Report of Findings for Development of Standards for Rooftop Solar Thermal Retrofits on Minneapolis and Saint Paul Residential Buildings

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EXECUTIVE SUMMARY

The Minneapolis Saint Paul Solar America Cities Program strives to expand the use of solar energy technologies in the Twin Cities. One of the pathways to expanded use of solar technology is to reduce barriers to and costs of solar installation. In this report, we examine the need for across-the-board structural engineering evaluations of certain common solar thermal system configurations. Installing a solar thermal system on a residential roof affects the roof load through increased weight, redistributed stresses, changes in snow and wind loading. As a result, care must be taken to determine structural loading associated with the collectors. But the cost to conduct a structural site assessment is significant and can be a barrier to greater market adoption of solar thermal systems. If common building types can be identified so that the structural issues can be addressed in a more streamlined fashion, without conducting a structural analysis for each installation, the installation costs can be reduced. Lowering solar thermal system installation costs can lead to wider acceptance of the technology. This report specifically relates to solar thermal installations and does not address solar photovoltaic installations.

In the eight rafter configurations evaluated under this project, the governing load case involving a theoretical solar thermal collector installation resulted in a reduction in bending stress relative to baseline loading. Therefore, provided the existing framing has capacity for a 40 pound per square foot (psf) snow load, the framing would also handle the effects of a typical solar thermal installation. Although a reduction in bending stress from adding a solar system to the roof may seem counterintuitive, the reasons for this result are as follows:

- Baseline cases assumed a design snow load of 40 psf, which was the typical uniform roof snow load recognized by structural engineers when most homes in the Twin Cities were built. 40 psf design snow load was part of the building code until 2003.
- Load cases with the collector installation used a snow load of 35 psf in accordance with the current code, providing an allowance of 5 psf.
- Factor of 0.75 for load combination involving wind and snow, per code.
- The design of solar collectors and racking systems to support their own weight plus the snow and wind loads was evaluated, and the effect of the solar system rack or support to transfer the structural reactions closer to the ends of the rafter, thus reducing the bending stresses.

The conclusions of this analysis should apply to homes built before 1920, when the engineering standard was a 30-psf snow load, provided the rafter span for these buildings are included in the tabulated results. Tabulated roof configurations were selected based on configurations that are judged to meet the 40-psf snow load design capacity.

*All scenarios evaluated in this study indicate that the bending stress in the roof rafters is actually **reduced** with the addition of a roof-mounted solar thermal system.*

The cost to conduct a structural site assessment is significant and can act as a barrier to greater market adoption of solar thermal systems.

BACKGROUND

The Twin Cities of Minneapolis and Saint Paul, Minnesota, are jointly recognized as Solar America Cities through the U.S. Department of Energy Solar America Communities Initiative. This report was made possible through funding from the Solar America Communities Initiative.

Conventional wisdom on solar installations is that installing a solar thermal system on a residential roof increases the load on the roof. In addition, the solar system is subject to wind loading and therefore must be secured appropriately and roof structures reinforced to accommodate the additional stresses and loads. To ensure that roof systems can safely handle the solar thermal installation, a structural analysis is required for most installations. The cost to conduct a structural site assessment is significant and can act as a barrier to greater market adoption of solar thermal systems. However, if common building types can be identified that are able to safely accommodate a solar system without reinforcement, the structural analysis can be addressed in a more streamlined fashion or may be waived, thus reducing the cost of solar thermal installations.

OBJECTIVE

The overall goal of this report is to simplify solar thermal installation for one- and two-family residences by demonstrating how typical configurations of residential systems affect roof loading by examining real projects. In particular, the report sought to identify circumstances in which installation of a rooftop solar thermal system would result in a zero or nominal increase in roof structure forces as determined by a structural engineering evaluation.

This document provides a tool for building officials and solar installers to estimate the stress change in the roof framing from a proposed residential rooftop solar thermal application. The analysis is not intended to serve as a design for actual installations. However, based on these data, building officials, solar installers, and homeowners may be able to better understand the structural loads and opportunities of solar thermal installations on one- and two-family residential buildings in Minneapolis and Saint Paul. Building officials and solar installers can better identify when a given circumstance is unlikely to require a full structural engineering assessment. Reducing unnecessary professional engineering assessments in the early stages of project planning will lower installation costs and may result in increased consumer adoption of residential solar thermal systems.

