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Prevention through Design (PtD) to Make Solar-Ready Houses Safe for Solar Workers

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Abstract

Solar-ready designs have become a new standard for residential houses in preparation for the future installation of a solar system on their roofs. However, the current literature largely lacks considerations of the safety of solar installers, and hence, the application of Prevention through Design (PtD) to solar-ready houses has been significantly limited. In response, the main objective of this study is to develop a PtD design checklist and BIM (Building Information Modeling) models for new solar-ready houses. The study involved interviews and a survey with industry professionals, and case studies of existing solar-ready houses. The study results are expected to support designers to proactively get involved in promoting PtD for solar-ready houses—through the use of the checklist and BIM models.

Key Findings

The key results of this study include:

- Development of a PtD design checklist through a series of interviews and an online survey. The design features in the checklist include Solar Zone Features, Installation Features, and Electrical Features.
- Development of three BIM models. The models were developed as illustrative examples of solar-ready houses featuring design components that are included in the checklist.

The key findings of this study are:

- The current solar-ready codes and requirements are mainly focused on optimizing energy production by securing solar zones for the future installation of a solar system, while lacking considerations of safety of those who will install the system.
- The identified design features include seven components in three categories:
 - *Solar Zone Features*: Solar Zone Area, Solar Zone Material, and Solar Zone Pitch
 - *Installation Features*: Fall Protection and Roof Access
 - *Electrical Features*: Conduit and Inverter
- This study provides evidence that PtD can improve solar installer safety by proactively eliminating safety hazards and mitigating risk — verified through interviews, surveys, and case studies.

Introduction

Solar installations in the U.S. have increased dramatically in recent years. Specific to the residential sector, the number of houses with solar panels increased exponentially, from 30,000 homes to 1 million homes in 10 years from 2006 to 2016, with record growth in 2015 (Harrington 2015; GTM/SEIA 2017). Most solar installations in the residential sector happen on small, sloped roofs, which exposes installers to unique safety concerns in terms of existing roof conditions. Furthermore, the installation processes involving roofing, electrical and mechanical work, and information technology (IT) create hazards for solar installers. To prevent those unique safety hazards and risks, especially related to fall hazards during solar installations, a previous Small Study conducted by the researchers investigated how Prevention through Design (PtD) can be applied to solar design and installation for small buildings (Lee et al. 2017). The small study led to the identification of seven PtD attributes based on roof conditions and rooftop solar system (hereafter solar system) characteristics: roofing material, roof slope, roof accessory, panel layout, fall protection system, lifting method, and electrical system. Based on the identified PtD attributes, the researchers developed a PtD protocol for solar installer safety. While the previous study focused on applying PtD to existing houses, the previous study actually revealed that to maximize the efficacy of PtD for solar installer safety, the application of PtD should also be considered for new houses as a way to make them both solar-ready and safe.

In recent years, making new commercial buildings solar-ready has become a requirement in cities like Seattle and San Francisco. Some cities have also started mandating solar-ready buildings in the residential sector as well. For example, the Phoenix Building Construction Code added solar-ready provisions on a proposed amendment for detached dwellings in the 2018 International Residential Code (IRC). Furthermore, California's 2019 residential building energy efficiency standards (which become effective on Jan. 1, 2020) include solar installation mandates and solar-ready provisions for new residential buildings (Pyper 2018). Currently, guidelines are available to support the design of solar-ready buildings (e.g., EPA 2011; Lisell et al. 2009; Watson et al. 2012). However, current literature largely lacks considerations of the safety of solar installers, and hence, the application of PtD to solar-ready houses has been significantly limited.

In response, this study aims to fill this knowledge gap by developing a design checklist to apply PtD to the design of houses as a way to make them both solar-ready and safer for solar installations. The results of the previous CPWR study (Lee et al. 2017) have contributed to the successful completion of the present study by serving as a foundation for the development of the design checklist. As an extension of the previous study, the present study is expected to contribute to promoting the concept of PtD during the design of new green buildings that pursue sustainability and energy efficiency.

Research Objectives

The overall objective of the study was to develop knowledge and resources that support the application of PtD to the design of new solar-ready houses. The study is expected to provide evidence that (1) PtD can improve solar installer safety by proactively eliminating safety hazards and mitigating risk—verified through interviews, surveys, and case studies; and (2) designers can proactively get involved in promoting PtD for solar-ready houses through the use of the checklist and BIM models.

Using mixed methods, the specific tasks conducted for the study are as follows:

1. Perform literature review
2. Investigate design features for solar safety
3. Categorize the components of solar-ready houses
4. Perform case studies of existing solar-ready houses
5. Develop a PtD design checklist and BIM (Building Information Modeling) models for new solar-ready houses
6. Obtain industry feedback on the checklist and model
7. Develop and submit a final report

Perform Literature Review

An extensive literature review was conducted to identify (1) design components and construction operations of solar-ready houses, and (2) safety hazards and risk mitigation measures for solar systems. Seven PtD components identified in the previous study (Lee et al. 2017) are: roofing material, roof slope, roof accessories, panel layout, fall protection system, lifting method, and electric system. These components were identified with respect to several types of safety hazards inherent in solar installation on a roof: falling (NY Daily News 2017), tripping, and electrocution (Valents 2015). The hazards are prevalent specifically when working on rooftops due to a variety of factors including, but not limited to, stability of the roof, placement of the ladder, weather conditions, openings in the roof, proximity of the roof edges, and pitch of the roof (Hamid et al. 2003). These factors were considered for the next steps in the development of features for a PtD design checklist of solar-ready houses.

In addition, the researchers reviewed energy codes to identify any required safety features. However, it was found that current codes mainly focused on energy production. Some states have adopted or developed energy codes from the federal government's energy standards, such as the International Energy Conservation Code (IECC). The newly updated 2018 IECC has APPENDIX RA solar-ready provisions, which include solar-ready requirements for detached houses, one- and two-family dwellings, and townhouses (IECC 2018).

California has its own standards, the 2016 Building Energy Efficiency Standards Title 24, Part 6, which actually exceed the requirements of 2015 IECC. California’s standards require new construction to have rooftop solar installation or to be solar-ready for those who are exempt from the solar installation requirement (CEC 2016). Similarly, in Seattle the residential solar-ready requirements (for single-family and low-rise multifamily dwellings) are included in the residential code, while commercial solar-ready requirements are in the city energy code (Seattle 2017). Specific to electrical safety, National Electric Code (NEC) Article 690 addresses safety standards for solar installations. An electrical permit, which is in accordance with electrical code from NEC, is required when a solar system is installed. Some cities, such as Seattle, have adopted NEC standards for their own electrical codes with additional code supplements.

Current solar-ready requirements and suggestions found in the energy codes and previous studies (e.g., Holm 2017) largely focus on securing *solar zones* in consideration of dimension, area, and orientation of future solar systems. A solar zone refers to a designated area for the future installation of solar panels on the roof or overhang without interruption due to shade, penetrations, and obstructions (CEC 2016). Solar zones should accommodate target solar system sizes based on the total available roof area while considering requirements for load, electric interconnection, and documentation (solar-ready information, such as structure loads, solar zone location, and the reserved interconnection pathways, should be provided to the occupant). While these requirements are primarily aiming at energy production by reserving sufficient spaces for future solar panels on the roof, the interview results of the present study (discussed in the next section) revealed that designating solar zones is expected by itself to be beneficial to addressing the unique safety risks and hazards that installers will likely be exposed to. For example, securing a solar zone can help prevent any obstructions (tripping hazards) from being present on the roof where a solar system is going to be installed.

Investigate Design Features and Categorize Components

A series of interviews with industry practitioners were performed to capture specific features that can be considered for improved safety of solar installations in solar-ready houses. Targeted in the Pacific Northwest region, the interviewees were identified through the previous CPWR study and the research team’s connections with the solar industry. The team tried to select professionals with varied backgrounds (from field installers to company principals) so as to capture broad perspectives. A total of 12 industry professionals were interviewed, as summarized in Table 1. The interviewees included one sustainability consultant, three solar contractors, one general contractor, two electric professionals, and five designers (including two principals). The interviews led to the identification of design features with recommendations to improve the safety of installers for rooftop solar installation in solar-ready houses.

Table 1: List of Interviewees

No.	Job Type	# of Interviewees	Date of Interview	Location of Interview	Durations (hours)
1	Electrical	1	Oct 15, 2018	Coffee shop, Seattle	1
2	Designer	1	Oct 20, 2018	Via phone call, Hawaii	1
3	Designer	1	Oct 22, 2018	Coffee shop, Seattle	1
4	Consultant	1	Oct 22, 2018	UW campus, Seattle	1.5
5	Electrical	1	Oct 25, 2018	Site office, Renton	1
6	Solar Contractor	2	Oct 26, 2018	Site office, Seattle	2
7	Solar Contractor	1	Oct 30, 2018	Site office, Seattle	1
8	Solar Contractor	1	Nov 04, 2018	Coffee shop, Seattle	1.5
9	Designer	1	Nov 06, 2018	Site office, Seattle	1
10	General Contractor	2	Nov 30, 2018	Site office, Seattle	1
11	Designer	1	Dec 03, 2018	UW Campus, Seattle	1
12	Designer	1	Dec 12, 2018	Site office, Seattle	1

Based on the interviews, the researchers identified the typical solar system installation process, which follows four steps: (1) installing safety equipment, (2) installing mechanical and electrical balance of system (BOS) such as mounting racks and overcurrent protection devices (OCPD), (3) carrying and positioning solar panels on the roof, and (4) installing final accessories. Out of the four steps, the interview results revealed

that the two most dangerous activities, from the perspective of those interviewed, are the installation of safety equipment such as anchor points and carrying solar panels to the roof.

