Structural Review Guidance for Rooftop Residential PV (<10 kW)

Prescriptive Process for Structural Approval of Small PV Systems

Contents

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1. Introduction to the Prescriptive Process

The goal of this prescriptive structural review process is to provide standard guidelines for the installation of rooftop solar PV systems on one- and two-family residences without the expense and time of utilizing a licensed structural engineer to evaluate load carrying capacity. This process is designed to be applied to all cities and towns in the Commonwealth of Massachusetts.

Residential PV systems, usually sized 10 kW and less, are typically very lightweight, approximately 3.0 to 3.5 pounds per square foot. Adding this amount of weight to a roof compares favorably to adding a second layer of roofing shingles, which does not require the advice of a licensed structural engineer in Massachusetts. The prescriptive method described herein is limited to flush-mounted PV systems, for which the effects of wind and snow accumulation can be better quantified using existing building code metrics.[1] PV systems are sometimes installed at a tilt to get the best exposure of the PV modules to the sun, but the tilt can cause an increase in the effect of wind and snow accumulation.

In order to qualify for the prescriptive structural review process, the building in question must be a 1-2 family dwelling built after 1975 with a light-frame wood construction and traditional rafters for the roof. Considering lightweight construction and rafter/truss data from 1997 and 2001, one could <u>roughly</u> estimate that approximately 10%-12% of homes in Massachusetts will qualify for the prescriptive process.[2] This translates to approximately 188,000 to 225,000 homes out of the 1,902,385 1-2 family dwellings in Massachusetts.[3]

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[1] In flush-mounted PV systems, the modules are installed parallel to the existing roof at a height of no more than 8 to 12 inches above the roofing.

[2] In 1997, 30% of homes were newer than 1975 x 74% were of light frame construction x 44.7% of homes were built with rafters = 10%. In 2001, 30% of homes were newer than 1975 x 82.8% were of light frame construction x 47.7% of homes were built with rafters = 12%.

[3] Comprised of 1,463,243 1-unit detached, 139,039 1-unit attached and 300,093 2-unit structures.

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The year 1975 was chosen because the first Massachusetts Statewide Building Code (MSBC) was adopted that year. One can safely assume that a house built later than 1975 was designed and built according to a set of quantifiable codes and standards. Therefore, the first qualifier in the prescriptive process is: "Was the house built in 1976 or later?" The year 1976 was chosen instead of 1975 based on the assumption that while the code was adopted in 1975, certain structures may have already been designed, permitted or under construction that year, prior to implementation of the code.

The prescriptive process outlined here accounts for a number of factors that must be included when considering the installation of PV on one- or two-family wood-framed dwellings. The additional weight of a PV system requires an increase in the roof framing support requirements. These requirements must be increased from the building code specified snow load at the time of construction to the sum of a) the proposed system weight, b) the increased effects of the snow load due to the inclusion of the coefficient of temperature, and c) possible increases in the snow load requirements in the current building code. The addition of these factors can increase the roof framing support requirements for applied loads at the time of construction by as much as 20%. The prescriptive process is designed to incorporate this increase.

2. *How to Use This Prescriptive Process*

A person knowledgeable in residential construction or engineering (see Section 3 for further clarification) should follow the steps outlined below in order to evaluate the structure in question for compliance with the "*Prescriptive Process Flowchart for Residential PV <10 kW*" (page 4) . The Flowchart – which consists of a set of yes or no questions – requires that structural components be observed and determined to be in accordance with the stated conditions. Where these components are observed to be in accordance with the stated conditions, the proposed PV system may be installed on the structure in question without further structural analysis. Where these components are not observable or not in such accord, it is recommended that a Registered Design Professional be used to evaluate the existing conditions and determine their ability to provide adequate support.

