Observations and Lessons Learned From Installing Residential Roofing-Integrated Photovoltaics

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List of Acronyms

BIPV	building-integrated PV
DOE	U.S. Department of Energy
kW	kilowatt
NREL	National Renewable Energy Laboratory
PV	photovoltaics
RIPV	roofing-integrated PV
TAG	technical advisory group

Executive Summary

Building-sited solar photovoltaics (PV) could play a key role in decarbonizing the building sector, either through racked and mounted PV or through building-integrated PV (BIPV). BIPV is installed into the building envelope itself, with solar cells and/or modules forming the outer layer of a building structure, thus transforming a single-purpose structure into one that serves the dual purposes of the building envelope and electricity. BIPV can be applied to building roofs, façades, awnings, pergolas, windows, skylights, balustrades, and other external surfaces. Given that BIPV products vary widely, the focus of this research is residential roofing-integrated PV (RIPV), where solar is incorporated into or replaces the roofing material.

Previous research suggests that residential RIPV could reduce customer acquisition, labor, supply chain, and equipment costs. These RIPV products have yet to realize these cost savings, and deployment remains significantly lower than conventional rooftop PV as a share of the addressable market in the United States. One potential barrier to broader residential RIPV deployment may be higher costs relative to conventional rooftop PV, primarily because the design and installation of these products is still evolving.

Here, we explore residential RIPV cost reduction opportunities by analyzing installation processes. Our study documents residential RIPV installations at two reroofing sites and the equivalent of nine new construction sites in California through a methodology known as time and motion study. We also conducted interviews with subject-matter experts to identify barriers and solutions to maximize these products' market penetration.

Our time and motion study breaks the RIPV installation process into four steps: (1) staging, unloading, and roof preparation; (2) fire-resistant underlayment(s) (the synthetic material laid between the roof shingles and roof deck); (3) flashings and PV installation; and (4) wiring and monitoring. We measure the time required for each step in terms of worker-hours (representing an hour of labor from a single worker). We further normalize the process time by dividing worker-hours by kilowatts (kW) of system capacity.

The most time-intensive step was flashings and PV installation, taking around 2.4 worker-hours per kW on average and accounting for around 60% of the process time for an average installation. On average, the total installation process took about 6.4 and 3.5 worker-hours per kW at the reroofing sites and new construction sites, respectively. For comparison, a previous time and motion study documented a time of 6.9 worker-hours per kW for conventional rooftop PV. The shorter RIPV installation times are consistent with previous studies suggesting that RIPV could be installed faster than conventional rooftop PV.

The time and motion results and feedback from interviewees provide insights into potential residential RIPV cost reduction opportunities. Several interviewees suggested that RIPV products would be more efficient if PV installation was more fully integrated into the roofing/construction industries, which currently use separate supply chains and skill sets. Further integration could reduce supply chain delays and labor force redundancies. Future research could explore specific ways to integrate these industries to help realize the cost savings potential of RIPV.

Table of Contents

List of Figures

List of Tables

1 Introduction

In 2020, buildings accounted for about 40% of primary energy use and 29% of emissions in the United States (Leung 2018; EIA 2021). Building energy decarbonization is thus critical to achieving national and global climate change objectives (DOE 2021). Building-sited solar photovoltaics (PV) provide one solution, among many, to reduce building emissions. PV can be installed on rooftops or unused building lots to offset significant portions of building energy use with zero-carbon, on-site electricity. Further, building-sited PV can increase energy system resilience through distributed generation and help defer or avoid investments in centralized grid infrastructure.

Realizing the full potential of PV in building energy decarbonization will require ongoing cost reductions in PV hardware and installation (DOE 2021). Ardani et al. (2018) concluded that achieving U.S. Department of Energy (DOE) cost targets could be achieved by integrating PV installation into residential building construction and reroofing. The authors found that the highest cost savings potential comes from integrating PV into the residential building envelope itself, such that PV serves as the outer layer of the building structure (as opposed to applying conventional rooftop PV on top of the building envelope). Building-integrated PV (BIPV) can serve the functions of various exterior building elements, such as roofs, façades, awnings, pergolas, windows, skylights, and balustrades (Norton et al. 2011; Tripathy et al. 2016).

This report focuses on one residential BIPV product: roofing-integrated PV (RIPV). In RIPV, the PV product is incorporated into or replaces the roofing material. RIPV systems can use conventional crystalline or thin-film technologies, may be aesthetically attractive alternatives to traditional racked and mounted PV systems, and may increase building property values. These products also have the potential to reduce the customer acquisition, labor, supply chain, and equipment costs associated with conventional residential rooftop PV systems (James et al. 2011; Ardani et al. 2018).

RIPV has consistently underperformed relative to market deployment projections and, as we shall show, has achieved significantly lower market penetration than conventional rooftop residential PV. One barrier to broader RIPV deployment is the higher initial costs relative to conventional rooftop PV. These high costs persist despite modeling exercises that suggest that RIPV could be cheaper than conventional rooftop PV (James et al. 2011; Ardani et al. 2018). However, the nascent nature of RIPV products suggests that installation cost savings opportunities are probable.

Effectively identifying installation cost savings opportunities first requires understanding how RIPV systems are installed and the associated time required. Our study documents these activities through time and motion studies of 21 IPV installations. The National Renewable Energy Laboratory (NREL) also conducted interviews with subject-matter experts to identify barriers and related solutions to maximize market penetration. This research can help residential customers, installers, and other market participants understand residential RIPV installation timelines, barriers, and opportunities to deploy RIPV products nationwide.

2 Background

RIPV offers unique advantages relative to conventional rooftop PV:

- Unique aesthetics. In a survey, around one-third of households cited aesthetic impacts as a reason to not adopt conventional rooftop PV (Moezzi et al. 2017). RIPV could surmount this aesthetic barrier by virtue of a more seamless integration into the roof structure through color, gloss, and line match, among other factors (James et al. 2011; Norton et al. 2011; Heinstein et al. 2013; Tripathy et al. 2016; Awuku et al. 2021).

- RIPV can fulfill multiple functions. RIPV is effectively a building construction material that generates electricity. RIPV can provide building structure, insulation, weather protection, shading, and heating benefits in one product, as opposed to installing two separate roofing and PV products to perform the same functions (Norton et al. 2011).

Despite its potential advantages, residential RIPV has underperformed relative to market deployment projections (Heinstein et al. 2013), and market uptake remains low compared to conventional rooftop PV. According to data from Barbose et al. (2021), residential BIPV installations accounted for as much as 1% of all residential rooftop PV installations from 2008–2010, but BIPV market shares subsequently declined through 2016.[1] Residential BIPV market shares have since increased, growing from a low of around 0.005% in 2016 to about 0.4% in 2021.

To estimate market uptake, we assume that the addressable market of residential RIPV in the United States comprises roughly 3.3 million homes that undergo new construction or roof replacements each year (Ardani et al. 2018). Here, we assume that the entire residential BIPV market identified in Barbose et al. (2021) is roofing-integrated. With this assumption, the RIPV market share of 0.4% in 2021 equates to about 2,100 residential RIPV systems installed in 2021, based on total deployment data from Davis et al. (2022). Together, these estimates suggest that annual residential RIPV installations are about 0.06% of the addressable market. In contrast, the addressable market for conventional rooftop PV is theoretically the entire U.S. residential building stock that has not already installed rooftop PV, or about 138 million housing units in 2021. In part because not all homes are viable for rooftop solar (e.g., due to shading), conventional rooftop PV installations were about 0.4% of the addressable market in 2021, meaning that residential BIPV market uptake is about an order of magnitude smaller than in the conventional rooftop PV market.

Installation cost premiums may be a barrier to residential BIPV adoption (James et al. 2011). Although residential BIPV system prices have declined, they are consistently higher than those of conventional rooftop PV systems (Figure 1). In 2021, the average installed price of a residential BIPV system was around \$5.02/W, compared to \$3.92/W for a conventional rooftop

[1] The Barbose et al. data are based on information collected from utilities. Definitions of BIPV may vary, but it is reasonable to assume that most BIPV systems represent PV integrated into roofing. The Barbose et al. sample accounts for around 80% of the U.S. market. Assuming that the 20% of the market excluded from these data does not vary significantly in terms of BIPV deployment, the Barbose et al. data provide a reasonable proxy for total BIPV market uptake.

PV system (Barbose et al. 2021). These observed cost premiums likely overstate true cost premiums, given that RIPV may offset other construction costs. For example, when RIPV is installed during roof replacement or new construction, the incremental cost of the PV system is the difference between the system cost and what the homeowner would have paid to replace or install the roof. Roofing cost savings are not reflected in the cost estimates depicted in Figure 1. Still, customers may perceive these higher installation costs as generating less economic value than installing a new roof and traditional racked and mounted PV separately.