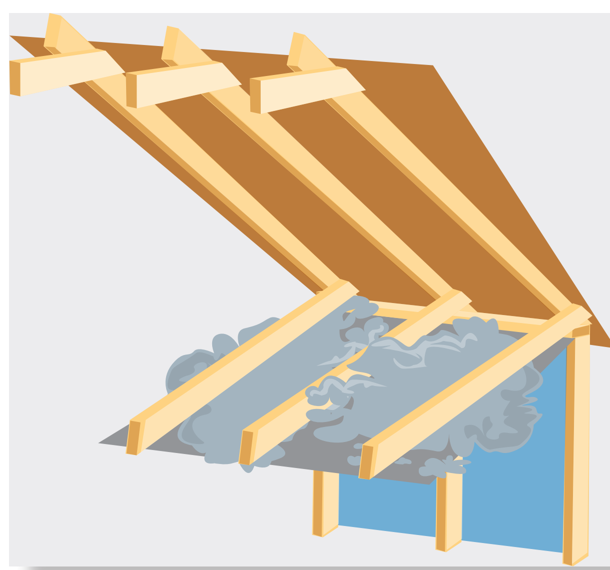
The information can also be used by installers to help them identify different installation scenarios when discussing options and costs with their clients.

ANALYSIS

This structural engineering study examined the capacity of eight existing residential homes in the cities of Minneapolis and Saint Paul to accommodate the addition of two-collector solar hot water systems. Homeowners interested in adopting solar hot water were identified through the Minnesota Renewable Energy Society's Make Mine Solar H2O program. All eight of these residential roofs were framed with wood rafters at slopes varying from 1/4:12 (a flat roof) to 14:12. Two solar thermal collectors, sized at four feet by eight feet each, were specified to be installed side by side in portrait orientation (short side horizontal) on the south-facing roof as close to the roof peak as possible to maximize solar gain. The stress increase in the roof rafters for six of the eight homes was determined structurally adequate without requiring any roof strengthening. The structural analyses for the two remaining roofs indicated that the roofs did not meet code even before solar collectors were installed, and thus required strengthening. In both cases the roof was strengthened prior to installation, based on engineering recommendations specific to the identified deficiency.

The results were used to devise solar thermal installation scenarios that would be common for Minneapolis and Saint Paul residences and to analyze the member forces for each scenario. Since the framing at all eight homes used wood rafters, this study focused only on rafter conditions. The analysis does not address residences with engineered wood roof trusses. The following assumptions were used for the installation scenarios:

- Collector size and weight were based on 4'x8' solar thermal flat plate collectors placed in the portrait orientation with a wet weight of 6 psf.
- Collectors were placed at a 45-degree angle.
- Roof slopes included 4:12, 6:12, 8:12, 10:12, and 12:12 (flush mount).
- 2x4 rafters spaced 16" o.c. in a two-span condition and 2x6 rafters spaced 24" o.c. in a single-span condition were analyzed.
- 2x4 rafters were analyzed at lengths of 8', 9', 10', and 11' measured along the slope for each roof slope condition. The second span of the two-span condition was equal in length to the first.
- 2x6 rafters were analyzed at lengths of 10', 12', and 14' measured along the slope for each roof slope condition.
- Each rafter length and slope was analyzed with and without the solar collector loads, and the member stresses were compared. Attic/ceiling purlins were assumed to be present and were included in the analysis at the support locations to resist outward thrust from the sloped roof configuration. Load combinations were in accordance with the 2006 International Building Code's (IBC) basic load combinations using allowable stress design.
- The 2x4 rafter condition was analyzed as a two-span continuous member to replicate common conditions observed in the field. Modeling assumed both spans in the two-span member were of equal length. The two-span configuration does not modify the maximum bending stress, but it does decrease deflection at the midspan of the rafters.



Solar Collector Information

The solar thermal system design evaluated included two 4'x8' flat plate collectors placed in a portrait orientation at a 45-degree angle, to be consistent with typical residential designs in Minnesota. The loads from the collectors were assumed to be supported by the roof at only the top and bottom rail locations in accordance with typical installation procedures. Also in accordance with typical installations, the top rail was placed 8 feet along the slope from the bottom rail, regardless of if it was a flush-mounted or tilted installation. The low end of the collector was assumed to be at the roof elevation. Only one collector was applied along the length of a rafter.

Point loads from the rails to the rafters were applied at each rafter, thus the rails were assumed to have connections consistent with the rafter spacing, not just at the corners of the collectors. To remain consistent with what was observed in the initial study with the collectors being placed as near to the roof peak as possible, collector point loads were placed at 1 foot and 9 feet into the rafter length, measured along the slope of the roof from the peak, as this was judged to approximate the worst load case scenario for the rafters.