After a list of building components pertaining to the design features were identified through the interviews, the researchers performed an online survey. In the survey, industry practitioners, including those who participated in the interviews, were asked to rank the identified design features based on their preference for enhancing safety. The ranking was determined based on evaluation criteria including (1) relevance to safety hazard risks, (2) applicability, and (3) cost-effectiveness. The relevance to safety hazard risks is a criterion to measure how much each design feature can influence worker safety. Applicability refers to the ease of application in practice. Cost-effectiveness refers to how cost-effective each feature can be. Based on the results of all the interviews, the identified design features were grouped into three categories and seven components, as follows:

- Solar Zone Features:
 - Solar Zone Area, Solar Zone Material, and Solar Zone Pitch
- Installation Features:
 - Fall Protection and Roof Access
- Electrical Features:
 - Conduit and Inverter

As seen Figure 1, the online survey aimed to evaluate the desirable design features for each of the seven building components. Professionals with different backgrounds show different preferences. For example, general contractors, who mainly work on commercial projects, seem to prefer flat and ballast mounting over other options regardless of criteria. One item to note is that the types of roofing material and mounting are likely determined by the design of the roof pitch. For example, a flat roof would entail the use of roofing membranes such as TPO (thermoplastic polyolefin, a single-ply roofing membrane covering the surface of the roof), EPDM (ethylene propylene diene terpolymer), and PVC (polyvinyl chloride) as well as ballast mounting for a solar system. The reason for using these materials is because composition and metal roofing materials are not suitable for flat roofs.

There are contradictory responses about the most desirable features in different evaluation criteria. For example, composition roofing material is considered to be safer than metal due to the less slippery condition it creates. However, the use of composition roofing results in penetrations on the roof when adding more mounting footholds, which can be avoided by the use of metal roofing material. Metal roofs, thus, make the installation easier and faster, which may reduce the overall safety hazards. In this regard, it is hard to evaluate which design feature is preferable for safety.

In general, features such as composition material, flat pitch, scaffolding, mechanical lift for roof access, and micro-inverter are found to be most desirable from individual perspectives for safety. The most desirable combination of features, however, is largely context-dependent. For example, scaffolding and mechanical lifts are deemed safer, but they are generally not preferred given their lower operational efficiency. A flat roof itself is safer due to reduced fall hazards, yet it requires having a ballast mounted solar system, which may involve carrying heavy ballast weights. Nevertheless, generally speaking, one continuous solar zone with designated access pathways, no obstructions present, installed tie-offs for fall protection on low-sloped roofs, and pre-installed conduit are determined to be the desired combination of features to enhance safety given current practice. Hence, application of the desirable features (identified through the survey) to the solar-ready house is expected to help design out safety risks and hazards effectively. The details for each design component are provided in the following sections.

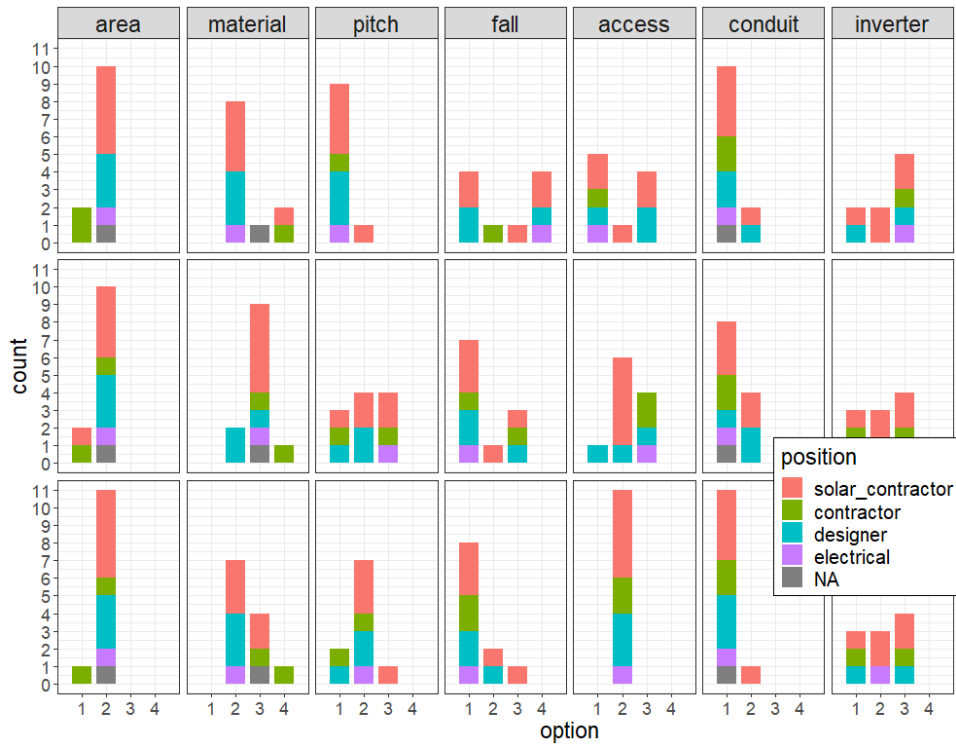


Figure 1: Survey results: Ranking of desirable design features (*Area: 1 = multi-split zones and 2 = one continuous zone; Material: 1 = tile or shake, 2 = composition, 3 = metal, and 4 is others; Pitch: 1 = flat, 2 = lower (less than 4/12), 3 = moderate (between 4/12 to 8/12), and 4 = steep (more than 8/12); Fall (Protection): 1 = hitch clip or tie-off, 2 = roof bracket, 3 = lifeline, and 4 = others; Access (to roof): 1 = scaffolding, 2 = ladder, and 3 = mechanical lift; Conduit: 1 = pre-installed and 2 = design decided but not pre-installed; Inverter: 1 = string inverter, 2 = power optimizer, and 3 = micro inverter*)

Solar Zone Features

Solar Zone Area

The designated solar zone area (where a solar system is going to be installed) should not contain any obstructions in order to avoid tripping hazards. Mounting accessories, such as footholds or racks and rails, can be pre-installed to make future installation easier. Having a simple roof shape is preferred for safer installations. If a complicated roof shape is unavoidable, the use of composition roofing material would make the installation easier and safer by effectively dealing with the complicated shape. Having access gaps around solar panels would lead to a safer condition for installers to walk around. The majority of the professionals in the survey considered one continuous zone more desirable than multi-split zones for all criteria. One of the reasons for this choice was that installation of a system in several areas would complicate the work and require installing additional accessories, given the same system size.

Furthermore, it is important to avoid overhead power lines around the solar zone, as the lines create potential hazards, especially during solar installation. An OSHA (Occupational Safety and Health Administration) Director reported on a recent incident involving a fatal electrocution by stating, “This tragedy could have been prevented if the employer had complied with electrical standards that require maintaining a safe distance from unprotected energized power lines, training employees, and providing personal protective equipment.” (EC&M 2019)

Solar Zone Material

In general, composition tile is the preferred roof material for worker safety since it is easier to work on and provides a less slippery condition. However, it requires more maintenance. Composition tile attracts moss growth and it is less durable, which incurs replacement of the roofing material and reinstallation of solar panels. The replacement allegedly costs about 25% of the initial cost of the solar installation. In that regard, metal is suggested for the roofing material of solar-ready houses for its durability. Metal, however, could cause a slippery condition when wet and heatstroke during summer. In general, a typical metal roof entails no penetrations to install a solar system, which results in safer conditions. Tile and shake roofs are easy to crack, and it takes longer to install a solar system on them. In addition, shakes are susceptible to fire risks. Housing aesthetics is another factor to consider when choosing roofing materials.

Safety hazards related to roofing materials are slip, fire, heat stroke, complexity, rework, and maintenance. The survey results reveal that composition was the preferred roofing material in terms of safety while metal (standing seam) is preferred in terms of applicability. Composition and metal were considered almost the same in terms of cost-effectiveness. In general, metal is expensive with higher upfront cost, yet it could be cost-effective as much as composition with respect to durability and maintenance in the long run.

Solar Zone Pitch

A roof pitch (vertical/horizontal) less than 5/12 or 7/12 (depending on the roofing material and climate) was suggested for the safety of solar installers while the optimal pitch for energy production largely depends on the location (e.g., 8/12 is the optimal in the Pacific Northwest). If the roof pitch is lower, any roofing material would be fine in terms of safety. There were, however, some concerns about flat roofs, which may require the use of ballast mounting for a solar system. Additional structural analysis would be required for a flat roof in order to accommodate ballast mounting structures and their weights. In addition, if solar installation on a flat roof requires membrane penetration, the potential for water intrusion should be verified by a roofing expert. A solar system with ballast mounting may also incur additional engineering costs and a building permit. The main safety hazard related to ballast mounting is from heavy lifting. In the survey, there was a concern that the use of ballast mounting likely requires carrying heavy objects to the roof, which may lead to a hazardous situation. In this regard, racking was more desirable than ballast mounting for applicability and cost-effectiveness.