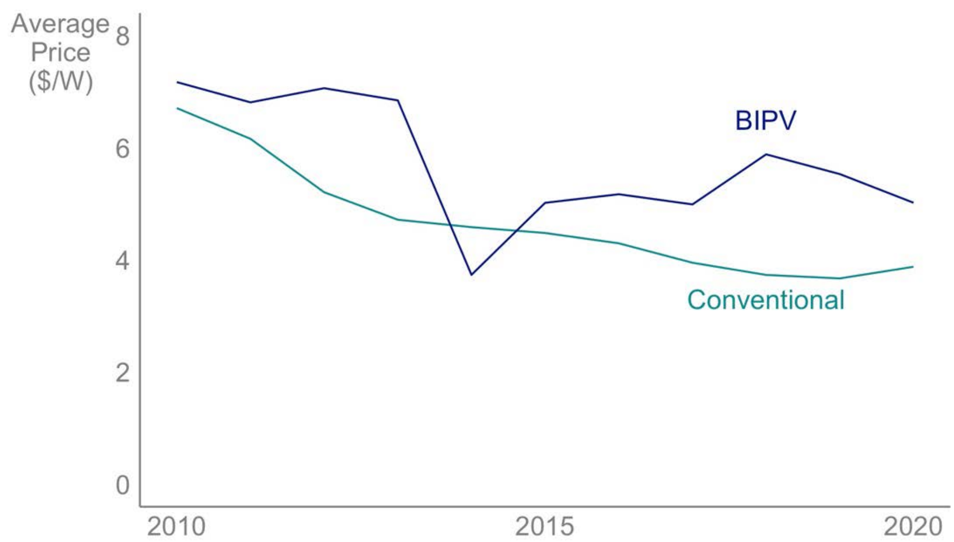

Figure 1. Average prices for residential BIPV and conventional PV systems, 2010–2020.

Based on data from Barbose et al. (2021).

Beyond the estimation issues described above, the difference in price premiums between residential BIPV products and traditional racked and mounted PV reflected in Figure 1 need not be characteristic of RIPV products. Modeled residential RIPV system installation costs are typically lower than those of conventional PV systems due to savings in module racking, customer acquisition, and building construction materials (James et al. 2011, Norton et al. 2011). Instead, the premiums may reflect market dynamics. RIPV installation is a niche industry that has not benefited from the same scale and cumulative experience as conventional rooftop PV installation. In 2020, only around 10 companies installed residential BIPV systems, compared to the nearly 3,000 companies that installed conventional residential rooftop PV systems (Barbose et al. 2021). The limited supply of BIPV installation services means that the market has been largely limited to customers willing to pay premiums for the aesthetic or other unique advantages of BIPV systems (James et al. 2011).

Although the potential cost advantages of residential RIPV have been understood for over a decade (James et al. 2011; Ardani et al. 2018), these cost advantages have yet to materialize in the market. This is partly due to some residential RIPV systems being marketed as premium products. The higher costs may also indicate that some potential cost reductions have yet to be realized. One potential area for RIPV cost reductions is installation labor. Residential RIPV system installation could be less labor-intensive than conventional rooftop PV installation because there are fewer balance-of-system parts to be installed (e.g., racking) and because of labor synergies with other construction processes. Conversely, RIPV installation could be more labor-intensive because these systems generally require more modules—and thus more installation labor—than similarly sized conventional PV systems (James et al. 2011). Determining which factors affect labor productivity can help identify potential cost reductions.

Time and motion study is a method for analyzing the time spent on discrete tasks to complete a process. Time and motion studies have been applied to analyze a variety of processes. Most relevant for our context is the use of time and motion studies to analyze labor productivity in industrial processes. Time and motion studies of labor productivity can be used to identify time- and cost-saving opportunities that could be achieved by accelerating slow steps or eliminating redundancies. In the context of rooftop PV, Morris et al. (2013) conducted a time and motion study of 21 U.S. and five German conventional rooftop PV installations. The authors used the time and motion studies to allocate installation costs across four components of the installation process. For the U.S. installations, Morris et al. attributed 32% of installation costs to racking and mounting installation; 32% to electrical work; 20% to meals, breaks, cleanup, and delays; and 16% to travel and installation preparation. Based on the same data, Quintanilla et al. (2014) presented time and motion results in terms of the time spent on each of these processes. Figure 2 shows these time and motion results for a residential PV system.

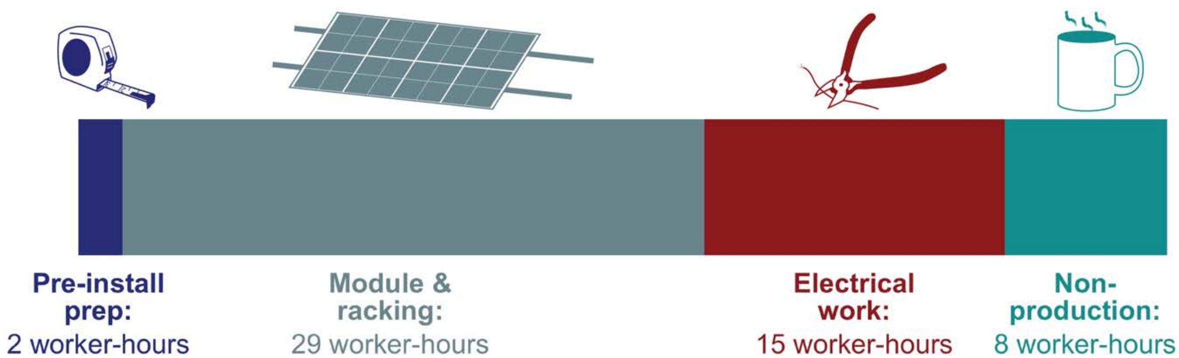

Figure 2. Time and motion study results for a conventional residential rooftop PV system.

3 Methodology

3.1 Expert Interviews and Technical Advisory Group

We conducted interviews with 15 experts across 11 organizations to identify opportunities, barriers, and related solutions to maximize residential RIPV deployment nationwide. Interviewees included representatives from various BIPV product manufacturers (including RIPV), solar installers, roofers, trade associations, and academics, among others. Interviewees were also invited to join a technical advisory group (TAG) to guide this research effort. The TAG comprised 17 participants from 15 organizations. The TAG met quarterly and provided feedback on the time and motion protocol described in the following section.

3.2 Time and Motion Data

Based on insights from the TAG and the literature, we developed a field observation time and motion data collection form to observe and study RIPV installations. The form has four sections: (1) preinstallation, (2) installation, (3) crew information, and (4) post-installation. We designed different time and motion forms for the new construction and reroofing markets.

We implemented the new construction and reroofing data collection forms across three field visits:[2]

- Field visit one: One reroof site in San Jose, California; duration: five days in June 2021
- Field visit two: Nineteen new construction observations near Sacramento, California; duration: five days in August 2021[3]
- Field visit three: One reroof site in San Jose, California; duration: five days in June 2022.

The literature and interviewees suggested that PV system layout may affect installation times (Quintanilla et al. 2014). To evaluate the impacts of system layout and other factors on installation times, we tracked the number of home stories, PV roof planes, and subarrays, as well as array shape(s) for each observation. The results of this analysis are summarized in Section 4.

We present time and motion results in terms of worker-hours, calculated as the product of the time involved in a task and the number of people working. For example, if a task was completed by three people working for four hours, the task took 12 worker-hours. Conceptually, a worker-hour represents the time a task would take a single worker to complete. It is common to normalize task times by dividing worker-hours by other metrics: system size, number of modules, or module area. We present normalized results in terms of worker-hours per kilowatt (kW) of system size. Other metrics related to system size yield proportional results. As a rough approximation, the worker-hours per kW results can be converted to worker-hours per module by dividing by three, and to worker-hours per square foot of module by dividing by 50. Readers can calculate other metrics using the data in the public data file.

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[2] For each visit, we collected data and conducted interviews with roofers, solar contractors/installers, product manufacturers, and homeowners, among others. These sites were selected based on the installation crew, roofing-integrated product manufacturer, and homeowners' willingness to allow access to the sites and travel schedules.

[3] We did not complete a full observation at any home, given the nonconsecutive trip installation process.

4 Field Observations

The RIPV installation process can be broken down into the four basic steps, summarized in Figure 3. Step 1 includes all preinstallation activities, including installation coordination, travel, unpacking of materials, staging, and preparing the roof for installation. Step 2 begins when the team marks the site and installs underlayment (the material between the roof shingles and the roof deck) and/or fire-resistant material. In Step 3, the team installs all solar-related equipment, including flashing (e.g., weather sealant), modules, and/or electrical equipment. Finally, in Step 4, the installation team runs electrical wire and performs final quality assurance steps, completiing the process. Although installers will typically follow these four basic steps, it is possible that these activities may occur over the course of multiple days for reroofing or multiple weeks for new construction, and they may not all occur sequentially.