Loads

Dead Load

Dead load for the roof and collector was set at 10 psf and 6 psf, respectively. These loads were judged to be representative of a typical shingled roof and at the high end of the range for solar collector weights. Collectors are mounted directly on the existing roofing system so the dead load assumes a combined weight of the roofing material and the solar collectors.

Snow Load

A uniform snow load of 40 psf was used for the roof for the baseline cases without the collectors, which was the code required roof live load from about 1920 to 2003. The current 2007 Minnesota State Building Code (MSBC) is based on the 2006 International Residential Code (IRC) and requires the roof be designed for a uniform snow load of 35 psf. This reduced snow load came into effect with the adoption of the 2003 MSBC. Since most homes in Minneapolis and Saint Paul were built before 2003 when a 40-psf snow load would have been in effect, this analysis took advantage of the 5-psf additional load capacity inherent in the original roof design. Note that the 2007 MSBC does not require consideration of snow drifting, nor does it allow reductions for slope or surface type.

Prior to 1920, a 30-psf uniform snow load was a design requirement in the Twin Cities. For Minneapolis and Saint Paul homes built prior to 1920, the conclusions of this analysis are valid for spans tabulated in the attached tables; these roof configurations were selected based on configurations that are judged to have potential for 40-psf snow load design capacity.

For the load case scenarios that included solar collectors, two snow load conditions were analyzed. Both cases used a uniform

35-psf snow load according to current code. The first case represents a snow load condition immediately following a snowfall. For this case, a uniform 35-psf snow load was applied to the collector and to the rafter outside of the collector footprint. The snow load on the collector was translated to point loads on the rafter at the rail locations.

The second snow load case represents a snow load condition after snow has melted or blown off the collector and accumulated under the collector in tilted configurations. This case used a 35-psf uniform snow load along the entire rafter length without any snow-induced point loads applied to the collector. Note that this second snow load case occurs only with tilted configurations. A 12:12 roof pitch results in a flush-mounted system and snow load is distributed to the roof rafters at the collector rail locations.

The two scenarios represent reasonable scenarios for snow loading in the Minneapolis Saint Paul area for one- and two-family dwellings. Note that snow loads are applied on a horizontal plane so the load to the rafters varies with roof slope.

The two scenarios represent reasonable scenarios for snow loading in the Minneapolis Saint Paul area for one- and two-family dwellings.

Wind Loads

Wind loads for the roofs are in accordance with the component and cladding loads tabulated in the 2006 International Residential Code. Roofs were assumed to be 30 feet or less in height with an effective wind area for the rafter of 20 square feet. The wind design for the Minneapolis-Saint Paul metropolitan area is 90 mph with Exposure B. Inward and outward pressures were analyzed, including the increased outward pressure near the edges of the roof. In the cases without the collector, wind loads were applied uniformly to the roof rafter. For the cases with collectors, wind loads were applied uniformly to the rafter outside of the 8-foot rail locations combined with point loads on the rafter at the rail locations from wind on. Wind load was applied perpendicular to the rafter slope.

Wind loads on the collector varied depending on the slope of the roof relative to the 45-degree collector installation. If the collector was within 10 degrees of the roof slope, the component and cladding load used on the roof rafters were also used on the collectors. For the cases when the roof slope was greater than 10 degrees different than the tilt, wind loading according to the solid signs provision of ASCE 7-05 Section 6.5.14 was used. For the solid sign provisions, the force coefficient Cf was considered only for cases A and B with a clearance ratio of 0.2. A clearance ratio of 1.0 could be justified, but the more conservative value was used in this analysis. The collector was assumed to be rigid so that the gust effect factor G was taken as 0.85. The topographic factor Kzt was set at 1.0 and the Importance factor I was set at 1.0. This approach is consistent with the methodology used in the structural analysis work performed by Sandia National Laboratories that was also funded through the Solar America Communities Program, as noted in their report "Structural Considerations for Solar Installations in the State of Wisconsin." Wind loads on the collector were applied perpendicular to the collector surface and were applied to the roof rafter as point loads at the rail locations.

RESULTS

Each rafter length and slope was analyzed with and without the solar collector loads, and the resulting member stresses were compared. Load combinations were in accordance with the 2006 IBC's basic load combinations using allowable stress design. A summary of the results is included in the tables at the end of this report. The analysis and tabulated results used rafter lengths measured along the slope of the roof. To convert these lengths to a horizontal projection to be consistent with the terminology "rafter span" used in the IRC, the tabulated length should be multiplied by the appropriate factor shown in the table notes.