Steps for Using the Prescriptive Process Flowchart for Residential PV <10kW:

1. Before evaluating the structure in question, familiarize yourself with the content and questions of the "*Prescriptive Process Flowchart for Residential PV <10 kW*" (page 4).
2. Evaluate the structure. Observe the structural components specified in the Flowchart and determine if they are in accordance with the stated questions.
3. If the structural components specified in the Flowchart are not observable, or are not in accordance with the stated questions, use a Registered Design Professional to evaluate the existing structural conditions and determine their ability to provide adequate support for the proposed PV system.

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4. If the structural components specified in the Flowchart are observed to be in accordance with the Flowchart, and to therefore "not require further evaluation," proceed to the Maximum Rafter Span Table (page 5).

5. Before using the Maximum Rafter Span Table, determine the ground snow load requirements (30, 40, or 50 psf) for the structure in question, based on the Snow Load Zones identified in the Massachusetts Building Code. Identify the structure's rafter species, grade, size, and spacing.

6. With these five factors (ground snow load; rafter species, grade, size and spacing), use the Maximum Rafter Span Table to identify the maximum span for the structure framing that can support the proposed PV system. If the structure's existing span is less than the maximum span listed in the table, the PV system may be installed on the roof without further structural analysis.

7. If the structure's existing span exceeds the maximum span identified in the Maximum Rafter Span Table, employee the services of a Registered Design Professional. An RDP may be able to identify other qualifying structural conditions, or recommend bracing or other improvements to the structure, which would enable the proposed PV system to be installed.

3. Recommended Personnel Approved to Utilize the Prescriptive Process

Prior to using the prescriptive process, a person knowledgeable in construction and/or engineering must become familiar with the structure under consideration. The phrase "person knowledgeable in construction and/or engineering" is meant to refer to someone with experience in building construction, framing, carpentry or codes who can differentiate between material dimensions, species or grades sufficiently to be able to properly evaluate the conditions discussed in the separate flow chart parameters. This person could be a framing carpenter, licensed construction supervisor (CSL), an Engineer-in-training, or a number of other persons involved in the home construction or development community.

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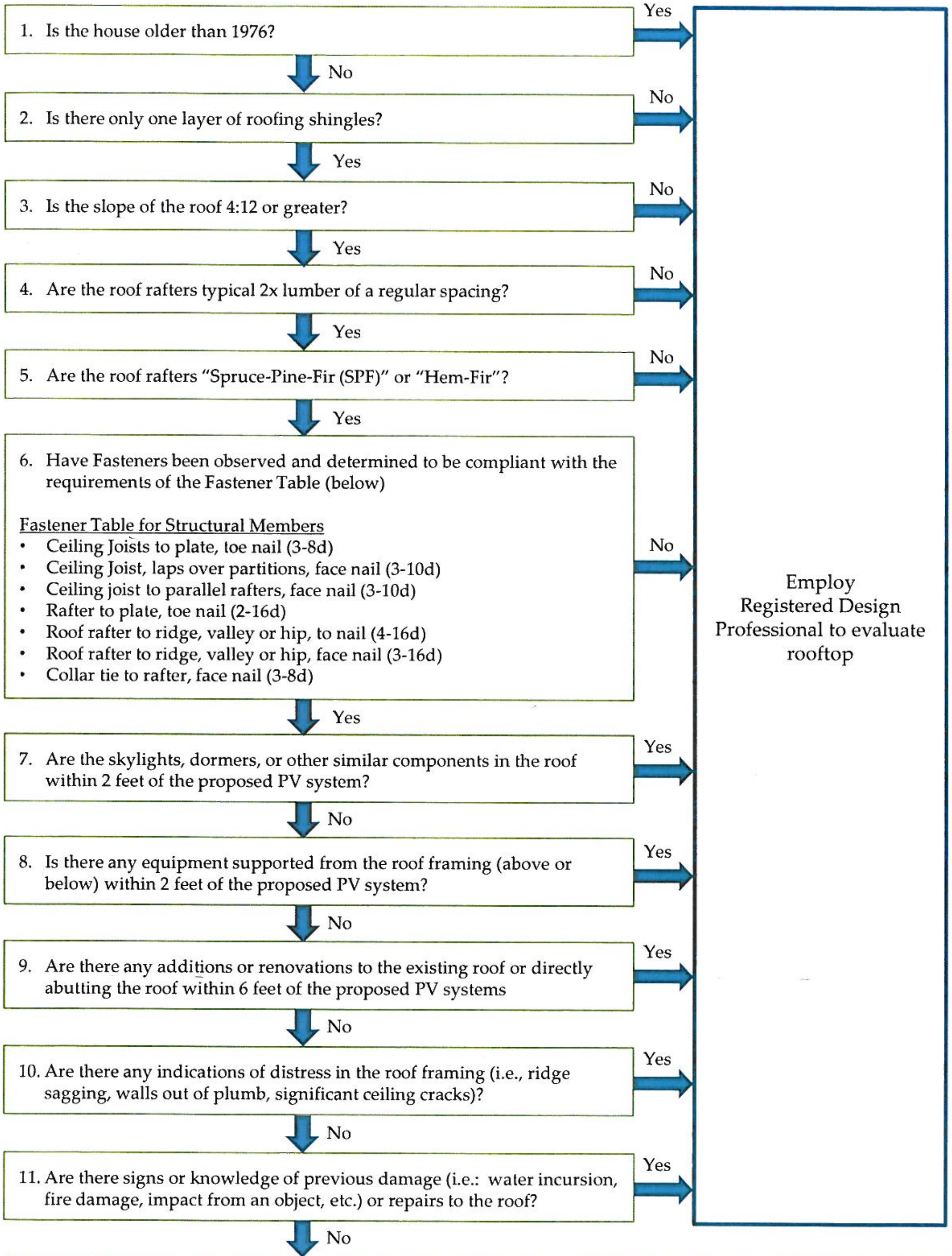
Prescriptive Process Flowchart for Residential PV <10 kW