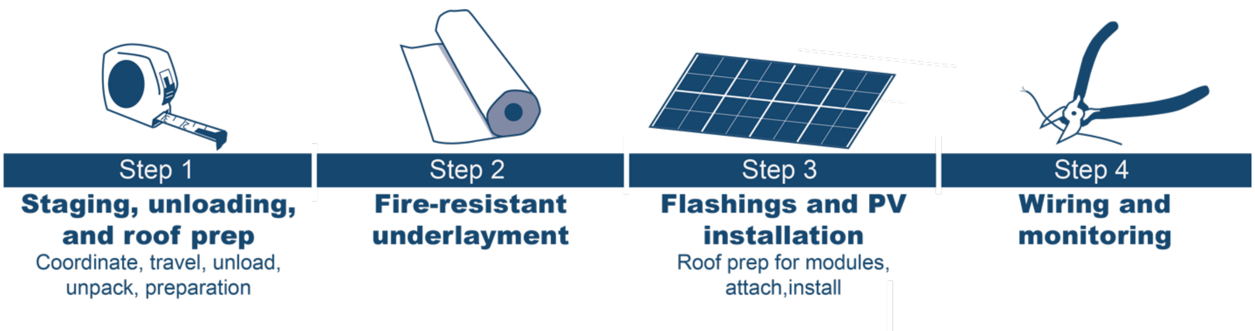

Figure 3. General RIPV installation process.

4.1 Reroofing Time and Motion Results

We collected data for two reroofing sites where RIPV was installed. Both projects were completed near San Jose, California, by the same crew, with the relevant licenses to perform the work. Although both projects were installed on one-story, ranch-style homes, the projects varied not only in terms of the product installed, but also in terms of system size, roof planes, and array design (see Table 1).[4]

Table 1. Reroofing Field Observations

Site	System Size (kW DC)	Number of Modules	Roof Planes	Roof Pitch	Array Area (sq ft)	Subarrays	Crew (Solar)*
Reroof A	6.48	18	3	4/12	226.59	3	2 to 5
Reroof B	14.04	312**	7	4.5/12	597	11	2 to 5

* Crew size varied across steps. **Solar shingles

[4] The crew was trained on how to install both products. The crew confirmed they had installed more of product A, but considered it easier to install product B such that their more limited experience would not skew installation time.

4.1.1 Presolar Activities: Roof Tear-Off and Preparation

Although project characteristics varied, the roofing crews began the installation process the same way: On the first day, a crew removed the existing roofing material, which took approximately 12 worker-hours and was conducted by a separate crew in both observations. After roof tear-off, the crew began roof evaluation and preparation, which took approximately 34 worker-hours. In Reroof A, roof tear-off and preparation were completed over the course of one day. In Reroof B, roof tear-off took 17.5 hours. Reroof B required significantly more roof preparation and was completed in 16.5 worker-hours—the home required installation of a new roof sheathing layer, as opposed to only replacing sections of the roof sheathing, as was done for Reroof A.[5] Once these roofing steps were complete, the crews began the solar and new roof installation activities.

4.1.2 Roofing-Integrated PV Installation Activities

For Reroof A (smaller system, less complex site), Step 1 took 3.8 worker-hours, Step 2 took 8 worker-hours, Step 3 took 24 worker-hours, and Step 4 took 7 worker-hours, for a total of 42.8 worker-hours.[6] For Reroof B (larger system, more complex site), Step 1 took 5.4 worker-hours, Step 2 took 5 worker-hours, Step 3 took 8.6 worker-hours, and Step 4 took 67.6 worker-hours, for a total of 86.6 worker-hours.[7] Figure 4 shows the durations for the four installation steps for the two reroofing sites on a per-kW basis. In each follow-up section, we discuss the activities completed within each step.

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[5] The crew was also delayed in part because of a delayed plywood delivery. In addition, the product's arrival to the site was also impacted by miscommunications between the delivery crew, the installation crew, and the homeowner.
[6] For Reroof A, in terms of total elapsed time (or the real time it took the entire crew to complete each solar installation step, as opposed to worker hours (equivalent of time for one person to complete the work)), Step 1 took 1.25 hours, Step 2 took 2.7 hours, Step 3 took 11 hours, and Step 4 took 7 hours, or about 22 hours in total elapsed time. This reroof project was completed over four working days and 22 total hours of on-site time. Presolar activities, which include roof tear-off and roof inspection, took 13.8 hours; installing gutters and vents took 2.5 hours; and the crew took 4.5 hours of breaks over four days.
[7] For Reroof B, in terms of total elapsed time, Step 1 took 2.7 hours, Step 2 took 1.7 hours, Step 3 took 4.3 hours, and Step 4 took 24.33 hours, or about 33 hours in total. This reroof project was completed over five working days and 33.1 total hours of on-site time. Presolar activities took 12.9 hours, installing gutters and vents took 9 hours, and the crew took 8.3 hours of breaks over five days.

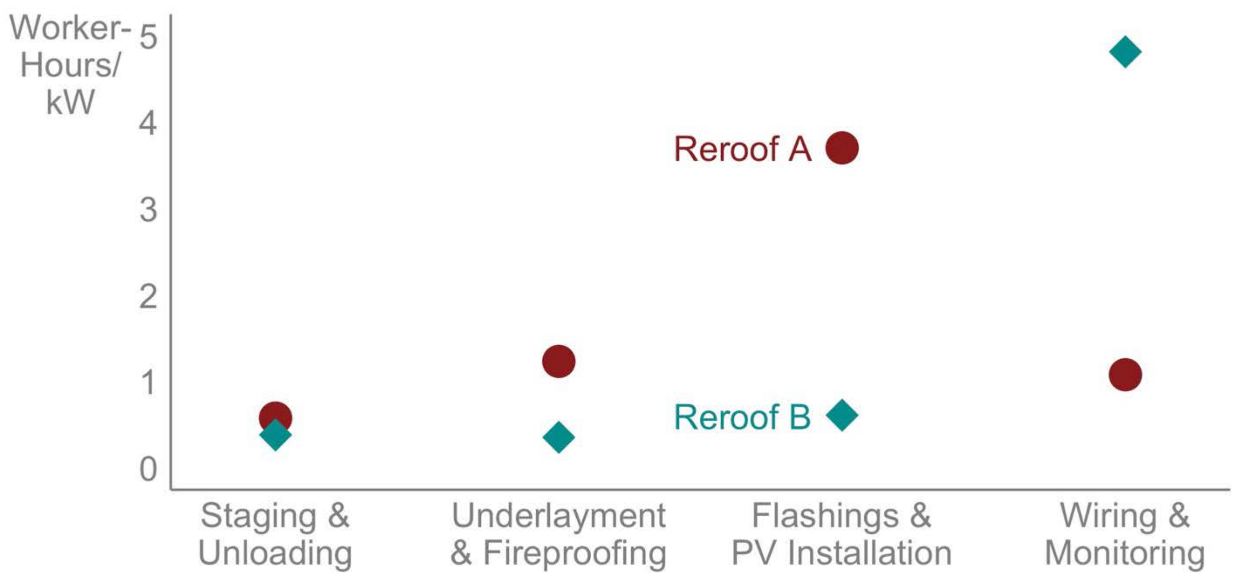

Figure 4. Step durations for reroof sites.

4.1.2.1 Step 1: Staging, Unloading, and Roof Preparation Lessons Learned

Some of the variation in the installation times for Step 1 was related to the different processes by which the products were delivered and the unique characteristics of the installations. First, in Reroof A, the roofing/solar contractor did not use a construction crane to move the solar equipment to the roof, but they did use a crane for the roofing material that was installed where PV was not being installed. In contrast, for Reroof B, the crew did use a crane to move the materials. For Reroof A, two crew members on the ground and one on the roof transported the RIPV equipment from the ground to the roof.

The crew suggested future efficiency improvements for Step 1. The installers indicated that the use of a construction crane can add an estimated $1,000 to the cost of a project, but it is the crew's preferred method of efficiently transporting the heavy RIPV material to the roof while protecting installer safety and avoiding damage to the equipment, as done with Reroof B.

At both sites, the RIPV product was delivered separately from other roofing materials. The crew confirmed that it would be more efficient if the supplier of plywood/roof sheathing and other roofing materials also delivered the RIPV product, and did so using the construction crane transporting the other roofing materials. The crew noted that discussions were underway to determine whether the roofing material supplier could also deliver the RIPV product.

There were also delays associated with the deliveries at the two sites, where deliveries did not occur on time and some RIPV equipment was not delivered in sufficient quantities to complete the installation. Given the frequency of these types of situations on all reroofing jobs, the contractor has a separate staff person who travels between locations with additional material deliveries. If that individual was not available, a crew member would need to leave the site to get materials. Reducing the need for these follow-up deliveries would be beneficial, but the crew argued that some unexpected delivery issues are inevitable.

The crew also noted that they were required to do less preassembly for the product used at Reroof B than at Reroof A. As a result, the crew preferred the product at Reroof B. The crew stated that assembling the Reroof A product was not intuitive or easy. Interviewees said that the Reroof A product combines features of roofing with traditional retrofit solar. As a result, this product did not utilize the same skill set that most roofers have. The crew argued that for RIPV products to gain market share within the reroofing market segment, the products need to be simpler and more like reroof installation. Crew members noted that the product installed in Reroof B meets that threshold, whereas the product installed in Reroof A does not.