The changes in bending, shear, and axial stress as a result of collector installation for each roof configuration were calculated. The bending stress was identified as the critical design element for the rafters; thus, only the change in bending stress was tabulated for each scenario. Additionally, one of two load combinations governed the maximum bending stress for each rafter length and slope configuration: dead plus snow (D+S) or dead plus three-quarter snow plus three-quarter inward wind (D+0.75S+0.75Wi). The changes in stress for these two load conditions were tabulated.

Separate tables are attached for 2x4 and 2x6 rafter systems. The first sub-table for each table is labeled "During Snow Event." These data correspond to the first snow load case where the uniform 35-psf snow load was applied to the collector and to the rafter outside of the collector footprint. The snow load on the collector was then translated to point loads onto the rafter. The second sub-table for each table is labeled "After Snow Event." These data correspond to the second snow load case where the uniform 35-psf snow load was applied on the entire rafter length without any snow load point loads applied from the collector.

All scenarios evaluated indicate the bending stress in the roof rafters is reduced with the addition of a solar thermal system. The reduction in bending stress is due to the 5-psf reserve snow load capacity (that resulted from a change in the code requirements) in combination with the solar system effectively reconfiguring the uniform snow and wind loads that were distributed evenly over the roof area to be point loads near the ends of the rafters. Shear stress is minimally impacted from the point loading of the collectors since the overall load on the rafter remains about the same; the load is just applied near the rafter ends. Therefore, provided the existing framing has capacity for a 40-psf snow load, the framing would also be structurally sound enough to accommodate a typical solar installation.

The stress reduction is greater for the "During Snow Event" load case than for the "After Snow Event" load case. The actual snow load at any given time on the roof is likely somewhere between these two load configurations, but both indicate solar installation does not increase the bending stress on the rafters.

Not all load combinations resulted in a stress reduction with the panel loads. Some load combinations resulted in a stress increase in the rafter with solar installation, but these load combinations did not govern the overall rafter design. For example, the analysis of the 10-foot long 2x6 rafter at a 6:12 roof slope indicates a stress increase of 16.4% from the solar installation with the load combination dead plus three-quarter snow plus three-quarter outward wind (D+0.75S+0.75Wo). However, the overall bending stress in the rafter under this load combination is only around 60% of the bending stress under the inward wind load combination (D+0.75S+0.75Wi) with and without the collector. Therefore, load combinations like D+0.75S+0.75Wo that resulted in an increased bending stress in the rafter with the collector installation did not govern the overall rafter design, and the associated stress increases from these load combinations were not tabulated.

Provided the existing framing has capacity for a 40-psf snow load, the framing would also be structurally sound enough to accommodate a typical solar installation.

ADDITIONAL CONSIDERATIONS

The roof configurations analyzed and tabulated in this report were selected based on configurations that are assumed to be designed for potential 40-psf snow load design capacity during the original construction, assuming proper installation, construction practices, fastenings, and other requirements of a correct installation are present.

The analysis parameters were determined based on typical one- and two-family residential solar hot water installations in Minneapolis and Saint Paul. For installations outside of this scope, care should be taken to verify that the assumptions used in generating the tables are applicable to the project.

Tabulated values require that the collectors have attachments at each rafter location. If the rafters are spaced 16" o.c., the collector rail must be connected to the roof at 16" o.c. for the tables to be applicable. Connections of the rail to the roof are ideally made by connecting the rails to blocking that is added between the existing roof rafters. Using blocking reduces the potential of the rafter section being damaged or the rafter strength otherwise reduced as a result of the solar installation.

A careful examination of the condition of the existing structure should be done in conjunction with the use of this document. Observations should be made to confirm the rafters and connections exhibit good workmanship and are in good condition, and that the rafters do not contain cracks, splits, large knots, or rot. Existing construction should be examined to confirm there are no questionable conditions such as other equipment placed on the roof or hung in the attic from the rafters, that there are no roof openings in the proposed collector area, or that the roof has features such as changes in roof configuration, a higher adjacent roof, or other factors near the installation that could cause snow drift.

Horizontal framing that ties the opposing roof slopes together to resist outward thrust must be in place. This requires a tie member located at the vertical support location and is typically the floor of the attic space. Rafter ties located near the roof peak are not an equivalent alternative. Additionally, attics were assumed unfinished and not used for storage.

If framing is such that horizontal ties exist but a portion of the roof rafter has an interior finish directly applied to the rafter, the installation of solar collectors will change the rafter load and consequently may increase the chance of cracks forming in the finish. This scenario would be most common for the low end of the 2x4 two-span conditions analyzed in this study.

This analysis only considered wood roof rafters. The results can be applied to rafters in both gable end and hip roof construction, but if an installation is to occur on a hip roof, the capacity of the hip or valley beams must be reviewed. The analysis is not applicable to engineered wood roof trusses, which have different structural characteristics than wood rafters.