1. Is the house older than 1976?
2. Is there only one layer of roofing shingles?
3. Is the slope of the roof 4:12 or greater?
4. Are the roof rafters typical 2x lumber of a regular spacing?
5. Are the roof rafters "Spruce-Pine-Fir (SPF)" or "Hem-Fir"?
6. Have Fasteners been observed and determined to be compliant with the requirements of the Fastener Table (below)

Fastener Table for Structural Members

- Ceiling Joists to plate, toe nail (3-8d)
- Ceiling Joist, laps over partitions, face nail (3-10d)
- Ceiling joist to parallel rafters, face nail (3-10d)
- Rafter to plate, toe nail (2-16d)
- Roof rafter to ridge, valley or hip, to nail (4-16d)
- Roof rafter to ridge, valley or hip, face nail (3-16d)
- Collar tie to rafter, face nail (3-8d)

7. Are the skylights, dormers, or other similar components in the roof within 2 feet of the proposed PV system?
8. Is there any equipment supported from the roof framing (above or below) within 2 feet of the proposed PV system?
9. Are there any additions or renovations to the existing roof or directly abutting the roof within 6 feet of the proposed PV systems
10. Are there any indications of distress in the roof framing (i.e., ridge sagging, walls out of plumb, significant ceiling cracks)?
11. Are there signs or knowledge of previous damage (i.e.: water incursion, fire damage, impact from an object, etc.) or repairs to the roof?

Employ Registered Design Professional to evaluate rooftop

If none of the answers to the above questions caused you to employ a Registered Design Professional to evaluate the structure, you may proceed to utilize the Maximum Rafter Span table for the evaluation of the roof framing to support the proposed PV system.