4.1.2.2 Step 2: Underlayment and Fire-Resistance Lessons Learned

After the crew loads material to the roof, the next step is to apply conventional underlayment and/or fire-resistant slip sheets. For both Reroof A and Reroof B, the crew had to install underlayment for the entire roof. However, Reroof A required a separate fire-resistant slip sheet specific to the RIPV arrays.[8] Because Reroof B only required one layer of conventional underlayment, which also incorporated a fire rating consistent with that of the entire roof assembly, the crew was able to complete the process faster than for Reroof A.[9]

The crew pointed out opportunities for process improvements. All new roofs require underlayment; the key difference is whether RIPV roofing products use fire-resistant underlayment. The crew said that eliminating the need for two layers of underlayment (Reroof A) results in time savings (Reroof B). Working with a single underlayment layer can also mitigate the risk of running out of underlayment or fire-resistant slip sheet, a problem that occurred in Reroof A. The manufacturer provided a specified amount to cover slightly more than the PV area of the installation. However, if the roofers do not exactly measure for placement of the material, they risk running out. In Reroof B, the crew did not run into this issue, likely because only a single conventional underlayment was required to achieve a Class A fire rating, thereby matching the roof assembly. The supply issue at Reroof A did not cause delays because the crew turned to other installation activities while additional fire-resistant slip sheet was delivered.

4.1.2.3 Step 3: Flashings and PV Installation Lessons Learned

After the underlayment is laid, the crew installs the RIPV product. All reroof projects must navigate around penetrations through the roof, such as skylights and vents. This requires weather sealing around those penetrations, typically referred to as flashing. Installers have experience navigating these obstructions. Some RIPV products are treated as though they are large obstructions that require flashing around the perimeter of the PV system. Neither of the two RIPV products covered the entire roof. Asphalt shingles were installed in the roof areas not covered with RIPV, and thus the crew needed to install flashing specific to the PV arrays. How much RIPV was installed on each home was based on the home’s consumption, homeowner preference, and available roof area. Reroof A had three PV arrays on three of eight roof planes. Reroof B had eleven PV arrays spread across all seven roof planes. RIPV products have some

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[8] Additional fire-resistant slip sheets were not needed under the product in Reroof B.

[9] We are also underreporting the total time for underlayment at Reroof A, given that we were unable to track underlayment placement on some nonsolar roof planes. We estimate that this could add an additional 4–5 worker hours to the installation time.

limitations on where they can be placed. They cannot be installed near certain obstructions, at the roof's edge, into valleys, or in ridge setbacks and access pathways for firefighters. In some cases, this required the roofing crew to make precise measurements for PV product placement. Because the two products are installed differently, the remainder of this section outlines those processes separately.

For Reroof A, the crew installed three RIPV arrays of comparable size and configuration, ensuring a repeatable installation process on each roof plane. Each subarray required the same flashing process. In Reroof A, the PV product was elevated above the deck and was designed in such a way that roof irregularities (warp or wave) could be seen from the street if the system was not adjusted or leveled. A roof wave was present on one roof plane. It required the crew to pay more attention to level the product, which took the crew an additional 0.5 worker-hours to complete. There were fewer irregularities on the other two roof planes, so leveling was faster. For Reroof A, the City of San Jose, California (the permitting and inspection authority) required a rough (in-process) inspection of the product prior to flashing the RIPV system. The inspector provided a four-hour arrival window (9 a.m.–1 p.m.) but did not arrive until 1:30 p.m. Despite the delay, the crew was able to complete other installation activities while waiting. The inspection took approximately 0.33 worker-hours. The inspector approved the installation, which allowed the roofers to flash in the remainder of the system and complete the final installation activities associated with the modules, such as installing the junction box.

For Reroof A, the installer was required to connect the modules to each other in combinations of six, nine, or 12. This required the installer to interpret the plans and ensure that the correct modules were connected to each other. At first, the arrays were incorrectly configured. The install team had to return to the site, remove the top flashing, and access the module wiring to correctly configure the arrays. The site visit took a total of three worker-hours.

For Reroof B, the installation process changed significantly. The RIPV product's design and installation process were both different. Reroof B used a PV product that was installed flush with the deck, which more effectively masked roof irregularities compared to Reroof A. The installer was also learning to install new equipment for rapid shutdown code requirements. Both the sizes of the subarrays and the distances between the arrays required adjustment. Additional education and discussion between the installer and the product design team relative to the new electrical equipment caused a delay and necessitated a rework of the installation (~0.25 worker-hours for the rework and ~0.33 worker-hours for the discussion). Similarly, the design team did not correctly identify the placement of a vent, requiring additional guidance on where to place the product, given its proximity to the obstruction. These measurement challenges were significant because of the quantity of RIPV installed and the limited roof space available to meet the system size target.

The crew also ran out of two products, the sealant used for traditional roofing and PV and a product related to the rooftop electrical equipment. Although the team had to stop PV work, the product shortage did not delay the completion of the entire reroof because the crew moved to other roofing tasks. Materials were delivered the next day, and RIPV work resumed.

To complete the installation of each subarray, the crew had to install a final, top module different from those previously installed. The design of each subarray also determined the method to complete the installation of the final module. In at least one case, the installer used the wrong equipment. The error was quickly caught, limiting the rework needed. Array modules were all connected to each other in a continuous string. The final step for each subarray was to pull home runs for roof panel installations to a junction box.

Both crews provided feedback for efficiency improvements in Step 3. For Reroof A, the crew said that leveling the product so that it is aesthetically appealing from the street takes a significant amount of time. This leveling issue is unique to this product (given that it is attached above the roof deck) and is not typically confronted by solar or roofing crews. Although the contractor cannot correct most underlying roofing irregularities, homeowners still expect the final product to look as aesthetically appealing as possible.

Crew members pointed out that several factors that could affect a contractor's desire to begin installing this RIPV product, including installation delays (material shortages and redesign/rework), the attention to detail required for leveling, and the difficulty of certain wiring tasks (especially in the attic). The crew also noted that while this product is installed similarly to roofing, it is not the same. The required installation training and related expertise was not intuitive to them and could cause others to avoid installing the product, given that it could be considered too different from their regular roofing practices.[10] Finally, the roofers stated that the team would have completed this reroof project faster without RIPV, allowing them to move on to another job sooner. On the other hand, the contractor confirmed that these installations come with a higher overall cost and associated profit margin. Thus, there could be an incentive to install this higher-profit-margin product instead of a traditional roof without PV, despite the longer installation and training times needed.

For Reroof B, the install crew had a different perspective. Here, the crew confirmed that the installation was more like installing traditional shingles. As a result, the team underwent less training. The team confirmed that there was no need to level the product because it was flush with the deck, thereby saving time. Finally, the crew asserted that the PV product could be installed at almost the same pace as regular shingles, while still providing a higher cost/profit margin to the contractor. As a result, the crew suggested that other roofing and solar contractors might be interested in installing the Reroof B product over the Reroof A product, citing its ease of install and profit margin potential over that of a traditional asphalt shingle roof without PV.

4.1.2.4 Step 4: Wiring and Monitoring Lessons Learned

The last step in the process for both products is the final electrical and wiring work. Electrical work, and the associated installation time, can be influenced by crew size, homeowner preferences, ambient and attic temperature, roof characteristics, array design, and the design/configuration of the interior attic.

For Reroof A, the electrical requirements were simpler, given that there were only three subarrays, compared to 11 subarrays for Reroof B. The location of the electrical equipment

[10] The crew suggested that installation was easier after completing more installations, but the installation was still significantly different from their regular roofing installation practices. The crew considered this a significant barrier to other roofers installing the product.

relative to the subarrays also reduced the length of the conduit and the electrical wire run through the attic and the external wall. Even though the electrician was working alone and confirmed that it is more typical to work with an apprentice, the electrician was able to complete the roof, attic, and equipment installation within one day over the course of seven worker-hours. In this case, the electrician was employed by the RIPV product manufacturer.

For Reroof B, the electrical design was far more complex, partly due to homeowner preferences. The homeowner had a specific vision for where the external equipment was to be installed, requiring the electrical team to navigate electrical wire inside the external wall, which took significant time. The electrical work was completed over the course of three days, again by an electrical crew provided by the RIPV product manufacturer. The electrician noted that the complexity of the original design required more support staff to complete the project, beyond the typical two-person crew. For example, electrical equipment had to be installed for each subarray, requiring significant internal attic work. As a result, 2–3 crew members were dispatched to perform the electrical work (two crew members on days one and three, and three crew members on day two). At the same time, the electrician pointed out that the standard electrical design and installation approach for the product at Reroof B, particularly relating to rapid shutdown compliance, had changed. As a result, the team had less experience in completing the electrical work for this product. It is likely that as the electrical team becomes familiar with the new installation process, related timelines may decrease. Finally, the equipment manufacturer was doing a training video recording of the electrical work, which also influenced the overall time.

The electrical crews had limited suggestions for how to improve the installation processes for these products. This is because they were using points of interconnection, inverters, and electrical equipment that are similar to those used in the rest of the solar industry. As a result, improvements in electrical design that are under development within the broader PV industry could also have similar installation timeline benefits when applied to RIPV.