Furthermore, on a flat roof it is harder to have an overhang, which is necessary in a climate such as Seattle to protect a house from frequent rains. Another issue raised was that accessing a flat roof would be more difficult because most residential houses with flat roofs are, in general, taller in order for securing more space on the top floor level. NIOSH (2013) offers a PtD reference for the flat roof parapets to prevent falls during installation. Safety hazards related to roof pitch are slip, fall, complexity, and maintenance. In the survey, a flat roof was identified as the safest feature based on the most desirable pitch while a low-slope roof was preferred in terms of cost-effectiveness. OSHA (2017) defines a low-slope roof as a roof having a slope of less than or equal to 4 inches of vertical rise for every 12-inch horizontal length (standard no. 1926.500).

Installation Features (Fall Protection and Roof Access)

Anchor points or tie-offs are suggested to be pre-installed on the rooftop because it would be more dangerous to install them after roof construction is complete. There is, however, a liability issue for homeowners to install anchor points. Any accidents related to the homeowner-installed tie-offs could get the homeowner in legal trouble with respect to reliability and maintenance of the tie-offs. Tie-offs are generally not required to be installed in building codes. In addition to anchor points, access pathways, snow guards, and guardrails were recommended as means of fall protection. Access pathways are required by the International Fire Code (IFC) 605.11.3.2 if certain conditions are not met. The conditions are, for example, having an automated fire sprinkler, roof pitch less than 2/12, system area less than 33% of total roof area (less than 1,000 sf), or detached, non-inhabitable structures such as a storage shed. For the purpose of safety, having access pathways for accessing and securing space on the roof should be required regardless, even if access pathways are exempt from the requirements. Depending on neighboring buildings, additional access points may be

needed for delivery of material and worker access via a ladder if the in-between space is too tight. A lower pitch makes easier access in this regard by allowing a gentle ladder slope.

Safety hazards are slip, trip, and fall in regard to fall protection and roof access. In the survey, hitch clips or tie-offs (anchor points) were the most desirable features for all criteria of the checklist. There were other suggestions such as guardrails and snow guards also. A snow guard could be the means for footholds for installers to step on, even though it is intended to prevent any sudden release of snow from the roof by allowing snow to drop off in small amounts. It should be noted that for roof access, ladders were the most preferred method for cost-effectiveness and applicability, while none of the participants selected ladders in terms of safety. Apparently, industry practitioners acknowledge that there is a trade-off among safety, economic efficiency, and applicability when using ladders for roof access compared to using a mechanical lift.

Electrical Features (Conduit and Inverter)

Pre-installing conduits for a solar system should be considered because it is easier and safer to install them during the house construction. It is complicated to install conduit internally after construction because doing so requires opening walls. Aesthetics is another factor to consider for conduit and inverter locations. Reserving spaces for electric equipment on the same side as the inverter or nearby is recommended. With regards to inverter types, efficiency and cost-effectiveness seem to be the most important factors. In general, micro inverters and power optimizers are preferred for a small system with less than 35 solar panels, while a string inverter is suggested for large systems such as commercial projects. Micro inverters and power optimizers offer better safety by allowing rapid shutdown that can instantly disperse direct current (DC) (all conductors within 1-ft boundary of an array have to be deenergized to 80 V or less within 30 seconds of rapid shutdown initiation, per NEC 2017).

Safety hazards related to electrical systems are fall, trip, electrocution, complexity, and rework. According to the survey results, most participants preferred pre-installing conduits for safety, applicability, and cost-effectiveness. This preference goes along with a suggestion from the interviewees that installation of conduits after construction would require more cost and time, in addition to harming the appearance of the house. A micro inverter was chosen as the most preferred inverter type in terms of safety. There is no significant difference among the inverter features for applicability and cost-effectiveness. In practice, inverter types selected depend on solar system size and roof condition. As mentioned previously, larger systems such as commercial projects benefit more from string inverters. Micro inverter and power optimizer are more desirable for smaller systems and more dynamic conditions such as having marginal shading and a complicated roof. A micro inverter leads to having many electronic components on the roof leading to higher maintenance cost. A power optimizer, on the other hand, requires fewer electronic components while providing similar outcomes to the micro inverter. The safety concern lies in where the inverter converts DC to alternating current (AC). A micro inverter converts DC to AC on the roof, which leads to better electrical safety compared to other inverter types. A micro inverter, however, can pose a trip hazard as it requires more electronic components up on the roof. In contrast, a string inverter requires installers to spend comparatively less time on the roof, and thus could help reduce worker exposure to potential safety risks and hazards.

Perform Case Studies of Existing Solar-Ready Houses

Case studies were conducted to verify the findings from the interviews and survey through real-life examples. A total of four houses were chosen for this study. It should be noted that Case Studies 1, 2 and 3 were awarded the U.S. Department of Energy (DOE) Housing Innovation Award in 2013, 2015, and 2016, respectively, for their energy efficiency, production, and green features. In addition, Case Studies 1 and 2 are certified with 5-Star Built Green, which means they are at least 30% more energy efficient than the current Washington State Code in addition to being pre-wired for any future solar installations (Built Green 2017). Note that pre-wired means making sure the ability to add something is present in the design, if the option needs to be added in the future. Case Study 3 is certified with Emerald Star Built Green, which achieved net-zero energy using a renewable source in addition to 70% reduction in water use, 90% reclaimed or Forest

Stewardship Council (FSC) certified wood materials, and higher indoor air quality. These three Case Studies were chosen to represent solar-ready houses. In contrast, Case Study 4 was specifically selected to represent a conventional residential single-family house that was not built solar-ready in comparison to Case Studies 1, 2, and 3.

Figures 2 and 3 present the satellite images of the solar panels installed on the roofs of the Case Studies. Note that the image for Case Study 4 does not show any solar panels installed because the image was captured before the installation of the solar system in 2018.



Figure 2: Case Studies 1 and 2 (Google Map 2019)

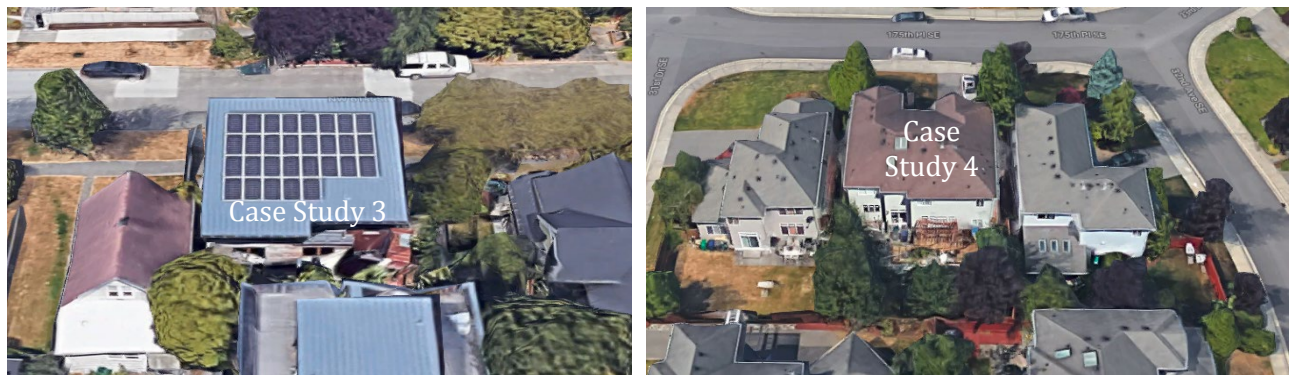


Figure 3: Case Studies 3 and 4 (Google Maps 2019)

Case Study 1

In terms of the solar zone features, Case Study 1 has a south-facing roof where solar panels are installed, which is 36' long and 22' wide, providing enough space for its solar zone. The pitch of the roof with the solar panels on is 4/12 and the rear side of the roof is 7/12, which is on the north side and has almost the same roof area. The interview with the architect who designed the house revealed that 8/12 is the most optimal for energy production in the Pacific Northwest region. For that reason, the pitch was designed to be 4/12. The architect confirmed that the pitch was decided in consideration of heat convection, saying, "It is a more about convective loop that is developed in the two-story great room providing for passive distribution of the in-floor radiant heat to the upstairs rooms." In terms of structural strength, the live load of the roof was designed with 25 pounds per square feet (psf) for snow, 5 psf for the solar panels, and 15 psf for the structural insulated panels (SIPs), totaling 45 lbs/sf.

Permanent tie-offs (i.e., installation features) were installed on the rooftop. The intended way to access the roof of this house is by a ladder. To be exempt from the fire code requiring 3 ft setbacks from roof edges and ridges, automated fire sprinklers are required, yet sprinklers were not added to the house. There are certain exceptions to the sprinkler requirement, such as when (1) the roof has less than 30% total solar panel coverage, and (2) the fire marshal determines that having a fire-fighter on the roof is not necessary. Exception #2 was true for Case Study 1. The principal designer stated: "That is always the case with an SIP roof. Fire-fighters should never be on top of an SIP that is on fire because if the bottom skin of the SIP fails,

the entire roof fails. Because there is no enclosed roof truss space that could house a fire, there is no need to ventilate the roof as would be needed for a structure with a trussed or stick-framed roof.”