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Maximum Rafter Span Table

Maximum Rafter Spans (for non-cathedral ceilings)

DL = 10 psf, Max PV weight = 3.5 psf, max PV supports at 2 x Rafter spacing (alternate rafter loading)

			12" RAFTER SPACING				16" RAFTER SPACING				24" RAFTER SPACING			
			2x6	2x8	2x10	2x12	2x6	2x8	2x10	2x12	2x6	2x8	2x10	2x12
P_g = 30 psf	Hem-Fir	SS	13' - 8"	18' - 0"	23' - 0"	28' - 0"	12' - 5"	16' - 5"	20' - 11"	25' - 5"	10' - 6"	13' - 11"	17' - 9"	21' - 7"
	Hem-Fir	#1	12' - 5"	16' - 5"	20' - 11"	25' - 5"	10' - 9"	14' - 2"	18' - 1"	22' - 0"	8' - 9"	11' - 7"	14' - 9"	18' - 0"
	Hem-Fir	#2	11' - 7"	15' - 4"	19' - 6"	23' - 9"	10' - 0"	13' - 3"	16' - 11"	20' - 7"	8' - 2"	10' - 10"	13' - 10"	16' - 10"
	Hem-Fir	#3	8' - 11"	11' - 9"	15' - 0"	18' - 3"	7' - 8"	10' - 2"	13' - 0"	15' - 9"	6' - 3"	8' - 3"	10' - 7"	12' - 10"
	Spruce-Pine-Fir	SS	13' - 5"	17' - 8"	22' - 6"	27' - 5"	12' - 2"	16' - 0"	20' - 6"	24' - 11"	9' - 11"	13' - 1"	16' - 9"	20' - 4"
	Spruce-Pine-Fir	#1	11' - 9"	15' - 6"	19' - 10"	24' - 1"	10' - 2"	13' - 5"	17' - 2"	20' - 11"	8' - 4"	11' - 0"	14' - 0"	17' - 0"
	Spruce-Pine-Fir	#2	11' - 9"	15' - 6"	19' - 10"	24' - 1"	10' - 2"	13' - 5"	17' - 2"	20' - 11"	8' - 4"	11' - 0"	14' - 0"	17' - 0"
	Spruce-Pine-Fir	#3	8' - 11"	11' - 9"	15' - 0"	18' - 3"	7' - 8"	10' - 2"	13' - 0"	15' - 9"	6' - 3"	8' - 3"	10' - 7"	12' - 10"
P_g = 40 psf	Hem-Fir	SS	12' - 10"	16' - 11"	21' - 7"	26' - 3"	11' - 8"	15' - 4"	19' - 7"	23' - 10"	9' - 7"	12' - 7"	16' - 1"	19' - 7"
	Hem-Fir	#1	11' - 3"	14' - 10"	19' - 0"	23' - 1"	9' - 9"	12' - 10"	16' - 5"	20' - 0"	8' - 0"	10' - 6"	13' - 5"	16' - 4"
	Hem-Fir	#2	10' - 6"	13' - 11"	17' - 9"	21' - 7"	9' - 1"	12' - 0"	15' - 4"	18' - 8"	7' - 5"	9' - 10"	12' - 6"	15' - 3"
	Hem-Fir	#3	8' - 1"	10' - 8"	13' - 7"	16' - 6"	7' - 0"	9' - 2"	11' - 9"	14' - 4"	5' - 8"	7' - 6"	9' - 7"	11' - 8"
	Spruce-Pine-Fir	SS	12' - 7"	16' - 6"	21' - 1"	25' - 8"	11' - 1"	14' - 7"	18' - 7"	22' - 8"	9' - 0"	11' - 11"	15' - 2"	18' - 6"
	Spruce-Pine-Fir	#1	10' - 8"	14' - 1"	18' - 0"	21' - 11"	9' - 3"	12' - 2"	15' - 7"	18' - 11"	7' - 6"	9' - 11"	12' - 8"	15' - 6"
	Spruce-Pine-Fir	#2	10' - 8"	14' - 1"	18' - 0"	21' - 11"	9' - 3"	12' - 2"	15' - 7"	18' - 11"	7' - 6"	9' - 11"	12' - 8"	15' - 6"
	Spruce-Pine-Fir	#3	8' - 1"	10' - 8"	13' - 7"	16' - 6"	7' - 0"	9' - 2"	11' - 9"	14' - 4"	5' - 8"	7' - 6"	9' - 7"	11' - 8"
P_g = 50 psf	Hem-Fir	SS	12' - 2"	16' - 0"	20' - 5"	24' - 10"	10' - 9"	14' - 3"	18' - 2"	22' - 1"	8' - 10"	11' - 7"	14' - 10"	18' - 0"
	Hem-Fir	#1	10' - 5"	13' - 9"	17' - 6"	21' - 4"	9' - 0"	11' - 10"	15' - 2"	18' - 5"	7' - 4"	9' - 8"	12' - 4"	15' - 1"
	Hem-Fir	#2	9' - 8"	12' - 10"	16' - 4"	19' - 11"	8' - 5"	11' - 1"	14' - 2"	17' - 3"	6' - 10"	9' - 0"	11' - 7"	14' - 1"
	Hem-Fir	#3	7' - 5"	9' - 10"	12' - 6"	15' - 3"	6' - 5"	8' - 6"	10' - 10"	13' - 2"	5' - 3"	6' - 11"	8' - 10"	10' - 9"
	Spruce-Pine-Fir	SS	11' - 9"	15' - 6"	19' - 10"	24' - 1"	10' - 2"	13' - 5"	17' - 2"	20' - 11"	8' - 4"	11' - 0"	14' - 0"	17' - 1"
	Spruce-Pine-Fir	#1	9' - 10"	13' - 0"	16' - 7"	20' - 2"	8' - 6"	11' - 3"	14' - 4"	17' - 6"	6' - 11"	9' - 2"	11' - 9"	14' - 3"
	Spruce-Pine-Fir	#2	9' - 10"	13' - 0"	16' - 7"	20' - 2"	8' - 6"	11' - 3"	14' - 4"	17' - 6"	6' - 11"	9' - 2"	11' - 9"	14' - 3"
	Spruce-Pine-Fir	#3	7' - 5"	9' - 10"	12' - 6"	15' - 3"	6' - 5"	8' - 6"	10' - 10"	13' - 2"	5' - 3"	6' - 11"	8' - 10"	10' - 9"