As noted, the primary contractor did not complete the balance-of-system electrical work themselves; instead, the product manufacturer provided the electrical support. Being able to outsource this work to the electricians working for the RIPV manufacturer favorably influenced the primary contractor's decision to offer the product, because the primary contractor could not support an electrician full-time (most roofing contractors do not keep an electrician on staff). In the future, residential RIPV products that minimize electrical work and provide electrician support services (or services of another subcontractor specialized in this equipment) may be essential to encouraging widespread adoption. In contrast, contractors who primarily do roofing and only limited PV may not have a sufficient workload to justify staffing an electrician. As the volume of RIPV installation grows, and RIPV products better match the practices of roofers, roofing contractors may be best positioned to add those products to traditional roofing. The reverse may also be true for solar contractors seeking to add RIPV to their offerings.

4.2 New Construction Time and Motion Results

Unlike in the reroofing cases, the solar crews did not complete new construction solar installations on consecutive days. Rather, the crews completed parts of steps 1–4 on one day and returned to the same site several weeks or months later to install the modules and complete installation once all exterior/painting work was completed. Given this schedule, NREL was not able to conduct a complete observation and instead observed crews complete the "Day 1" installation activities (before exterior/painting work) and "Day 2" installation activities (after exterior/painting work) on separate homes. In total, we collected installation data from 19 new homes across four communities near Sacramento, California. Although each of these projects installed the same product, the project characteristics and crews varied (Table 2).[11]

Table 2. New Construction Field Observations

	System Size (kW)	Array Area (sq ft)	Module Count	Mounting Planes	Crew Size	Rectangular Shape	Temp (°F)	Roof Pitch	Roofing Material Obstructing Work Area - Yes/No	Building Floors
1	4.2	215	12	2	2	No	100	6:12	Yes	2
2	3.5	179	10	1	5	No	100	5:12	No	2
3	3.15	161	9	1	5	Yes	100	5:12	No	2
4	4.2	215	12	1	3	No	89	4:12	Yes	2
5	3.85	197	11	1	3	No	89	4:12	Yes	1
6	3.15	161	9	1	3	No	79	5:12	No	1
7	3.5	179	10	1	3	Yes	76	5:12	No	2
8	3.5	179	10	1	3	Yes	73	5:12	No	2
9	3.5	179	10	1	4	Yes	77	5:12	Yes	2
10	3.5	179	10	1	4	Yes	77	5:12	Yes	2
11	3.15	161	9	1	4	No	77	5:12	Yes	1
12	3.85	197	11	1	1.5	No	71	4:12	No	2
13	4.2	215	12	2	1.5	No	71	4.5:12	No	2
14	3.85	197	11	2	1.5	No	84	4:12	No	2
15	3.85	197	11	2	1.5	No	84	4:12	No	2
16	4.55	233	13	3	1.5	No	84	4:12	No	2
17	4.55	233	13	3	1.5	No	84	4:12	No	2
18	3.85	197	11	2	3	No	66	4:12	No	2
19	3.85	197	11	1	3	No	73	4:12	No	2

[11] This was a third unique product observed, in addition to the products installed at Reroof A and Reroof B.

4.2.1 Roofing-Integrated PV Installation Activities

Given that we did not gather complete installation activity data for any of the 19 homes, we estimated total installation times by pairing 13 Day 1 observations with Day 2 observations from homes with similar characteristics. We paired observations based on installation mounting planes (1–3), home floors (1 or 2), and, where possible, array shape (rectangular or not). For example, we observed Day 1 installation activities at the first site listed in Table 2, but not Day 2 activities. To estimate the installation time for Day 2 at site 1, we averaged the installation times from three similar homes: sites 13, 14, and 15. These homes were selected because they matched site 1 on mounting planes (2), array shape (rectangular), and home floors (2).[12]

Across the 13 observations, Step 1 took 1.5–4.3 worker-hours (0.4–1.2/kW), with a median duration of 2.6 worker-hours (0.8/kW); Step 2 took 0.4–1.5 worker-hours (0.1–0.5/kW), with a median duration of 0.7 worker-hours (0.2/kW); Step 3 took 4.9–11.1 worker-hours (1.3–3.2/kW), with a median duration of 5.7 worker-hours (1.6/kW); and Step 4 took 2–5.2 worker-hours (0.5–1.6/kW), with a median duration of 3.1 worker-hours (1/kW). The total time across all four steps ranged from 9.45–19.75 worker-hours (2.6–5.6/kW), with a median of 13.2 worker-hours (3.4/kW). Figure 5 depicts these ranges by step. Given that we observed many more new construction sites than reroofing sites, the following sections discuss the activities completed within each step across all sites, as opposed to at individual sites.

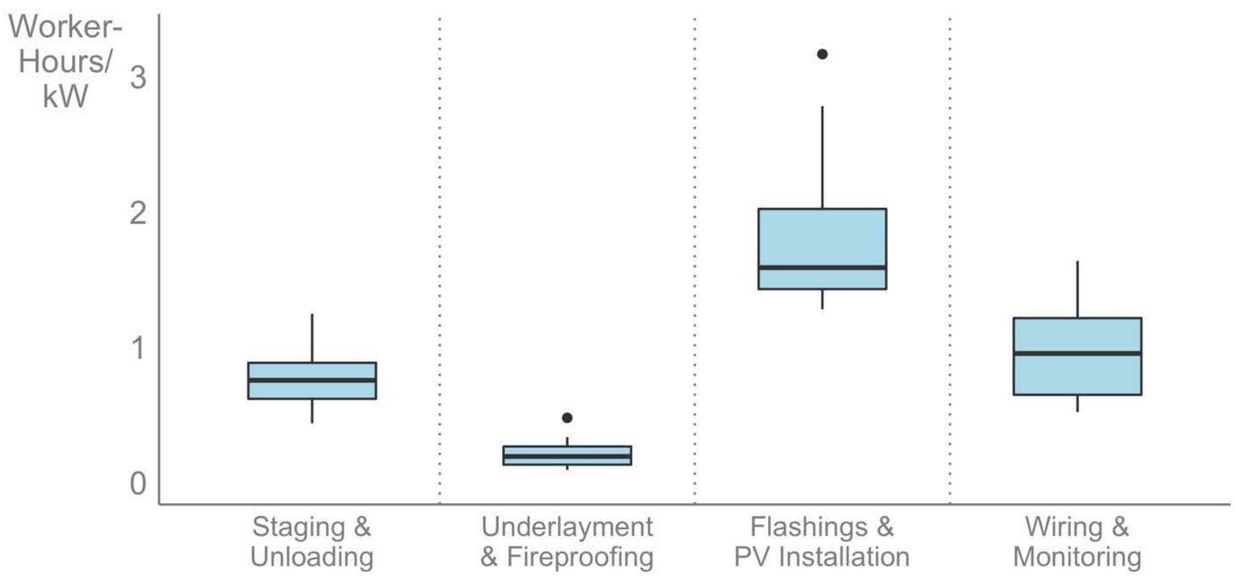

Figure 5. Distributions of step durations for new construction sites.

Middle lines are medians, boxes are interquartile ranges, and black dots represent statistical outliers.

4.2.1.1 Step 1: Staging and Unloading Lessons Learned

On Day 1, the crew arrived on site in one truck with all the material they expected to need to complete installation activities for 2–3 new homes. The crew began by staging, unloading, and

[12] This same approach was taken for matching the other projects, and the public data file describes this methodology in more detail.

roof preparation to prepare the site for the future installation of modules (Day 2). In each case, a separate roofing crew prepared the roof with one layer of underlayment. The solar crew was tasked with installing the fire-resistant slip sheet and any solar mounting/support equipment. This equipment was transported to the roof by the crew members, as opposed to a construction crane. Staging was typically completed by 2–5 crew members.

In 13 observations, the roofs were cleared with just underlayment on the roof. In the remaining six cases, the roofing material was present on the roof and was often stored in the location where the RIPV was to be installed. When this occurred, the team had to make room for their work, which added about 0.5 worker-hours to this stage. In at least one other case, a plumbing vent was installed in the array area, requiring discussion between the crew and the design team to determine next steps; ultimately the vent was removed.

Once the crew returned to complete the installation of the modules (Day 2), a smaller, three-person crew was needed. In all observations, the PV modules were transported to the roof via a crane. One individual was stationed on the roof to receive each module, while another loaded the modules onto the crane from the ground. This process took 1.5 worker-hours on average.[13]

Crew members had few suggestions to improve this stage in the process (either for Day 1 or Day 2), especially when considering RIPV. For example, better communication between contractors could help reduce the delays associated with improperly placed vents or materials in locations where the PV installation is to occur, but this is also be true of conventional PV systems. The crew did mention that they preferred the delivery of the modules to the roof via crane, and that a crane could potentially be used for the materials installed on Day 1. It is unclear how much this could improve loading times, especially in instances where the crew must make space on the roof for the material.

