on average, 84 kW of capacity; with 30%-efficient modules, industrial customers, on average, are installing 108-kW systems. This significant increase in system size indicates that for some agents, the total system capital cost can still be higher in the high-efficiency scenarios, even with cheaper system capital costs per W.

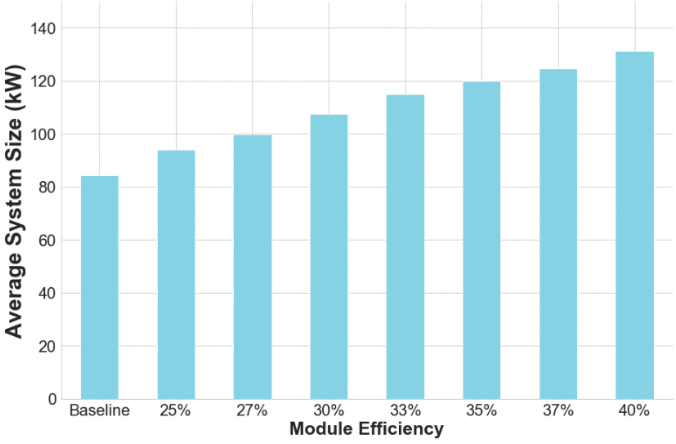

Fig. 8. Average system size adopted by industrial agents by efficiency at baseline costs in years 2029 and 2030

With this in mind, we project the adoption between technologies when higher-efficiency system costs are cheaper than those of c-Si modules on a per W basis. Figure 9 shows the results of the competition when higher-efficiency systems are $0.20/W cheaper than c-Si systems. In this cost scenario, higher-efficiency modules account for a vast majority of the projected adoption. A 30%-efficient module has projected adoption of 14.9 GW from 2029 to 2030, or around 94.8% of the market share. Across efficiencies, market share remains around the same percentage. C-Si modules still retain a small percentage of the market, due to some agents having significantly lower total system capital costs.

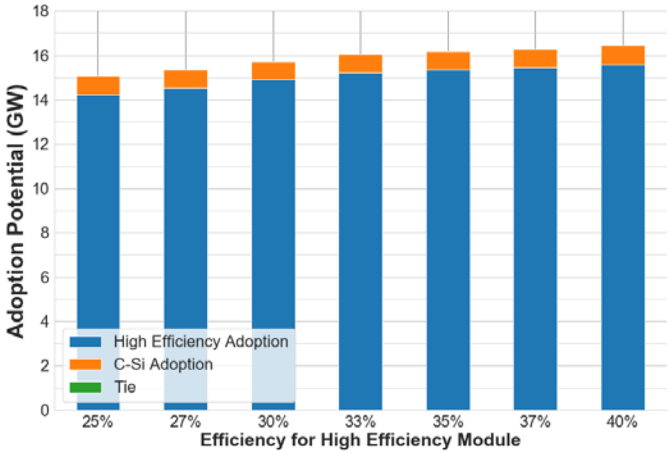

Fig. 9. Projected adoption with competition when high efficiency system costs are $0.20/W below c-Si costs in years 2029 and 2030

If single-junction c-Si costs per W can remain below that of higher-efficiency modules, the projected adoption of high-efficiency modules plummets (Figure 10). With high-efficiency modules at $0.20/W above c-Si costs, c-Si modules retain 9.9 GW-10.7 GW of projected adoption across the different efficiencies in 2030. Higher-efficiency modules still capture a notable piece of the market, however. A 30%-efficient module, even with $0.20/W higher system costs, has a projected adoption of 1.5 GW, or 12.8% of market share. A 40%-efficient module could capture 1.9 GW of the market. This result suggests that higher-efficiency modules can still provide additional value over c-Si modules, even with an $0.20/W increase in system costs.

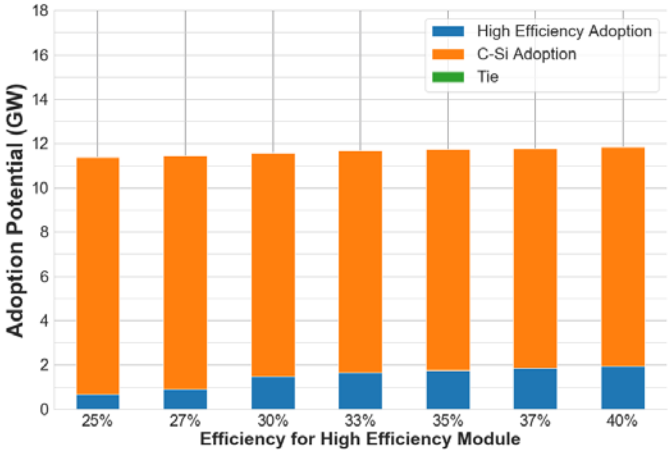

Fig. 10. Projected adoption with competition when high efficiency system costs are $0.20/W above c-Si costs in years 2029 and 2030