Notes and Assumptions for Use of Above Table

1. Prior to use of this Table, comply with the Prescriptive Process Flowchart for Residential PV <10 kW.
2. This Table to be utilized by appropriately knowledgeable engineering or construction individuals.
3. Use of this table assumes construction is Code Compliant, i.e., collar ties exist at appropriate spacing, rafters are correctly located on opposing sides of ridge beam.
4. Actual spans exceeding the Table values may be reduced by installing rafter braces to appropriate bearing wall locations, employ a Registered Design Professional (RDP) for proper details.
5. Ground Snow Loads (P_g) based on 780 CMR 58.00.
6. Allowable stress design based on NDS-2005, maximum total load deflection limited to L/180.
7. PV panels installed parallel to the roof plane and the distance between the roof covering and bottom of the PV panel is ≤ 12".

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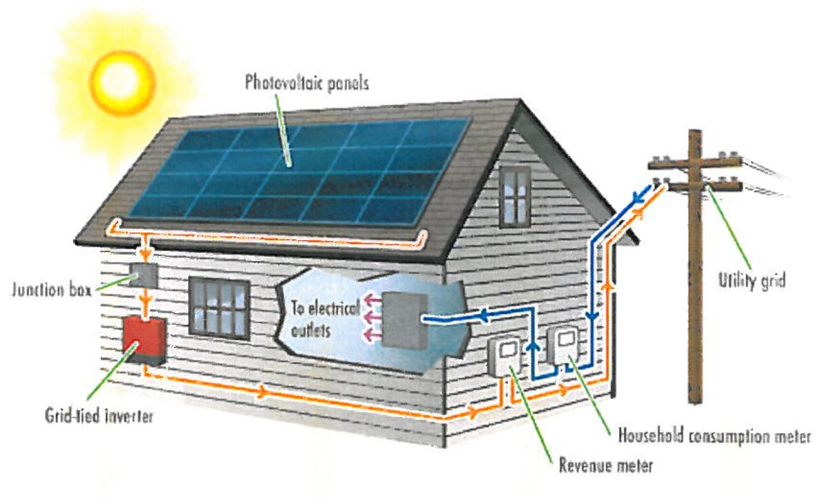
Appendix A: General Structural Considerations of Rooftop Solar PV Systems

1. Introduction to Rooftop PV Systems

The major components associated with a rooftop solar PV system are the modules, inverter(s), racking and sometimes combiner boxes (Figure 1). Depending on the nature of the installation there may be various electrical disconnecting means, meters and a site specific solution for the interconnection into the existing electrical system (typically a back-fed breaker).