4.2.1.2 Step 2: Underlayment and Fire-Resistance Lessons Learned

As noted, the roofing crew, rather than the solar contractor, installs the roof underlayment. On Day 1, the solar crew is required to install the fire-resistant material that must cover the area on which the array is to be installed. This requires measuring the area and ensuring the array is installed per the plan. At this time, the crew can also identify whether the plan matches the unique roof characteristics. For example, during this measurement phase, they may identify that a roofing vent or other obstruction is inside or too close to the planned array area. When no obstructions are identified, and there are few subarrays, this step can take 0.7–2.7 worker-hours.[14]

Interviews and observations allowed us to identify a couple of savings opportunities at this stage. First, crew members suggested that it would be valuable to have more information from the homebuilder regarding the building construction schedule so that they could better time their roof prep work. For example, the contractors could more easily complete their tasks prior to roofing material being laid or otherwise staged on the roof. The crew was working while either the roofing material was staged on the roof, or while the roofing crew was actively installing the

[13] We are excluding the crane operator, but if you add that individual, the average increases to 2.25 worker-hours.
[14] This reflects a crew of two or four, depending on the site.

material. If less material and fewer individuals are on the roof, the work can be completed faster, with fewer risks of rework.

Another opportunity for savings relates to the underlayment installed. As was done for Reroof B, the roofing crew could have installed one layer of underlayment that also served the fire-resistance function. In this case, the roofing crew installed the first layer of underlayment and the solar crew installed a fire-resistant underlayment on top. Had the roofing crew installed the fire-resistant underlayment instead of the second solar crew, it might have reduced installation labor and material costs.

Finally, a separate solar crew conducted these steps, but it might be possible for the crew that installed the roof to perform these functions, if they were properly trained. This would eliminate the need for a separate crew, and perhaps help address manual staging issues and the need for two separate crews to come to the site for the roofing and Day 1 solar installation activities.

4.2.1.3 Step 3: Flashings and Mounting Equipment Installation Lessons Learned

On Day 1, the crews installed mounting equipment for the PV modules; this product was not direct-to-deck. The crews then flashed around that equipment, as required for the RIPV products in the reroof cases. In some cases, where the design was not a standard rectangular shape, the configuration of the subarray required adjustments to the mounting equipment that took additional time to install, especially for each design variation required for each subarray. This crew also installed the junction box to allow for an easier process for the final electrical work completed on Day 2. The team also performed quality checks at the end of this step, prior to leaving the roof.[15]

At this stage, there were noticeable differences in crews' installation times of the mounting equipment (4.9–10.55 worker-hours). Interviewees confirmed that crew training, roof complexity, available working space, and experience can all influence these installation timelines. As noted, roofing material and roofing crew presence on the roof can also cause delays when installing both the mounting equipment and the associated flashing. Further, once the mounting equipment was placed, the crew could walk on that equipment, but heat could result in a more slippery walking surface. Here again, it was clear that a smaller crew size may be valuable given the limited working space.

As noted, the subarray location and shape can also influence mounting installation timelines. In this instance, the solar contractor had little ability to influence the home roof designs, thereby making it challenging to both maximize solar potential and reduce installation costs. Interviewees suggested that installation timelines could be reduced if the solar contractor were more involved in the design phase of the installation process.

As was the case in the Reroof A and B observations, there were instances where crews lacked sufficient installation materials to complete the work. In one instance, a crew did not have

[15] Given that the crew was a subcontractor, a quality manager from the solar contract conducted quality checks—typically after installations—to ensure the product was installed per the manufacturer's instructions and design plan. This individual can conduct multiple quality checks in one site visit to a new home community, and an individual quality check can be completed in less than 10 minutes.

sufficient material to install the mounting equipment, and a crew member had to leave the site to collect that material. That individual was gone for 2 hours and 55 minutes, and upon return was only able to support the team for the remaining 2 hours of the workday.

Finally, there is an opportunity to eliminate a portion of Step 3 related to the mounting equipment. In this case, the solar modules are not installed direct-to-deck. As a result, a two-step installation process is required. As noted, other RIPV products do not require such mounting equipment, although flashing is always required for the products observed. Although eliminating this equipment could reduce installation times, it could require innovation related to the solar module installed. Changes to the module could require developing unique supply chains associated with that product, while also increasing the cost such that the installation time savings are cancelled or exceeded by the costs of innovation elsewhere.

A second, smaller crew returned to the site for installation of the modules. In all instances, one individual was on the roof installing the modules, which included wiring the modules together. The individual also tracked the serial number of each module installed to enable more efficient inspections and quality checks by the product manufacturer. Installing the modules took 3.8 worker hours on average. One crew of two individuals and one support staff stationed on the ground completed six homes on the day of the NREL observations. However, the crew confirmed that it is more typical to complete 3–4 homes per day. The crew did not have many suggestions for cost savings/improvements for installing the modules. In most cases, the installation of modules took 2.8–3.8 worker-hours from start to finish. There were some wiring-related delays (to ensure the wires did not dangle from the modules and the modules were correctly connected to each other), but these delays are still reflected within the 1–3 worker-hours installation timeline.

4.2.1.4 Step 4: Wiring and Monitoring Lessons Learned

On Day 1, the team completed the rough wiring, running wire from the roof to the planned location of the main panel. Rough wiring can occur any time after the home is framed out, but in our observations, it was typically completed in parallel with Step 1 and Step 2. The roofing crew would assign one individual to rough wire the home or set of homes that were on the schedule for completion that day. The crews confirmed that one individual could rough wire four or more homes in one day if all were ready at the same time. In our observations, no more than three homes were ready for rough wiring at a given time. As noted, the other crew members (1–4) completed the staging and roof prep processes.

The crews did not offer suggestions to improve rough wiring activities. Like in the reroof case, the wiring of this product was not significantly different from that of traditional solar. Further, rough wiring when the home is framed but not drywalled in makes it easier to run the wire efficiently. This benefit exists for both RIPV and conventional racked and mounted PV.[16]

[16] The NREL team was unable to observe the final wiring of the system at the main panel for any of the observations completed. As a result, our reported timing for wiring relative to entire installation is incomplete. Even so, we tracked junction box wiring self-inspection, voltage testing and labeling. Given the limited nature of the activities we did observe, we did not gather lessons learned for this stage of the process.

4.2.2 Installation Characteristics and Installation Timeline Impacts

Given that we had more data points for the new construction market segment, it was possible to explore correlations between installation complexity and installation timelines. This analysis is shown in Figure 6. The figure shows the correlations between the complexity variables and installation times in terms of worker-hours per kW installed. The analysis has limited statistical power due to the small sample size (N = 19). Our data sample suggests a significant positive correlation between crew size and installation times per kW and a significant inverse correlation between system size and installation times per kW. The latter result is consistent with economies of scale. The remaining complexity variables depicted in Figure 6 did not exhibit statistically significant correlations in our sample.

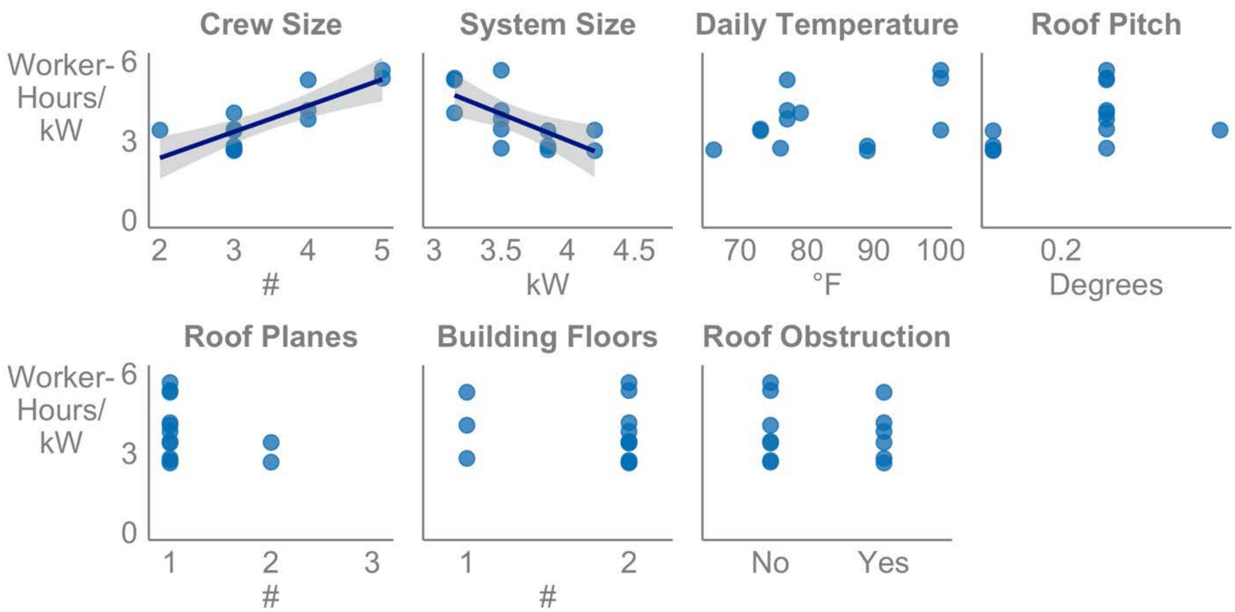

Figure 6. Correlations between installation characteristics and per-kW installation times.

