FINAL REPORT

SOLARSTRAP

ROOFTOP SOLAR RACKING SYSTEM

WIND ENGINEERING CONSULTING SERVICES

RWDI #1803163

December 3, 2019

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EXECUTIVE SUMMARY

RWDI was retained to assess the wind loads for the SolarStrap Rooftop Solar Racking System. The system has several attachment options and can be configured to multiple different angles; namely 5°, 10°, 15°, and 20°. Additionally, the 15° system can be mounted at a higher height off the roof surface to take advantage of bifacial panels.

Key points

- The wind loading coefficients were determined using RWDI's aerodynamic knowledgebase. The data in the knowledgebase is from wind tunnel test procedures that met or exceeded the requirements set out in the ASCE 7-10 and ASCE 49-12. No specific wind tunnel test was performed for the SolarStrap system geometry.
- Recommended wind loading coefficients are provided for uplift, downforce and drag as appropriate. The wind loading is presenting as coefficients such that they are compatible with the approaches outlined in American Society of Civil Engineers (ASCE) 7-05 / International Building Code (IBC) 2009, ASCE 7-10, ASCE 7-16 / IBC 2012, IBC 2015, IBC 2018, National Building Code of Canada (NBCC) 2005 / Ontario Building Code (OBE) 2006, NBCC 2010 / OBC 2012, NBCC 2015.
- The recommended pressure coefficients are provided in Tables 2 through 6. The array is divided into aerodynamic zones as indicated in the key plan following the pressure coefficient tables.
- Effect of building size is discussed in Section 3.2.2.
- Racking system applicability tolerances are presented in Section 3.
- Guidelines to determine required ballast or array penetrations are presented in Section 4.
- Guidelines on how to apply RWDI's recommended wind loading coefficients to smaller arrays are included in Appendix A.
- **It is important to identify which averaging scenario is appropriate for a given installation. A test could be performed physically on a mock-up of a typical array of panels or the stiffness could be determined analytically. It is the responsibility of the design team to select the appropriate averaging area for the particular racking system that is being installed. The selection of the appropriate averaging areas and ballasting scheme assume that the ballast will remain in place during the design wind event.**

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2	August 21, 2018	Title Page Made Final	Sarah Stenabaugh
3	December 3, 2019	All	Sarah Stenabaugh

1 INTRODUCTION

Rowan Williams Davies & Irwin Inc. (RWDI) was retained by SolarStrap to provide Wind Engineering Consultation on the SolarStrap Rooftop Solar Racking System. This report presents the project objectives, background, approach, and provides a discussion of the results from RWDI's assessment. A summary of the overall recommendations from the assessment is presented in the Executive Summary.

1.1 Project Description

It is our understanding that the SolarStrap Rooftop Solar Racking System has several attachment options (see images below) and can be configured to multiple different tilt angles (namely 5°, 10°, 15° and 20°).

NON PENETRATING SOLUTION
TPO, PVC, Asphalt

POSITIVE ATTACHMENT SOLUTION
Plywood, OSB, Concrete, Metal Deck

FRAMELESS SOLUTION
Non Penetrating or Positive Attachment

BALLASTED SOLUTION
Non Penetrating or Hybrid System

1.2 Objectives

The objective of this assessment was to recommend the wind loads acting on the solar panels when mounted on a typical flat roof commercial building. The primary consideration for design was the wind-induced upward force, in the interest of determining the ballast required to resist it.

The intent was to recommend simplified procedures for prescribing wind pressures on the PV modules, for use in ballasting considerations, consistent with the following standards:

- ASCE 7-05, and therefore the International Building Code (IBC) 2006 and 2009;
- ASCE 7-10, and therefore IBC versions 2012 and 2015 as well as State/county adoptions of these IBC versions, such as the California Building Code 2016 (which is based off IBC 2015);
- ASCE 7-16, and therefore IBC version 2018 as well as State/county adaptations of the 2018 IBC;
- National Building Code of Canada (NBCC) 2005, and therefore the Ontario Building Code (OBC) 2006; and
- NBCC 2010 and therefore OBC 2012, and NBCC 2015.