Figure 1 Typical Rooftop Photovoltaic Installation



The modules are typically connected in series to create the array building blocks called strings. Depending on the size of the system these strings can either be run directly to the inverter or to a combiner box where a parallel connection is made to combine multiple strings into one circuit to then be run to the inverter. The inverter is the component that converts the DC power generated by the module into AC power, matching the site power. Again, depending on the architecture of the system and the code requirements there will often be some form of disconnecting means and meter(s). Finally there will be a means of final interconnection into the site's existing electrical system; often a breaker landed in the main panel of the site.

2. Common Structural Elements

Small residential rooftop systems are often designed to be flush-mounted, whereby the modules are in the same plane as the roof and typically no more than 8 to 12 inches above the roof. The common structural elements associated with these types of systems start with the lag bolt attachment of a mount into a roof structural member. The design, size and distribution of these bolts are often included in the overall racking design and serve as the main point of structural attachment of the PV system to the roof and house framing system. From the mounts there are typically one or two layers of racking beams or framing members installed to support the PV modules. The modules are typically aluminum framed and

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thus typically only require lengths of racking to support them. There are various solutions for the module to rail connection but it is often done with a clip or clamp that is located between two modules on a shared span of racking rail holding the module frame to the racking.

A block or section of module rows and columns make up what is called an array, ideally containing whole strings to make efficient use of the available roof space and to minimize the number of roof penetrations. In the case of the prescriptive process proposed, it is recommended that the number of connectors be spaced no further than twice the rafter spacing and alternated along the rafters to evenly distribute the system weights and loads throughout the roof framing members.

3. Consideration of Design Wind Speed

As discussed in Appendix B and contemplated in the creation of the Maximum Rafter Span Table the ground snow load and corresponding roof snow load are determining factors in the analysis of a rooftop PV system. While the Commonwealth of Massachusetts does experience high wind conditions, and the Massachusetts Building Code does contemplate variable design wind speed conditions throughout the state, for the purposes of this analysis the snow load affects were found to be the governing factor.

Appendix B: How the Prescriptive Process Was Developed

The first step in developing the prescriptive process was to determine the increase in load a rooftop would endure from a PV system and snow load, adjusted for temperature. Figure 2 contains this analysis, which is also described below.

Figure 2. Roof Load Considerations

A	B	C	D	E	F	G	H	I	J	K	L	M
City/Town	5/6 Ed P_f	8th Ed P_g	8th Ed P_f	Increase/ decrease	1/2 family P_g	1/2 family P_f	P_f, adjusted for temp	PV Dead Load	Roof Dead Load	Original Total Load	With PV Total Load	% increase in Total Load
	lbs/ft^2	lbs/ft^2	lbs/ft^2	lbs/ft^2	lbs/ft^2	lbs/ft^2	lbs/ft^2	lbs/ft^2	lbs/ft^2	lbs/ft^2	lbs/ft^2	%
			C x 0.7	D - B		F x 0.7	G x 1.15			G + J	H + I + J	L / K - 1
Boston	30	45	31.5	1.5	40	28	32.2	3.5	10	38	45.7	20%
Cambridge	30	45	31.5	1.5	40	28	32.2	3.5	10	38	45.7	20%
Falmouth	25	35	24.5	-0.5	30	21	24.2	3.5	10	31	37.7	21%
Harvard	35	55	38.5	3.5	50	35	40.3	3.5	10	45	53.8	19%
Hatfield	35	55	38.5	3.5	40	28	32.2	3.5	10	38	45.7	20%
Pittsfield	40	65	45.5	5.5	50	35	40.3	3.5	10	45	53.8	19%
Rutland	35	55	38.5	3.5	50	35	40.3	3.5	10	45	53.8	19%
Winchester	30	55	38.5	8.5	40	28	32.2	3.5	10	38	45.7	20%
											Average	**20%**