Regarding the electrical features, Case Study 1 has conduits installed on the outside wall with outdoor electric equipment unlike Case Studies 2 and 3. The principal stated that the solar electrical balance of systems (BOS) was installed outside because it would be easier to add more solar panels and another inverter in the future when an electric car is used. The electrical equipment is located on the west wall. Furthermore, this house has a string inverter rather than micro inverters, which is the case for Case Studies 2 and 3. Case Study 1 does not have access pathways along the lines of the roof eaves and edge. Although this arrangement does not violate the IFC code, it is still suggested to have access pathways around the solar panels for safer working conditions.

Case Studies 2 and 3

Case Studies 2 and 3 are solar-ready houses with access pathways around solar zones. Their roofing materials are all metal (standing seam) requiring no penetration for mounting footholds to install solar panels. The roof design and access to the roof on the two houses are different, even though they share similar characteristics in terms of the housing design and the solar system because the same designer, builder, and solar contractor worked on both houses.

Case Study 2, however, has a higher roof pitch (8/12) where solar panels are installed and has a single skylight. The shade impact from the height of the skylight is not significant given that the shading equation of distance is larger than twice the height of any obstructions around solar panels (California 2019 residential compliance manual). Thus, the skylight does not affect solar panels with the shade. A roof without roof accessories, however, is expected to be safer for installers in terms of trip hazards. On the other hand, Case Study 3 has a lower roof pitch (2/12) with no obstruction and plenty of space around the solar panels for the installers. This design provides a safer condition between the two case studies. Figure 4 shows the building section and elevation of Case Study 3 featuring the low-slope roof.

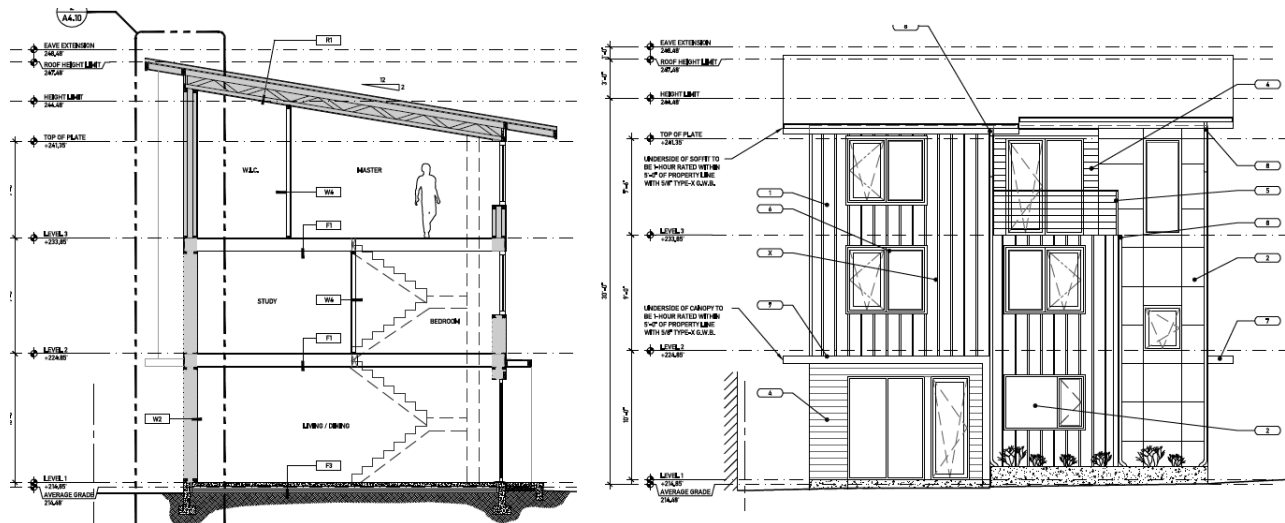


Figure 4: Section and Elevation View of Case Study 3 (Excerpt from Seattle Department of Inspection and Construction)

The deck on the 3rd floor of Case Study 2 can be used to locate a ladder for accessing the roof. This access point may have been considered from the design process to allow people to access the roof more easily and safely. Electrical conduits are installed inside the walls, thus not visible from the outside. Their inverter systems are micro inverters installed under solar panels on the roof where DC generated from the panels is converted to AC. This electrical design leads to a safer condition by preventing electrocution. The researchers were told that it took about two to three days to install the solar systems at the end of construction of the houses in both Case Studies 2 and 3.

Case Study 4

Case Study 4 represents a conventional residential house that is not designed to be solar-ready. This house has several obstructions on the roof, which are complex in shape, thus solar panels had to be installed in the multi-split zones, as opposed to one continuous solar zone. In particular, the south facing roof area was not large enough to have all the panels, and so some of the panels had to be installed on the east-facing and west-facing sections of the roof. Thirteen panels were installed on the west section, 12 on the south section, and 10 on the east section. Even the solar panels installed on the south facing roof had to be split into three zones (zones of two, four, and six panels). The roof pitch is 8/12 and roofing material is composition, requiring roof penetrations. The roof shape made access pathways difficult around the solar panels. Conduits for the solar system were installed outside wall. Tie-offs were installed at the start of the solar installation. The researchers were told that it took about five days to install the solar system on this house.

Table 2 summarizes the four case studies in terms of the PtD design features.

Table 2: Summary of Case Studies

Description		Case 1	Case 2	Case 3	Case 4
Features		5 Star Built Green	5 Star Built Green	Emerald Star	Conventional
Solar Zone	One continuous zone	Yes	Yes	Yes	No
	Obstructions	Yes	No	Yes	No
	Roofing material	Composition	Metal	Metal	Composition
	Penetrations	No	Yes	Yes	No
	Pitch	4/12	8/12	2/12	8/12
	Roof area (L x W)	22' x 36'	20' x 38'	33' x 34'	Multi-split
	Roof area (sqft)	792	760	1122	1282
	Solar zone area (sqft)	505	487	523	631
Solar zone ratio	0.64	0.64	0.47	0.49	
Installation	Anchor points	Yes	Yes	Yes	No
	Access to roof	Ladder	Ladder	Ladder	Ladder
	Access pathways	No	Yes	Yes	No
	Conduit	External	Internal	Internal	External
	Duration (days)	Not sure	3	2	5
	Year	2011	2014	2015	2018
Solar System	Solar panels (ea)	28	27	29	35
	Module capacity (W)	230	270	280	300
	System capacity (kW)	6.44	7.29	8.1	10.5
	System weight (lbs)	1176.0	1134.0	1218.0	1502.0
	lbs/sf (estimated)	2.39	2.39	2.39	2.37
	Inverter type	String	Micro	Micro	Optimizer

Developing a PtD Design Checklist and BIM models for Solar-Ready Houses

Design features for the application of PtD to solar-ready houses have been identified, analyzed, and verified through the interviews, survey, and case studies. The results were used for the development of a PtD design checklist (Figure 5 and Appendix A). The checklist is designed to support designers of solar-ready houses to effectively apply the PtD concept during their design processes to improve safety of solar installers. The checklist has three sections: Solar Zone Features (Solar Zone Area, Solar Zone Material, and Solar Zone Pitch), Installation Features (Fall Protection and Roof Access), and Electrical Features (Conduit and Inverter) for future solar systems on solar-ready houses. Each feature has checklist items concerning the application of PtD for worker safety. The checklist also suggests the use of modular solar system and standardized design templates to support easier and faster installations (Morris et al. 2014). It is expected that the checklist will encourage the active involvement of designers to implement PtD during the design process of solar-ready houses by serving as a guideline that points out how to improve worker safety during the construction of solar-ready houses. The full checklist is presented in Appendix A.

Prevention through Design (PtD) CHECKLIST for Solar-Ready Houses



Solar Zone Features

Solar Zone Area

- Consider a modular solar system and standardized design templates for easier and faster installation.
- Design a simple roof shape.
- Incorporate a designated solar zone on the roof and communicate the location of the zone in the design plans and specifications.
- Design the solar zone by considering the future solar system layout.
- Eliminate obstructions, such as skylights, chimneys, and vents, around the solar zone to reduce tripping hazards.

Figure 5: Screenshot of PtD Checklist

Based on the PtD checklist, three BIM models were developed as examples of solar-ready houses featuring design components included in the checklist. As discussed in the case studies, a simple roof shape is promoted, with one continuous and spacious solar zone to provide safer working conditions. Figure 6 shows the roof shape of Case Study 2 in comparison of Case Study 4, which highlights the significance of simple roof shapes.