This document is intended to be a tool to facilitate the review process and guide decision making by installers and building officials. The building official has the ultimate authority in determining whether or not a site-specific structural assessment is necessary.

Observations should be made to confirm the rafters and connections exhibit good workmanship and are in good condition, and that the rafters do not contain cracks, splits, large knots, or rot.

CONCLUSIONS

In all rafter configurations analyzed, the governing load case for theoretical scenarios in which a new solar hot water system is installed showed a reduction in bending stress relative to the base-line load (the load without a solar system). Therefore, provided the existing structure has a capacity for a 40-psf snow load, the existing framing would be adequate to accommodate a typical two-collector solar thermal installation without structural improvements.

Table 1:

Change in Bending Stress with Solar Module Installation from Base Case Without Collectors 2x6s @ 24" o.c.

During Snow Event

Rafter length along slope **Roof slope**

	4:12	6:12	8:12	10:12	12:12
10 feet	-44.0% (-40.4%)	-45.3% (-40.6%)	-46.2%(-43.9%)	-46.4% (-47.7%)	-45.6% (-47.6%)
12 feet	--	--	-23.5% (-16.5%)	-23.5% (-22.2%)	-23.2% (-22.0%)
14 feet	--	--	--	--	-7.8% (-6.2%)

After Snow Event

Rafter length along slope **Roof slope**

	4:12	6:12	8:12	10:12
10 feet	-5.9% (-10.8%)	-5.6% (-10.4%)	-5.1% (-15.2%)	-4.7% (-19.8%)
12 feet	--	--	-2.9% (-5.7%)	-2.6% (-11.3%)
14 feet	--	--	--	--

Table Notes:

1. Panel size is based on a 4x8' module in portrait orientation with a maximum weight of 6 psf.
2. Panel point loads are applied with the top point load located 1' maximum into the rafter length measured along the slope from the peak.
3. Tabulated values are for the load case of D+S. Values in parentheses are for the load case of D+0.75S+0.75W.
4. Tabulated values are based on a uniform snow load for base case of 40 psf and a uniform snow load with panel installation of 35 psf.
5. Panel attachments of top and bottom rail must be 24" o.c. to blocking (preferred) or to rafters.
6. Wind loads are based on 90 mph basic wind speed in Exposure B.
7. Tables are based on designs for Minneapolis and Saint Paul one- and two-family residential applications. See the full report for additional analysis and load information.
8. To convert the tabulated rafter length along the slope to the horizontal projection length (rafter span), multiply the length by the following adjustment factor:

Roof Slope	Adjustment Factor
4:12	0.95
6:12	0.89
8:12	0.83
10:12	0.77
12:12	0.71

Example: the rafter span for the 10-foot rafter length at a 10:12 roof slope would be 10' x 0.77 = 7'-8".

Table 2:

Change in Bending Stress with Solar Module Installation from Base Case Without Collectors 2x4s @ 16" o.c.

During Snow Event

Rafter length along slope **Roof slope**

	4:12	6:12	8:12	10:12	12:12
8 feet	-12.7%/- 7.8%	-13.3%/- 7.3%	-14.0%/- 8.7%	-14.3%/- 12.5%	-14.3%/- 12.5%
9 feet	--	-31.7% / -29.0%	-32.2%/- 30.4%	-32.3%/- 31.4%	-31.6%/- 31.3%
10 feet	--	--	--	-23.5% / -22.2%	-23.0%/- 22.1%
11 feet	--	--	--	--	-16.7%/- 15.1%

After Snow Event

Rafter length along slope **Roof slope**

	4:12	6:12	8:12	10:12
8 feet	-5.4%/- 2.0%	-5.1%/- 1.0%	-5.0%/- 2.3%	-4.1%/- 6.0%
9 feet	--	-8.8% / -11.6%	-8.5%/- 13.8%	-8.0%/- 15.3%
10 feet	--	--	--	-6.1%/- 10.6%
11 feet	--	--	--	--

Table Notes:

1. Panel size is based on a 4x8' module in portrait orientation with a maximum weight of 6 psf.
2. Panel point loads are applied with the top point load located 1' maximum into the rafter length measured along the slope from the peak.
3. Tabulated values are for the load case of D+S. Values in parentheses are for the load case of D+0.75S+0.75W.
4. Tabulated values are based on a uniform snow load for base case of 40 psf and a uniform snow load with panel installation of 35 psf.
5. Panel attachments of top and bottom rail must be 24" o.c. to blocking (preferred) or to rafters.
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