Definitions

P_f	Flat roof snow load (pounds per square foot)
P_g	Ground snow load (pounds per square foot)
C_t	Coefficient which relates snow load including effective temp of supporting structure

In order to consider all four original Massachusetts State Building Code (MSBC) snow zones (see Figure 3), we selected eight cities and towns from the 25 that we surveyed as part of this assignment that have a significant amount of PV installed. The first step was to determine the expected snow load for

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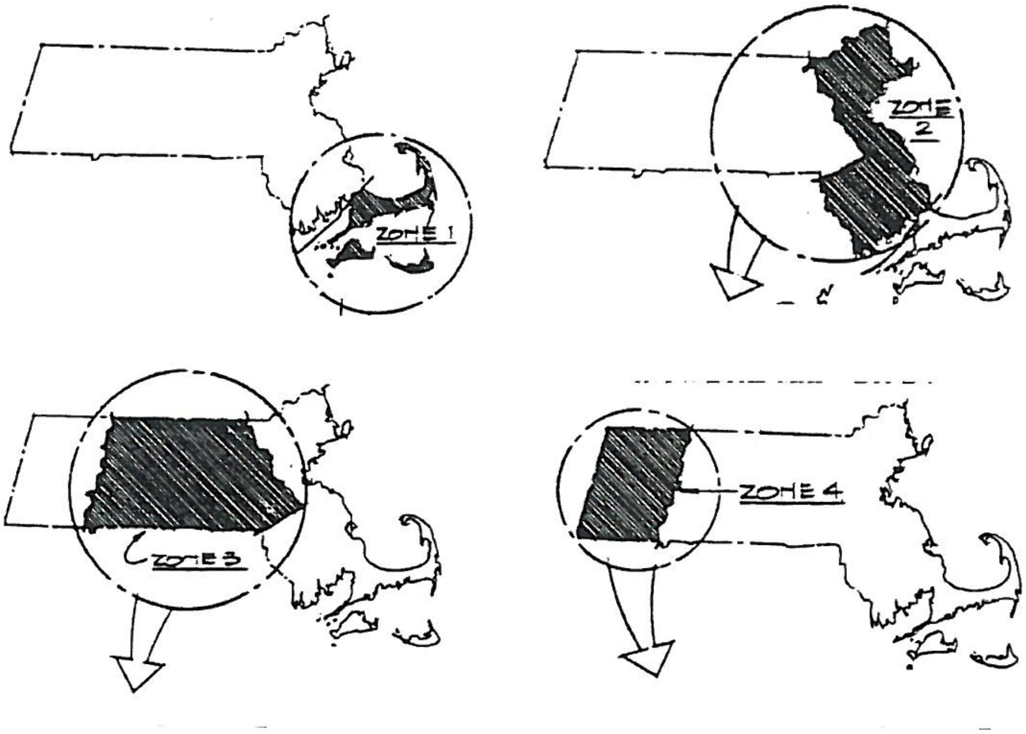
each municipality in flat roof snow load, rather than ground snow load. The 5th and 6th editions of the MSBC use P_f (flat roof snow load) (values shown in Column B), while the current 8th edition MSBC utilizes P_g (ground snow load) (values shown in Column C). Employing the ASCE 7 recommended conversion coefficient we converted the P_g numbers in the 8th edition to P_f (Column D). The resulting P_f numbers for the 8th edition were compared to the P_f numbers in the 5th and 6th editions to determine whether the 8th edition MSBC represented an increase or a decrease in the snow load effects for each town (as shown in column E). This comparison showed that expected snow load decreased for some municipalities by 0.5 pounds per square foot (psf) and increased for some municipalities by as much as 8.5 psf, as a result of the "re-drawn" snow zone differentiating lines prior to the issuance of the 7th edition MSBC.