Trend lines are depicted for statistically significant correlations based on univariate linear regressions ($p < 0.05$).

Figure 6 generates two findings that are worth further exploration. First, most of the analyzed complexity variables do not significantly affect installation times, in contrast to the hypothesis from Quintanilla et al. (2014) that project complexity likely increases installation times. While it is possible that such impacts could be measured in larger statistical samples, our analysis suggests that crews efficiently navigate these complexities. Second, we find that crew size is correlated with longer installation times per kW. This correlation may partly reflect the fact that the larger crews were not equally skilled as the smaller crews included within the study. Often, the larger crews were training 2–3 new staff, possibly increasing installation times. However, our observations also suggest that large installation crews can be inefficient, such as when insufficient roof space limits a crew's ability to navigate the roof (e.g., few access points, steep roof pitch, and obstructions).

5 Discussion

In this section, we discuss three topics related to our time and motion studies and informed by insights from our TAG meetings: (1) a comparison of RIPV installation times and conventional rooftop PV installation times, (2) RIPV cost reduction opportunities, and (3) related market opportunities, barriers, and potential solutions.

5.1 Roofing-Integrated PV and Conventional Solar Installation Time Comparison

The only comparable time and motion study of conventional retrofit solar, to our knowledge, is the analysis presented in Quintanilla et al. (2014).[17] Quintanilla et al. implement a time and motion study of one residential rooftop PV system and one nonresidential PV system. The small sample size of the Quintanilla et al. study is problematic, given that we do not know whether the observations were more broadly representative. Further, the observations in the Quintanilla et al. study occurred nearly a decade before our study. It is likely that typical conventional rooftop PV installation timelines have declined in the interim. With these caveats in mind, Figure 7 compares installation timelines across system types in per-kW terms. The reroofing timelines are comparable to the conventional PV timeline, whereas the average new construction timeline is about half as long as the conventional and integrated PV reroofing timelines. The results suggest that a typical conventional rooftop PV system takes about 2.6 working days to install, compared to 2.4 working days for RIPV during reroofing, and 1.4 working days for RIPV during new construction (based on a 6-kW system, two-worker crew, and eight-hour working days).

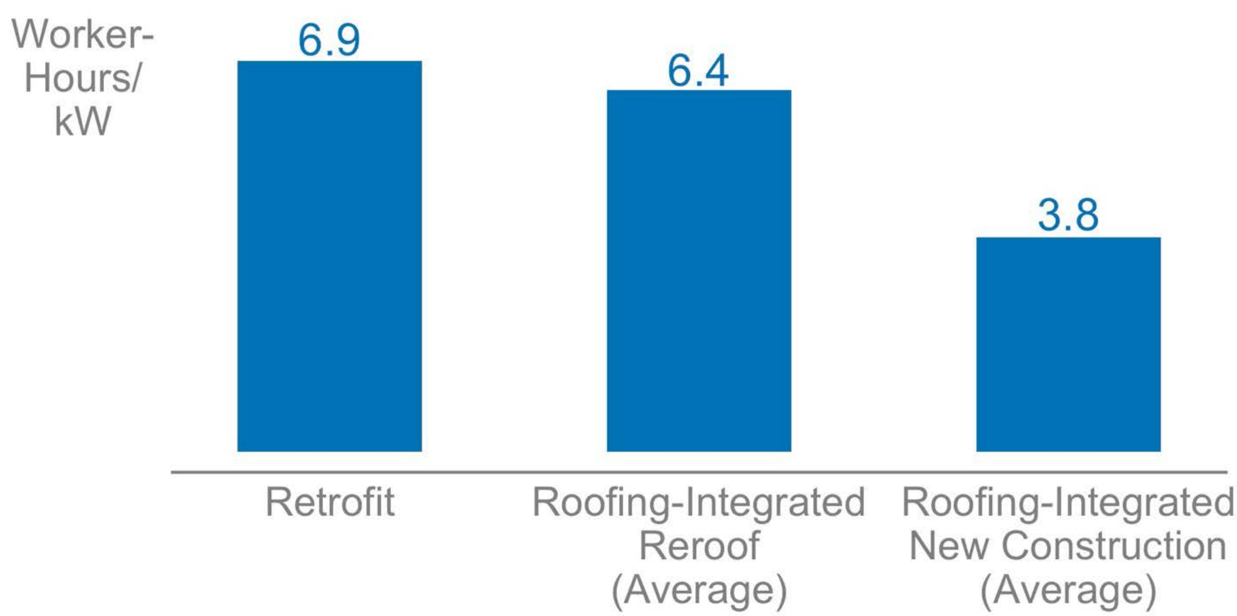

Figure 7. Comparison of average total installation times across system types.

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[17] Morris et al. (2013) present results based on a broader sample of time and motion studies. However, Morris et al. present all results in terms of value ($/W) rather than time.

The comparison in Figure 7 is based on timelines for solar installation processes. This comparison understates the total process time savings by excluding synergies between RIPV installation, reroofing, and construction. According to feedback from installation crews, RIPV installations during reroofing may not always add time to roofing construction timelines. As a result, RIPV installations can save time by making two upgrades in less time than doing them separately, at least in the reroofing context. Future research is required to precisely quantify the time savings associated with these synergies and any associated with new construction.

5.2 BIPV Cost Reduction Opportunities

Our field observations and interviews yielded various cost reduction opportunities for RIPV installations by step (see Table 3).

Table 3. Cost Reduction Opportunities

Step	Key Observations	Cost Reduction Opportunities
1 – Staging and Unloading	Supply chain issues led to staging delays; some sites used construction cranes to haul materials to roofs.	Integrated supply chains across PV installation, roofing, and construction could reduce staging delays; construction cranes may be cost-efficient for certain sites.
2 – Fire-Resistant Underlayment	RIPV may result in additional underlayment requirements.	Installing a single fire-resistant underlayment layer can reduce costs in some cases; better coordination with roofers and home designers can reduce rework during roofing installation.
3 – Flashings and PV Installation	Flashings and PV installation is the longest step; RIPV product design affects time requirements.	RIPV products that more closely mimic conventional shingles (e.g., direct-to-deck) are typically quicker to install and easier for roofers to learn to install.
4 – Wiring and Monitoring	Product design and homeowner preferences influence wiring installation times.	For small- and medium-scale installers, outsourcing wiring to an electrical contractor may be a cost-effective arrangement.

5.3 RIPV Market Opportunities

Installation time is a critical factor in identifying cost reduction opportunities. Interviewees suggested two other factors that might influence the likelihood that RIPV products will gain market share:

- New construction mandates: RIPV could be incorporated into requirements for solar installations or solar-ready construction in building codes. Alternatively, homebuilders could be required to inform consumers about these products as an option to meet building code requirements for solar. Given the aesthetic benefits of these products, homeowners may be more likely to elect for RIPV than racked and mounted PV, thereby increasing market deployment.

- Reroofing RIPV deployment: Homeowners typically must replace their roof on a regular schedule. Some RIPV products have been designed such that roofers can install them efficiently and at a higher profit margin than a standalone roof (as shown in Reroof B).

This can make roofers more likely to install or market them to customers, particularly as compared to the traditional racked and mounted PV that they are less comfortable installing. This could result in RIPV products gaining market share, with lower acquisition costs, without the need for additional mandates or policy incentives. However, some stakeholders suggested that incentives, training programs, and decision support tools targeted at roofers may be necessary to open this market opportunity.

5.4 Roofing-Integrated PV Market Barriers and Potential Solutions

Although a variety of opportunities exist that could result in increased RIPV deployment, truly unlocking these opportunities will require addressing the barriers identified by interviewees, which are summarized in Table 4.

Table 4. Barriers to Widespread RIPV Deployment

Barrier	Description
Cost Uncertainties/Trade-Offs	Interviewees said that customers often focus on the sticker price or perceived price of RIPV, but not on roofing and solar as a cumulative cost. No neutral, third-party roofing or PV cost tools exist that can be used to compare RIPV to a standalone roof, a roof with PV at the time of reroofing, or a roof with PV installed after reroofing to help customers understand these trade-offs. This results in cost uncertainties that can reduce customer interest in RIPV.
Permitting, Inspection, and Code Enforcement	RIPV products are rapidly evolving, and so are the fire and electrical building code requirements related to them. Interviewees asserted that local government permitting and/or inspection staff often do not have training or familiarity with these RIPV code requirements, causing installation delays and associated costs. More training for local governments on RIPV code requirements and continued improvement in the clarity of model building codes could help reduce delays/costs.
Qualified and Trained Labor	Installing RIPV products requires unique training on these products, and rapid product evolution also requires retraining staff. Reducing the complexity of these products and/or reducing product design changes can limit training needs.
Architectural and Design Integration	RIPV technologies are not incorporated into architectural design software. This can increase the costs of adding RIPV after the architectural design is complete, as compared to incorporating RIPV into the initial design process. Once a design has been selected, it can be more difficult to add RIPV into the design, especially if the customer has already approved the design.
Roofing Industry Integration	Although some RIPV products have been developed to be installed by traditional roofing crews, others have not. Encouraging roofers to offer these products can be difficult, given that roofers may not be open to adjusting their sales, installation, and related business models to offer these products. Convincing roofers will likely require proving ease of installation and higher profit margins and ensuring that warranties are clear.
Product Manufacturing and Supply Chain	RIPV products differ from traditional racked and mounted PV, requiring the development of their own unique manufacturing and related supply chain industries, which are still in their infancy. This can result in higher-cost products and/or delivery delays. Supply chain channels can be especially problematic for reroofing and new construction markets that are time-sensitive.
Awareness and Education	Roofers, new homebuilders, policymakers, code officials, homeowners, and a variety of other stakeholders do not know about the range of RIPV products that are available today. Those that are familiar with these products may assume that they are similar to earlier products. Education or reeducation of key decision makers may be necessary for the new generation of RIPV products to gain market share.