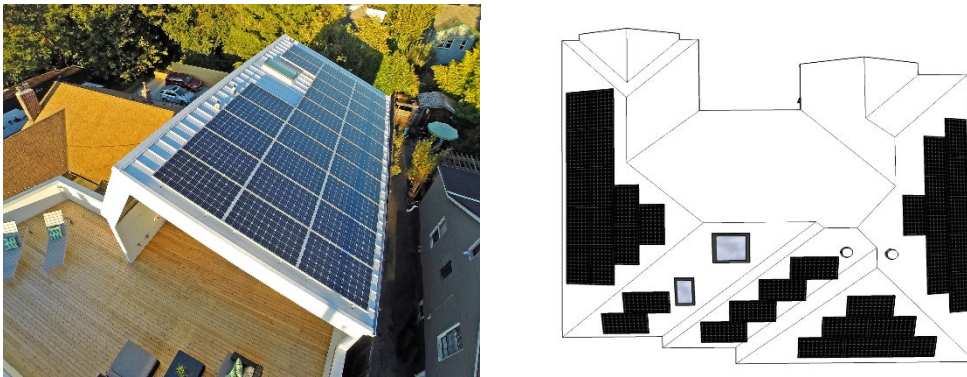


Figure 6: Solar Modules on Roofs of Case Studies 2 and 4 (courtesy of Project Designer)

The three BIM models are based on different roofing materials and different roof pitches (Figure 7). The safety design features from the checklist are all applied: a 3-foot access pathway around solar zone, tie-offs installed on roof ridge, roofing material types, low-slope roof, and conduit installed close to ridge, hip or valley (if not installed inside the wall). For example, access pathways should be secured around solar zones and close to hip, valley, eave, and edge to make sure installers can move around safely. Metal (standing seam) or composition are suggested for the roofing material while avoiding tile and shake (Ciosek 2018). Durability of the roofing material and expected lifecycle should be checked in advance for the installation of a solar system. A flat or low-slope roof is recommended although flat roofs may require ballast mounting for a solar system leading to additional structural engineering for dead and live loads. Ballast mounting likely requires carrying heavy weights, thus it would be necessary to use mechanical lifts in addition to ladders for better safety. It is also necessary to identify protection measures such as guardrails around the area where fall hazards exist. Pre-installing conduit inside walls is suggested during house construction because it is easier, safer, and more economical, in addition to improved aesthetics related to conduit pathways, inverter, and BOS locations. It is also encouraged to have conduit, wiring systems, and raceways for photovoltaic circuits close to the ridge, hip or valley, if installed on walls.

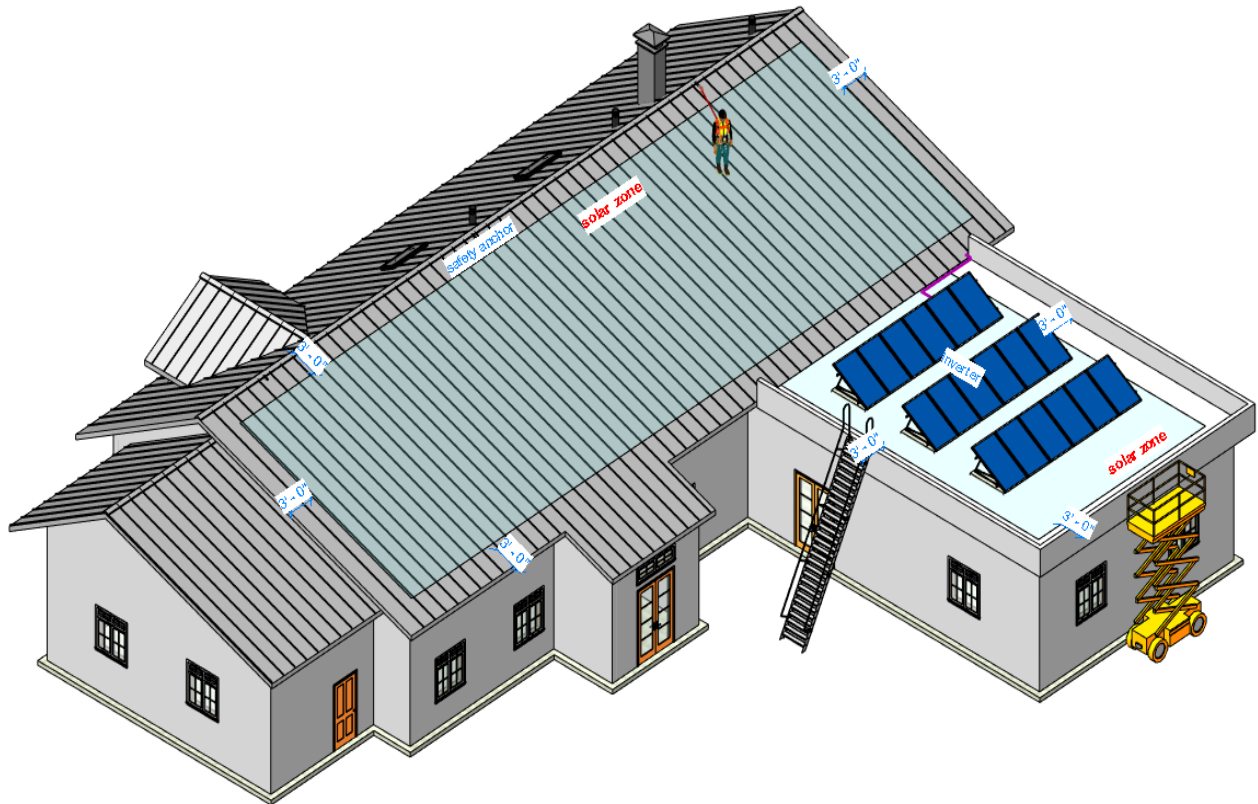


Figure 7: BIM Model Representing Solar-Ready House for Improved Worker Safety (Model 3)

Obtaining Industry Feedback on PtD Checklist and BIM Models

Three industry professionals (one residential housing designer and two solar installers) reviewed the checklist and BIM models. They provided valuable feedback that was used to refine the PtD checklist and models. One reviewer mentioned that specific to solar zone material, composition roofing material should not always be avoided because composition materials below solar panels are expected to last longer due to less sun damage. More attention should be paid to the areas surrounding the solar panels in this regard. In addition, a higher grade composition such as 50-year could be used around the perimeter of solar panels. Furthermore, when selecting roofing materials, geographical factors should be considered. For example, some regions such as Arizona have a greater use of tile roofs because tile roofs are known for better performance under extreme weather such as heat, hurricanes, and earthquakes. Tile roofs are also fireproof and considered to be better in terms of lifecycle costs than other materials. Another comment on roofing material was that reflective roofing such as a ‘cool roof’ absorbs less heat, while it affects solar installers on hot sunny days due to the reflective sunlight.

Conclusions

Solar-ready houses have become a new standard for residential houses in preparation for the future installation of a solar system on the roofs. Literature reviews on the energy codes of several states revealed that this trend has been based on the International Energy Conservation Code (IECC), and the California Energy Code (CEC) even exceeds the solar-ready requirements of the IECC. These solar-ready requirements, however, have mainly focused on optimizing energy production by securing solar zones for the future installation of a solar system and do not consider the safety of those who will install the system. In response to this gap in safety planning, the present study aimed to develop knowledge and resources that support the application of PtD to the design of new solar-ready houses. The study provided evidence—created through interviews, surveys, and case studies—that (1) PtD can improve solar installer safety by proactively

eliminating safety hazards and mitigating risk; and (2) designers can proactively get involved in promoting PtD for solar-ready houses—through the use of the developed checklist and BIM models.

PtD design features related to building components and solar system features were verified and categorized through a series of interviews and an online survey. These features include Solar Zone Features, Installation Features, and Electrical Features.

- Solar Zone Features include the solar zone area, solar zone pitch, and solar zone roof material. Designers should consider these features in terms of design constraints (e.g., rearranging obstructions such as vents and chimneys) for the design of solar zones as opposed to conventional rooftop designs.
- Installation Features are about how solar installers perform their installation in terms of fall protection and access to the roof.
- Electrical Features are intended to address a time gap between solar-ready designs in the new construction and actual solar system installation in the future. The identified features include electrical configurations that determine conduit routes and reserved spaces for electrical components of solar systems depending on inverter types.

The online survey was used to identify the most desirable features for each evaluation criteria: safety, applicability, and cost-effectiveness. Furthermore, it was found that there are conflicts among features when different objectives are pursued. For example, consideration of energy production requires a higher roof slope in the Pacific Northwest region compared to other regions in the US, while a steep slope is not preferred for safety. Composition roofing material is cheaper, but less durable, which may lead to replacement of the roofing material in the middle of the lifespan of a rooftop solar system. A flat roof, which is safer, may accompany additional engineering costs and installers carrying heavy weights on the roof. These trade-offs of the most desirable features were further investigated through the four case studies of the three solar-ready houses and one conventional house.

The case studies confirmed the most desirable design features for each building component. The design features promoting safer conditions are reflected in the PtD design checklist and BIM models, which are intended to help designers to implement PtD by their active involvement in designing for safety. This study is unique in that it promotes safety in solar-ready design, while other studies or code requirements mostly focus on securing solar zones to secure a certain level of energy production (note that any direct correlation between worker safety and solar production cannot be determined from this study). Desirable safety features suggested in this study, while not present in the current solar-ready requirements from the general energy code such as IECC, include but are not limited to: (1) access pathways around solar zone, roof eave, and edges; (2) simple roof shape, modular solar system, or standardized roof design template, making the roof more suitable for the future solar system installation; (3) composition or metal standing seam roofing materials; (4) flat or low-slope roof pitch; (5) permanent installation of anchor points for fall protection; (6) strategic assessment of access to roof; and (7) electrical considerations of conduit pre-installation and safer inverter options. The checklist and BIM models will help to reduce safety hazards and mitigate risks by involving designers during the design processes, especially for green buildings that pursue sustainability and energy efficiency.