Figure 3 Snow Load Zones – Massachusetts State Building Code, 6th Edition



We also recognized that the one- and two-family dwelling building code requirements were included as Chapters/Articles through the 6th edition of the MSBC. However, these residential buildings requirements are now contained in the International Residential Code (IRC) with Massachusetts amendments. From the IRC with Massachusetts amendments, we determined the current P_g for one-two family dwellings for each municipality (Column F) and converted these numbers to a basic P_f (snow load on flat roofs) (Column G). This P_f was then further modified as required by ASCE 7-05, by applying coefficients I, C_e and C_t to the code values. I refers to the importance factor of the building based on its occupancy category. C_e is the coefficient associated with exposure, where less exposure to wind (i.e., confined within high conifer type trees) translates to a higher coefficient. C_t is the coefficient that adjusts snow load given the existing temperature of the supporting structure. In the case of the

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prescriptive analysis that is described later in this report, I=1.0 (Type II: Occupancy Category). Terrain Category B or C was considered as "partially exposed" resulting in $C_e = 1.0$ (which is not overly conservative but considered realistic for normal residential buildings in neighborhoods and communities; as opposed to isolated buildings on mountainsides or deep within a heavily wooded environment.). $C_t = 1.15$ was used as an average of the unheated attic space and a space kept intentionally below freezing.

Applying the described coefficients, the snow load for the average of the combinations of the coefficients resulted in an adjusted P_f as shown in column H.

Typical 60 cell PV modules weigh 2.48 psf. The associated framing required to adequately support these modules include 2 module rails per module and 1 base rail per module. These are customarily aluminum and weigh slightly less than 1 pound per linear foot. Typical module dimensions are 40 inches wide by 65 inches long resulting in approximately 12 feet of framing per module, equaling approximately 11 pounds of framing, plus approximately 5 pounds for the stainless steel lag screw and aluminum offset post and flashing. The area of the module is approximately 18 square-feet which results in approximately 1 psf of framing. This 3.5 psf dead load of a PV system is shown in Column I.

The assumed roof dead load of 10 psf, which is currently included in the IRC, is shown in Column J. This dead load accommodates a composition shingle or other lightweight material roofing, not clay tile or any other cement based products.[4]

Based on the above components, the gravity design loading was determined consistent with the original design conditions without PV, as shown in column K. Adding PV to the roof necessitates that the inclusion of the PV dead load and the temperature effects of snow on the slightly elevated modules be added to the roof dead load, summed to a new gravity design loading as shown in Column L. A comparison of total gravity design loads is shown in column M. This shows that the addition of the PV can result in an increase of total gravity design load by an average of approximately 20%.

The above comparative analysis results in the decision to develop a span table for frequently used roof framing members, spacing, lumber species and grade of material to reflect the slightly increased gravity design loading effects by reducing the spanning capability appropriately. Deflections were also included in the analysis by limiting total load deflection to L/180, where L is the length of the rafter. The table lists the maximum allowed span for the rafter member size based on allowed stress or limiting deflection to L/180, whichever is less.

The use of the Maximum Rafter Span table requires the user to determine the Code required ground snow load, and to identify the rafter species and grade, size and spacing to identify the maximum span for the framing. If the existing span is less than the maximum span of the table for the ground snow, rafter material and species and rafter size and spacing, then PV may be installed on the roof without further analyses. Otherwise, a Registered Design Professional (e.g., a Professional Engineer, a Structural

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[4] If clay tiles or any other cement based products are used in the roof, an engineer should be involved to determine weight considerations as well as fastening and support details.

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Engineer, or an Architect who can perform the required services) should be consulted. The maximum spacing of PV supports is stipulated to be twice the rafter spacing and alternating such that all rafters carry the proposed system. There are several limiting conditions contained in the table such as the shorter of the stress limiting span and the maximum span where deflection will be limited to L/180 is listed.

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