Our field observation partners and interviewees also identified a variety of solutions and pathways to address or mitigate RIPV barriers. These solutions can address several barriers at once. They can also improve BIPV market competitiveness generally, beyond just RIPV. In these cases, we describe these solutions relative to BIPV broadly, as opposed to just RIPV. Finally, we present these solutions as a list, but this list was not prioritized by interviewees, and rather is a menu of options that can help address barriers:

- **Decision support tools:** National labs and other neutral, third-party tool developers could incorporate specific functions for modeling RIPV and other BIPV system installation processes and costs into existing or new decision support tools. For instance, renewable energy decision support tools such as the System Advisor Model could be expanded to include a variety of BIPV functionalities.[18]

- **Workforce training:** Solar workforce training initiatives and programs could incorporate specific workforce goals related to BIPV installations. For instance, residential solar or roofing apprenticeship programs could include specific training related to RIPV installations.

- **Code reform:** Local permitting and code authorities could issue clearer guidance and language around relevant fire, electrical, and structural codes relative to each BIPV product type and use case.

- **Informational campaigns:** BIPV stakeholders and trusted neutral third parties could promote awareness of BIPV products, how they perform, and how they are different from older models.

- **Manufacturing and supply chains:** RIPV products represent an opportunity to build domestic manufacturing and supply chains to support them. RIPV supply chains and manufacturing facilities must be developed to meet the needs of the market, and these facilities could be sited domestically. Interviewees noted that domestic manufacturing may have a competitive advantage, given the transportation costs associated with this heavier equipment and custom design of the products.

- **BIPV consortium working group:** Given that BIPV products can be deployed across a variety of industries, including roofing, new construction, glass, and glazing, among others, interviewees suggested that a consortium of BIPV stakeholders could be formed to identify and address challenges across the industry. This consortium could also serve as a BIPV data repository that can better address misinformation and/or outdated information on BIPV products and markets, while also covering critical topics such as fire safety, electrical, and code standardization.

[18] More information about the System Advisor Model can be accessed here: https://sam.nrel.gov/.

6 Conclusion

Previous studies have demonstrated how residential RIPV could be more cost-effectively installed than conventional rooftop PV. Residential RIPV cost savings and synergies with roofing and construction could help optimize the overall role of PV in building decarbonization. However, RIPV has yet to realize these cost savings, and residential BIPV market uptake remains well below that of conventional rooftop PV. In this study, we use time and motion analysis to study residential RIPV installation processes and identify potential cost reduction opportunities. We implemented the time and motion studies at two reroofing sites and 19 new construction sites in California. We arrived at three primary conclusions:

- Flashing and PV system installation is the most time-intensive stage of the RIPV installation process. PV system installation and flashing accounts for around 60% of the installation process for an average system and is consistent with the findings of Quintanilla et al. (2014) for conventional systems.

- Our time and motion results suggest that RIPV systems can be installed more quickly than conventional rooftop PV systems due to synergies with reroofing and new construction. The average total process times in our study were 6.4 and 3.5 worker-hours per kW for the reroofing and new construction sites, respectively, compared to an estimated 6.9 worker-hours per kW for conventional, retrofit residential rooftop PV from a previous study (Quintanilla et al., 2014). However, that study was completed in 2014, and a more recent analysis is necessary to ensure that installation times are still comparable. It is possible that conventional installation times have decreased, thereby influencing this conclusion.

- The field observations and interviewees identified several cost reduction opportunities. A commonly observed opportunity was further integration between the PV installation, roofing, and new construction industries. Better integration could reduce supply chain redundancies and drive more efficient site design, staging, and installation. Integration could be facilitated by RIPV products that more closely resemble conventional roofing and construction materials.

We conclude by noting the limitations of this study and how future research could build on our results. Our study was based on a relatively small sample of field sites and contractors working exclusively in California. Future work could expand on these results by applying time and motion analysis or similar methodologies over a larger and more diverse sample of technologies (roofing-integrated and conventional), sites, contractors, and geographies. Further, although we compared our results to previous research on conventional rooftop PV, our study lacked a true "control" group with which to compare results. Future research could more systematically evaluate process and time differences between different PV installation methods, such as conventional rooftop PV on existing buildings, conventional rooftop PV during reroofing, conventional rooftop PV during new construction, RIPV during reroofing, and RIPV during new construction. A systematic analysis of distinct PV installation methods will help identify specific ways to hone installation processes, reduce costs, and maximize the role of these products in building decarbonization.

References

Ardani, K., J.J. Cook, R. Fu, R. Margolis. 2018. *Cost-Reduction Roadmap for Residential Solar Photovoltaics (PV), 2017–2030*. Golden, CO: NREL. NREL/TP-6A20-70748. https://www.nrel.gov/docs/fy18osti/70748.pdf.

Amo Awuku, S., A. Bennadji, F. Muhammad-Sukki, N. Sellami. 2021. "Myth or gold? The power of aesthetics in the adoption of building integrated photovoltaics (BIPVs)." *Energy Nexus* 4: 100021.

Barbose, G., N. Darghouth, E. O'Shaughnessy, S. Forrester. 2021. *Tracking the Sun: 2021 Edition*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Bodini, Nicola, Dino Zardi, and Julie K. Lundquist. 2017. "Three-Dimensional Structure of Wind Turbine Wakes as Measured by Scanning Lidar." *Atmospheric Measurement Techniques* 10: 2881–2896. https://doi.org/10.5194/amt-10-2881-2017.

Davis. M., B. White, R. Goldstein, S. Leyva Martinez, S. Chopra, K. Goss, M. Sahd, X. Sun, S. Rumery, C. Silver, J. Baca. 2022. *U.S. Solar Market Insight: 2021 Year in review*. Wood Mackenzie.

DOE. 2021. *Solar Futures Study*. Washington, D.C.: U.S. Department of Energy. https://www.energy.gov/sites/default/files/2021-09/Solar%20Futures%20Study.pdf.

EIA. 2021. *U.S. Energy Consumption by Source and Sector*. U.S. Energy Information Administration.

Heinstein, P., C. Ballif, L.E. Perret-Aebi. 2013. "Building Integrated Photovoltaics (BIPV): Review, Potentials, Barriers and Myths." *Green* 3 (2): 125–156.

James, T., A. Goodrich, M. Woodhouse, R. Margolis, S. Ong. 2011. *Building-Integrated Photovoltaics (BIPV) in the Residential Sector: An Analysis of Installed Rooftop System Prices*. Golden, CO: NREL. NREL/TP-6A20-53103. https://www.nrel.gov/docs/fy12osti/53103.pdf.

Leung, J. 2018. *Decarbonizing U.S. Buildings*. Arlington, VA: Center for Climate and Energy Solutions.

Moezzi, M., A. Ingle, L. Lutzenhiser, B. Sigrin. 2017. *A Non-Modeling Exploration of Rooftop Solar Photovoltaic Adoption and Non-Adoption*. Golden, CO: NREL. NREL/SR-6A20-67727.

Morris, J., K. Calhoun, J. Goodman, D. Seif. 2013. *Reducing Solar PV Soft Costs: A Focuson Installation Labor*. Boulder, CO: Rocky Mountain Institute.

Norton, B., P.C. Eames, T.K. Mallick, M. Jun Huang, S.J. McCormack, J.D. Mondol, Y.G. Yohanis. 2011. "Enhancing the performance of building integrated photovoltaics." *Solar Energy* 85: 1629–1664.

Quintanilla, N., S. Yarmohammadi, B. Ashuri, M.M. Wren, M.S. Shahandashti, J. Goodman. 2014. "Time and motion study for solar contractors." *Construction Research Congress*: 817–826.

Tripathy, M., P.K. Sadhu, S.K. Panda. 2016. "A critical review on building integrated photovoltaic products and their applications." *Renewable and Sustainable Energy Reviews* 61: 451–465.

Zhu, Lei, Jacob Holden, Eric Wood, and Jeffrey Gender. 2017. "Green Routing Fuel Saving Opportunity Assessment: A Case Study Using Large-Scale Real-World Travel Data." Paper presented at the 2017 IEEE Intelligent Vehicles Symposium (IV), Los Angeles, California, June 11–14. https://doi.org/10.1109/IVS.2017.7995882.