With high-efficiency module system costs at a $0.50/W premium over c-Si module system costs, c-Si modules dominate; however, our model still projects that high-efficiency modules retain some adoption. As shown in Figure 11, a 30%-efficient module has a projected adoption of 340 MW, and a 40%-efficient module has a projected adoption of 430 MW.

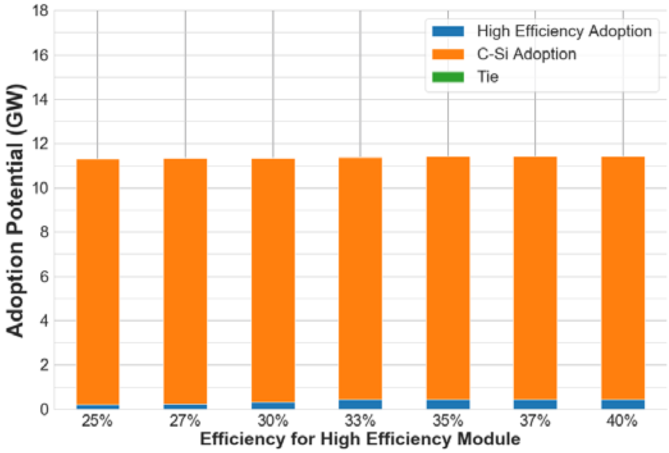

Fig. 11. Projected adoption with competition when high efficiency system costs are $0.20/W above c-Si costs in years 2029 and 2030

The results from these different competition and cost scenarios illustrate how high-efficiency modules would perform in the market with the presence of single-junction c-Si modules.

IV. Discussion and Conclusion

The purpose of this analysis is to quantify the relationship between efficiency, system costs, and the adoption of distributed, rooftop solar. Pursuing this objective resulted in two main areas of study: the projected adoption added by high-efficiency cells compared to a c-Si baseline, and the sensitivity of this adoption to capital cost. Our analysis simulated a suite of efficiency and cost scenarios to effectively estimate the response of adoption to these variables. We further study the value of high-efficiency modules by projecting their adoption when competing with baseline c-Si modules.

Results reveal that high-efficiency systems can offer a modest increase in adoption over c-Si systems if system costs can reach c-Si, or baseline, prices. Distributed solar systems with 30%-efficient modules at baseline costs can increase projected economic potential and adoption by 5.4% and 3.5%, respectively, over baseline levels from 2029 to 2030. Cumulatively, these same systems achieve a 4 GW, or 7.8%, higher total adoption than our baseline scenario by 2030. Systems with 40%-efficient modules could offer 7.6% more annual adoption from 2029 to 2030 and 5.4 GW in cumulative projected adoption by 2030.

Adoption of high-efficiency cells is restrained by total system costs. From 2029 to 2030, systems with 30%-efficient modules have greater projected adoption than baseline c-Si modules for installed prices up to $0.05/W higher than baseline costs. As efficiency rises, this margin relaxes; systems with 40%-efficient modules must achieve costs below $0.09/W over the baseline. Furthermore, in 2030, a $0.1/W decrease in system costs at baseline efficiency adds more projected adoption than a 40%-efficient module at baseline costs. These results suggest that the potential for reduction in BOS costs could have more impact on adoption potential than changes in efficiency alone.

When introducing competition between high-efficiency and c-Si modules, high-efficiency modules achieve a notable portion of the PV market share, but that share dramatically drops at higher system costs per W. When system capital costs are equal between the two module types, a 30%-efficient module would capture 8.1 GW of projected adoption, representing 65% of the market. If system costs can undercut c-Si modules by $0.20/W, high-efficiency modules would seize roughly 95% of the distributed PV market. If higher-efficiency module systems have a $0.20/W premium over c-Si modules, they could still retain roughly 13% of the market share for efficiencies above and including 30%.

By establishing these relationships between efficiency, system costs, and the success of rooftop solar, we provide insight into the potential value of increasing PV efficiency.

V. Acknowledgements

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