Lastly, the interviews performed in this study reveal the benefits of solar-ready design in various aspects, including cost-effectiveness, productivity, safety, house marketability, and green adoption. In fact, promoting occupational safety increases the effectiveness of solar-ready designs in cost-effectiveness and marketability in addition to the safety of the installers and maintainers of the system. Implementing solar-ready designs can contribute significantly to lowering the soft costs of solar systems by reducing time for system permitting, pre-construction engineering, marketing, and, most importantly, installation when installers are at risk of falling from the roof. Solar-ready designs also help to increase installation productivity, leading to improved worker safety by promoting easy access, a simple layout, fewer tripping hazards, and fewer openings. Some interviewees pointed out that marketing of the solar-ready features can also enhance the property values of solar-ready houses. There were some concerns raised about solar-ready designs that most federal tax credits

for residential solar are currently not applicable to solar-ready designs. Nonetheless, the general trend in the industry is that solar-ready designs have become a new standard and requirement for new residential building or energy codes over time.

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Appendix A: PtD Design Checklist for Solar-Ready Houses

Prevention through Design (PtD) CHECKLIST for Solar-Ready Houses



Solar Zone Features

Solar Zone Area

- Consider a modular solar system and standardized design templates for easier and faster installation.
- Design a simple roof shape.
- Incorporate a designated solar zone on the roof and communicate the location of the zone in the design plans and specifications.
- Design the solar zone to take into consideration the future solar system layout.
- Eliminate obstructions, such as skylights, chimneys, and vents, around the solar zone to reduce tripping hazards.
- Pre-install solar system mounting accessories for future installation by considering penetrations, flashing, and capped sleeves.
- Designate access pathways between the solar zone and roof hip, valley, eave, or edge to prevent fall hazards.
- Avoid having the solar zone under overhead powerlines.

Solar Zone Material

- Avoid using roofing materials such as tile and shake in the solar zone.
- Select a roofing material that can outlast the expected lifespan of the solar system, when possible.
- When selecting a roofing material, consider its ability to support bases and accommodate penetration of the solar system.
- If metal roofing is used, make sure the lip size of its standing seams matches the clamp size of the solar system.
- Take into account possible heat stroke of workers on metal roofs in the summer.

Solar Zone Pitch

- Design a lower roof slope for the solar zone area.

Flat Roof

- Note that ballast mounting is likely needed for flat roofs. The use of ballast mounting requires adding additional load for its weight (in addition to 6 lb per square foot for solar panels and racking) to the structural analysis and design of the roof.
- Review any interferences of solar system accessories with the roof membrane.



Sloped Roof

- Note that a metal roof creates slip hazards if the roof slope is considerably higher than a low-slope roof.
- Consider possible snow collection on the future solar panels if the house is located in a snowy climate.

Installation Features

Fall Protection

- Identify fall protection measures (such as setbacks, snow guards, and guardrails) around the roof hip, valley, eave, and edge.
- Maintain setback pathways at hip, valley, eave, and edge to prevent fall hazards.
- Pre-install anchor points and develop a maintenance plan for the installed anchor points.

Roof Access

- Ensure safe access points and installation sequences for the future solar system.
- Improve access by considering a lower roof height for the solar zone and a lower solar zone roof pitch.
- Develop an access plan for how to lift heavy materials (such as solar panels, racking, and ballast mounting) to the roof.
- Consider the presence of neighboring houses in the roof access plan.

Electrical Features

Conduit

- Pre-install conduit, wiring systems, and raceways for photovoltaic circuits in close proximity to the ridge, hip, or valley.
- Take into account aesthetics for the locations of conduit pathways, inverters, and balance of system (BOS).
- Designate a preferably shaded space for electrical equipment in close proximity to the solar system to prevent potential sun damage.

Inverter

- Consider micro inverters or power optimizers for rapid shutdown to prevent direct current (DC) electric shock.
- Consider micro inverters or power optimizers for small solar systems (with less than 35 panels) for electrical safety.
- Consider string inverters for larger systems (with more than 35 panels) to prevent tripping hazards and reduce the time spent on the roof for installation.



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Appendix B: Additional Information about PtD Checklist

Solar Zone Features

Solar Zone Area

- Consider a modular solar system¹ and standardized design templates² for easier and faster installation.
- Design a simple roof shape³.
- Incorporate a designated solar zone on the roof and communicate the location of the zone in the design plans and specifications.
- Design the solar zone to take into consideration the future solar system layout.
- Eliminate obstructions, such as skylights, chimneys, and vents around the solar zone to reduce tripping hazards.
- Pre-install solar system mounting accessories⁴ for future installation by considering penetrations, flashing, and capped sleeves.
- Designate access pathways⁵ between the solar zone and the roof hip, valley, eave, or edge, to prevent fall hazards.
- Avoid having the solar zone under overhead⁶ power lines.

Solar Zone Material

- Avoid using materials such as tile and shake in the solar zone⁷.
- Check the roofing material durability with respect to the expected lifespan of the solar system and the expected installation timing⁸.

¹ This means to have roof ready for the future solar system

² For example, integrative racking, process optimization, PV-ready electrical circuits, and conduit redesign.

³ Complex roof shape makes it harder to install a solar system

⁴ These are not necessary for standing seam metal roofs with appropriate lips as the standardized clamps can assemble racking without penetration.

⁵ IFC 605.11.3.2.1 Residential buildings with hip roof layouts. Panels/modules installed on residential buildings with hip roof layouts shall be located in a manner that provides a 3-foot-wide (914 mm) clear access pathway from the eave to the ridge on each roof slope where the panels/modules are located. The access pathway shall be located at a structurally strong location on the building capable of supporting the live load of fire fighters accessing the roof. (Exception: roof slopes $\leq 2:12$). IFC 605.11.3.2.2 Residential buildings with a single ridge. Panels/modules installed on residential buildings with a single ridge shall be located in a manner that provides two, 3-foot-wide (914 mm) access pathways from the eave to the ridge on each roof slope where panels/modules are located (Exception: roof slopes $\leq 2:12$). IFC 605.11.3.2.3 Residential buildings with roof hips and valleys. Panels/modules installed on residential buildings with roof hips and valleys shall be located no closer than 18 inches to a hip or valley where panels/modules are to be placed on both sides of a hip or valley. Where panels are to be located on only one side of a hip or valley that is of equal length, the panels shall be permitted to be placed directly adjacent to the hip or valley. (Exception: roof slopes $\leq 2:12$).

⁶ IFC 605.11.3.2.4 Residential buildings with smoke ventilation. Panels/modules installed on residential buildings shall be located no higher than 3 feet below the ridge in order to allow for fire department smoke ventilation operations.

⁷ Tile is known for the better performance under harsh conditions caused by extreme weather such as hurricanes and earthquakes. Tile roofing is also fireproof and considered to be cheaper than other roofing materials. This type could be typically found in sunnier region such as Arizona. Tile roofing, however, still needs to be evaluated from the safety perspectives on behalf of solar installers as it makes the installation complex.

- When selecting a roofing material, consider its ability to support bases and accommodate penetration of the solar system.
- If metal roofing is used, make sure the lip size of its standing seams matches the clamp size of the solar system.
- Take into account possible heat stroke of workers on metal roofs in the summer⁹.

Solar Zone Pitch

- Design a lower roof slope¹⁰ for the solar zone area¹¹.

Flat Roof

- Note that ballast mounting is likely needed for flat roofs¹². The use of ballast mounting requires adding additional load for its weight (in addition to 6 lbs per square foot for solar panels and racking) to the structural analysis and design of the roof.
- Review any interferences of solar system accessories with the roof membrane¹³.

Sloped Roof

- Note that a metal roof creates slip hazards if the roof slope is considerably higher than a low-slope roof.
- Consider possible snow collection on the future solar panels if the house is located in a snowy climate.

Installation Features

Fall Protection

- Identify fall protection¹⁴ measures (such as setbacks, snow guards¹⁵ and guardrails¹⁶) around the roof hip, valley, eave, and edge.

⁸ If the system targets 30+ years, the use of composition should be considered with respect to the degradation to composition roofing because of solar exposure. The roofing over the solar panels are expected to last longer. More attention should be paid to the surrounding roofing material.

⁹ Reflective roofing such as a cool roof is suggested to absorb less heat while it could affect solar installers on a hot sunny day.

¹⁰ Low-slope roof: OSHA defines a “low-slope roof” as a roof having a slope of less than or equal to 4 inches of vertical rise for every 12 inches horizontal length (4:12) (1926.500(b)—definitions).

¹¹ Low-slope benefits safer condition while steep slope could be desirable for the maximum energy production. For example, it is known the slope of 8/12 is optimal for energy production in Northwest.

¹² A single-ply roofing membrane covering the surface of the roof such as TPO (Thermoplastic polyolefin), EPDM and PVC.

¹³ Membrane on a flat roof: Minimum slope for water to run off is 1/8" per 1'. Minimum slope for a flat roof by building code is 1/4" per 1'. A type of membrane roofing may be necessary even if its slope is over 2 % (1/4" per 1').

¹⁴ OSHA 1926.501(b)(10): ... each employee engaged in roofing activities on low-slope roofs, with unprotected sides and edges 6 feet (1.8 m) or more above lower levels shall be protected from falling by guardrail systems, safety net systems, personal fall arrest systems, or a combination of warning line system and guardrail system, warning line system and safety net system, or warning line system and personal fall arrest system, or warning line system and safety monitoring system. Or, on roofs 50-feet (15.25 m) or less in width (see Appendix A to subpart M of this part), the use of a safety monitoring system alone [i.e. without the warning line system] is permitted.

¹⁵ Rooftop devices that allow snow and ice to drop off in small amounts or allow snow and ice to melt completely before falling to the ground. The installation of snow guards prevents the sudden release of snow and ice from a roof, which is known as a roof avalanche. Snow guard could support installers and prevent them from falling.

- Maintain setback pathways at hip, valley, eave, and edge to prevent fall hazards.
- Pre-install anchor points¹⁷ and develop a maintenance plan for the installed anchor points¹⁸.

Roof Access

- Ensure safe access points and installation sequences for the future solar system.
- Improve access by considering a lower roof height for the solar zone and a lower solar zone roof pitch.
- Develop an access plan¹⁹ for how to lift heavy materials (such as solar panels, racking, and ballast mounting) to the roof.
- Consider the presence of neighboring houses²⁰ in the roof access plan.

Electrical Features

Conduit

- Pre-install conduit²¹, wiring systems, and raceways for photovoltaic circuits, in close proximity to the ridge, hip, or valley²².
- Take into account aesthetics²³ for the locations of conduit pathways, inverters, and balance of system (BOS)²⁴.
- Designate a preferably shaded space for electrical equipment in close proximity to the solar system to prevent any sun damage²⁵.

¹⁶ OSHA 1926.501(b)(11): ... Each employee on a steep roof with unprotected sides and edges 6 feet (1.8 m) or more above lower levels shall be protected from falling by guardrail systems with toeboards, safety net systems, or personal fall arrest systems.

¹⁷ Anchor point: OSHA standard regarding anchorages can be found in 29 CFR 1926.502(d)(15): Anchorages used for attachment of personal fall arrest equipment shall be independent of any anchorage being used to support or suspend platforms and capable of supporting at least 5,000 pounds (22.2 kN) per employee attached, or shall be designed, installed, and used as follows: 1926.502(d)(15)(i) as part of a complete personal fall arrest system which maintains a safety factor of at least two; and 1926.502(d)(15)(ii) under the supervision of a qualified person.

¹⁸ There is a potential liability issue with pre-installed anchor point because building codes, in general, do not require to install nor maintain the anchor point. A homeowner may be in trouble if an accident happens due to the poorly installed or maintained anchor point.

¹⁹ IFC 605.11.3.1 Roof access point. Roof access points shall be located in areas that do not require the placement of ground ladders over openings such as windows or doors, and located at strong points of building construction in locations where the access point does not conflict with overhead obstructions such as tree limbs, wires, or signs.

²⁰ Ladder: angle 75 degree, one-quarter the working length of the ladder (a 1:4 ratio) (29 CFR 1926.1053(b)(5)(i)). 3 rungs (1 ft apart) above the roof, The side rails of the ladder generally must extend at least 3 feet above the upper landing surface that the worker is trying to access (29 CFR 1926.1053(b)(1)).

²¹ Outside conduit: if protection sections are not more than 10 ft or 10 % of the circuit length, then free air ampacities can be used. NEC 310.15(A)(2); if 4 - 6 current carrying conductors are bundled in the same conduit, 80 % adjustment is needed for conduit fill. NEC Table 310.15(B)(3)(a). Conduit spec: fill (NFPA 70 NEC, Article 310); type (NFPA 70 NEC, Article 690); size (NFPA 70 NEC, Article 300)

²² IFC 605.11.1.2: Conduit, wiring systems, raceways for photovoltaic circuits shall be located as close as possible to the ridge or hip or valley, and from the hip or valley as directly as possible to outside wall to reduce trip hazard and maximize ventilation opportunity.

²³ Because this is one of the significant factors to homeowners and marketability of the house.

²⁴ The balance of system (BOS) encompasses all components of a photovoltaic system other than the photovoltaic panels.

Inverter

- Consider micro inverters or power optimizers for rapid shutdown²⁶ to avoid direct current (DC) electric shock²⁷.
- Consider micro inverters or power optimizers for small solar systems²⁸ (with less than 35 panels) for electrical safety.
- Consider string inverters for larger systems²⁹ (with more than 35 panels) to prevent tripping hazards and to reduce the time spent on the roof for installation.

Appendix C: BIM Models for PtD in Solar-Ready Houses

Three BIM models are developed as illustrative examples that designers can refer to when implementing PtD during the design process of solar-ready houses. The three models are based on different roofing materials and different roof pitches. Model 1 features composition roofing material for its solar zone while Model 2 features a metal roof. Note that a metal standing seam roof leads to having no flashing due to no penetrations on the roof (Model 2 does not have flashing that is shown on Model 1). Model 3 represents a solar-ready house with a flat roof. Other than the roofing material and roof pitch, all of the safety features identified in this study are applied to the models as follows.

- Metal (standing seam) or composition roofing materials are applied while avoiding tile and shake. Composition roofing needs to be checked with respect to durability and expected lifecycle for a solar system that is planned for future installation.
- A flat or low-slope roof is applied. A flat roof requires ballast mounting for a solar system with necessary structural engineering for dead and live loads and a review of any penetrations of solar system accessories into the roof membrane. To ensure safety of the installers, a mechanical lift is used with a flat roof with ballast mounting because of the need for carrying heavy weights.
- As one of the protection measures, anchor points are installed on the roof ridge.
- Access pathways around solar zones and close to a hip, valley, eave, and edge are applied with a 3-foot width to provide clear access for installers and help prevent tripping and falling.
- Conduit, wiring systems, and raceways for photovoltaic circuits are secured in close proximity to a ridge, hip or valley for the purpose of visualization in the models. It is recommended that conduits be installed inside the walls during house construction because doing so provides for easier, safer, and more economical installation in addition to better aesthetics.

²⁵ More sun exposure would curtail power, and shorten equipment life by heating the components.

²⁶ NEC rapid shutdown: The Section 690.12 update to the 2017 National Electrical Code (NEC) calls for module-level rapid shutdown of solar systems instead of NEC 2014's array-level shutdown requirement. Starting Jan. 1, 2019 when NEC 2017 goes into effect in certain jurisdictions, all conductors within an array's 1-ft boundary have to be reduced to 80 V or less within 30 seconds of rapid shutdown initiation.

²⁷ A fatal electrocution: a recent incident cited by OSHA about fatal electrocution leading to the company facing penalties at Kansas. OSHA Wichita Area Director, Ryan Hodge (2019) mentioned, "This tragedy could have been prevented if the employer had complied with electrical standards that require maintaining a safe distance from unprotected energized power lines, training employees, and providing personal protective equipment."

²⁸ A system with less than 35 panels is economical to have micro inverters or power optimizers.

²⁹ Typically a system with more than 35 panels is economical to have a string inverter. Micro inverters with a large system entails many electronic components on roof

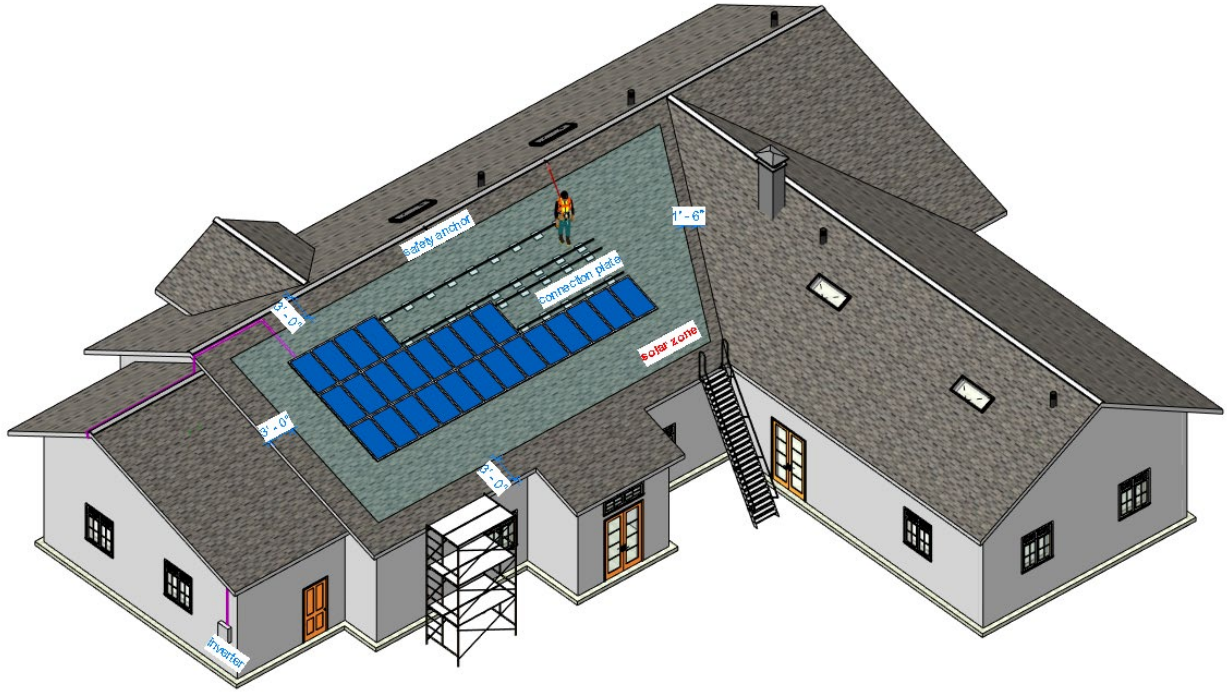


Figure A: Model 1 with Composition Roof

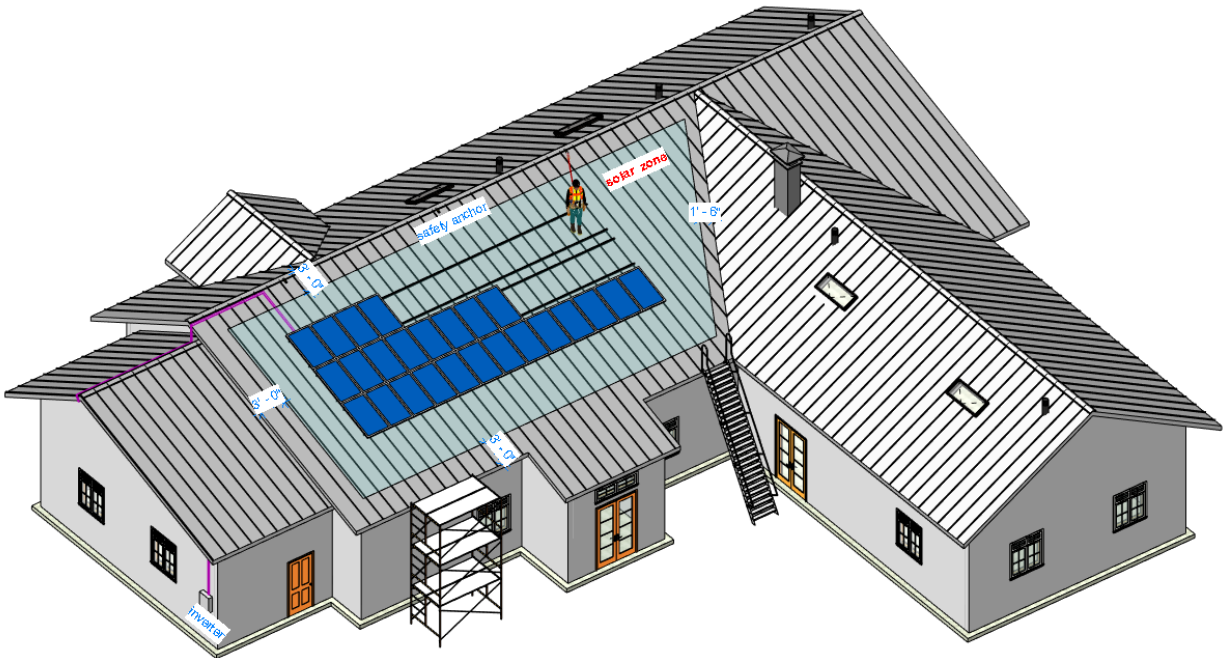


Figure B: Model 2 with Metal Roof

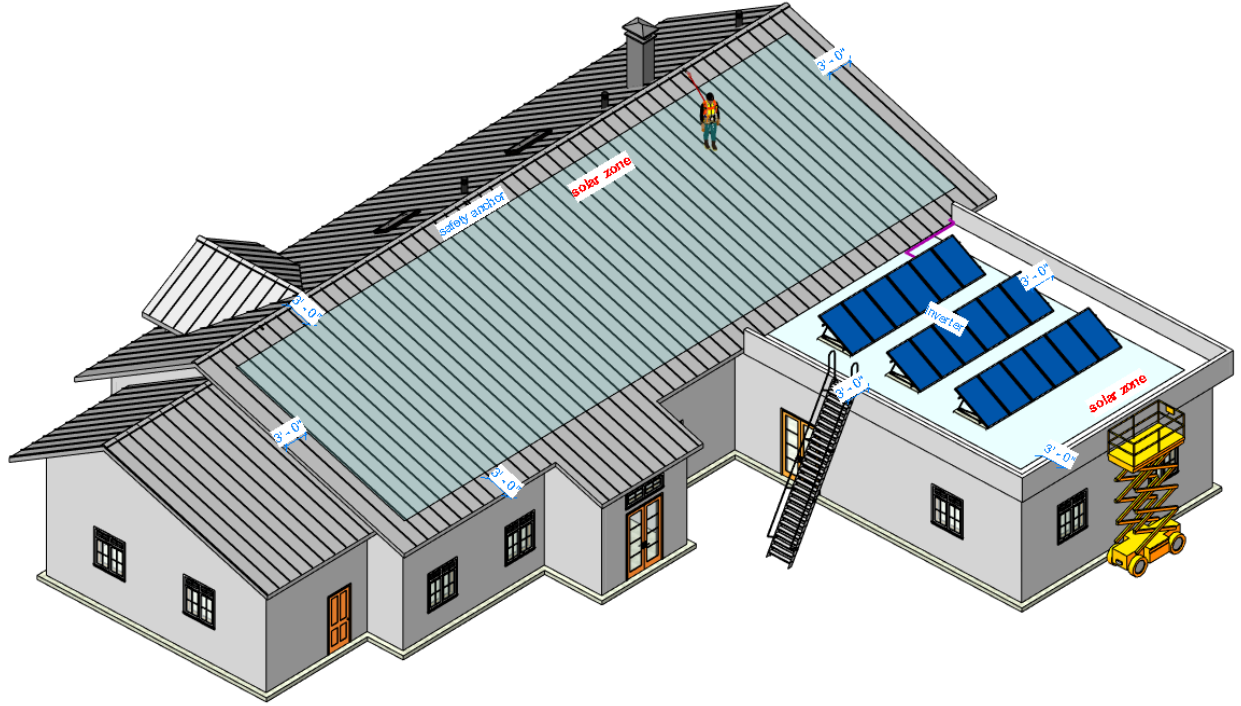


Figure C: Model 3 with Flat Roof and Metal Roof

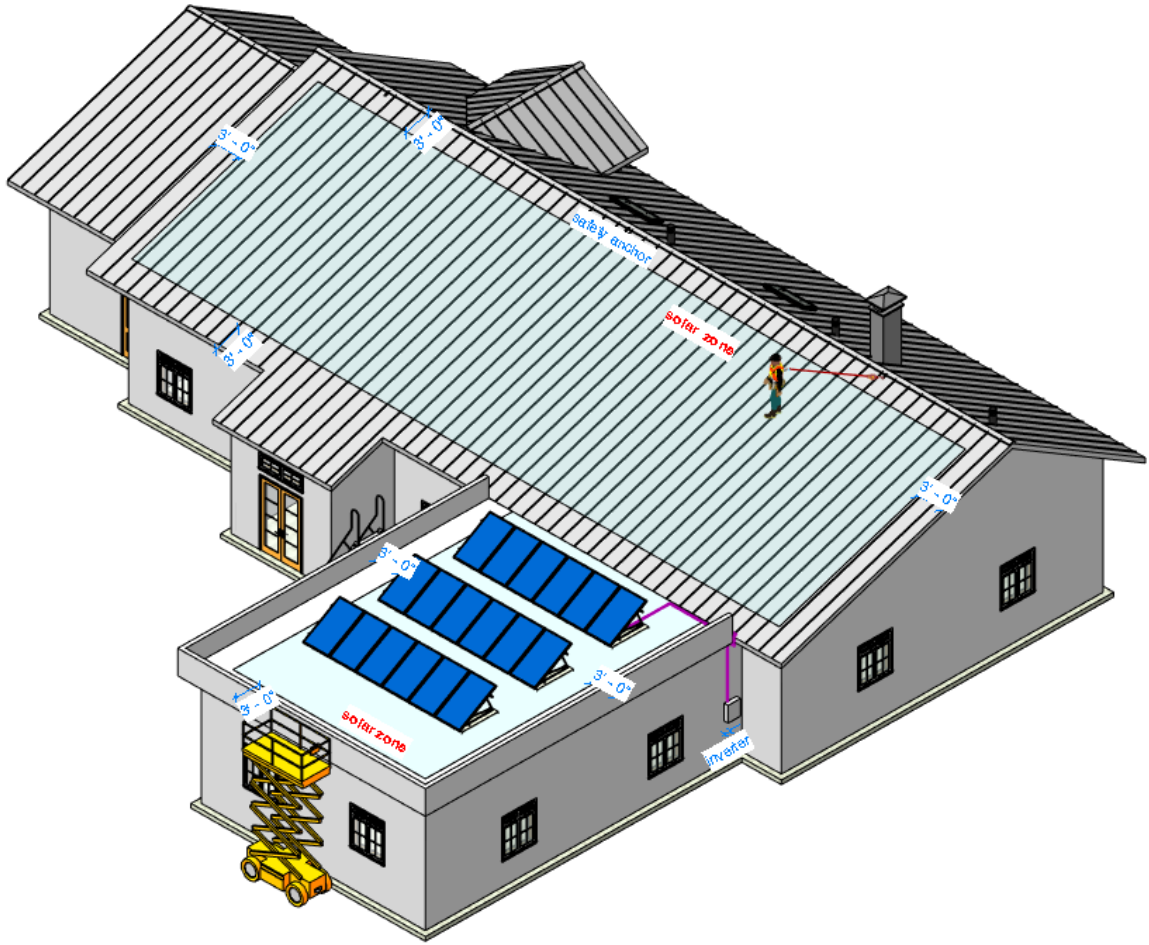


Figure 11: 3D Model of the Benchmark Solar-Ready House (Flat and Metal Roof from East South)