2 BACKGROUND AND APPROACH

2.1 Methodology

2.1.1 Aerodynamic Knowledgebase

RWDI has established an aerodynamic knowledgebase of wind load information for roof-mounted solar arrays. This knowledgebase has been developed through numerous wind tunnel investigations of roof-mounted solar racking systems with varying aerodynamic properties. The majority of the data are based on generic industrial buildings approximately 30 ft (9 m) in height, and plan dimensions on the order of 100 ft × 100 ft (30 m × 30 m). Taps and instrumentation that measure fluctuating wind pressure were installed on the top and bottom surfaces of the panels at numerous locations. Images of representative wind tunnel models are shown in Figure 1. This knowledgebase was leveraged to generate wind loading coefficients in the absence of system-specific wind tunnel research.

2.1.2 Upwind Terrain

Beyond the modeled area, the influence of the upwind terrain on the planetary boundary layer was simulated in the knowledgebase testing by appropriate roughness on the wind tunnel floor and flow conditioning spires at the upwind end of the working section for each wind direction. This simulation was targeted to represent a generic suburban terrain condition (Exposure B as defined in the ASCE 7 and NBCC) for all wind directions. The coefficients were determined by normalizing the wind tunnel measurements by a reference wind pressure in the same exposure. This is consistent with the approach taken by the building codes to develop coefficients. As such, the coefficients can be utilized in more open exposures, Exposure C and D (ASCE 7) or Exposure A (NBCC), provided the appropriate exposure factor is applied.

2.1.3 Wind Speed

To obtain full-scale wind pressures for U.S.A. installations, the GC_p (equivalent to GC_n) values are multiplied by a 3-second gust wind pressure (q_z), as defined in the ASCE 7-05, ASCE 7-10, and ASCE 7-16. To obtain full-scale wind pressures for Canadian installations, the C_pC_g values are multiplied by a design reference pressure (q) and exposure factor (C_e), as defined in the NBCC. The NBCC and OBC (Ontario Building Code) provide tables giving a specific value of q for each community listed.

As an example, a reference wind pressure of 0.46 kPa corresponds to a basic wind speed consistent with the ASCE 7-05 definition of a 3-second gust at 33 ft (10 m) in open country terrain of 90 mph; this value is the typical non-hurricane 50-year design wind speed for the majority of the continental U.S in ASCE 7-05.

Table 1 provides a summary of the conversions between the ASCE and NBCC definitions of wind speed and pressure. In other jurisdictions, it is possible that the definition of the design wind speed could be different. To convert to gust durations other than mean hourly or 3-second, Figure C6-4 in the ASCE 7-05 (Figure C26.5-1 in ASCE 7-10 and 7-16) may be used.

It should be noted that the design reference pressures in the NBCC, and the basic wind speeds specified in ASCE 7-05 correspond to a nominal return period of 50 years. This means that the probability of experiencing this speed in any given year is 1/50 or 2%. Building codes/standards often provide design wind speeds or pressures for multiple return periods. If a different return period is determined to be appropriate by the design team, the corresponding design wind speed or pressure should be used. The results of the knowledgebase testing are not specific to any one particular location, and therefore, local wind speeds and directional biases in the wind climate are not reflected in the predictions. It is assumed that the wind for design purposes approaches from the worst direction for the panel under consideration.

2.1.4 Determination Design Wind Pressures from Wind Tunnel Test Results

For design of solar arrays, the differential (net) wind pressure acting across an appropriate PV element must be considered. The results provided in this report include the contributions of the wind pressures acting on both the upper and lower surfaces of the PV modules (measured directly on the scale model during the knowledgebase wind tunnel testing). The net pressure acting on each array element was determined by directly measuring the instantaneous area-weighted pressure difference across the element. The wind pressure patterns affecting any structure vary both spatially and with time and are very complex. The force or stress generated in any one component of the structure depends to some extent on the continually changing pressure pattern over the entire structure. For the design of a particular structural element which in this case can be an individual panel or a connected group of panels, the relevant wind loads are those acting simultaneously over the element's tributary area. For example, assume one loading condition of interest to be that which causes the highest overall upward force on an array.

In this case, to determine the upward force, L, one would need to determine the highest instantaneous value of

$$L = p_1 A_{1p} + p_2 A_{2p} + p_3 A_{3p}$$

where p_1, p_2, p_3, etc. are the instantaneous pressures measured at representative pressure taps 1, 2, 3, etc. and A_{1p}, A_{2p}, A_{3p}, etc. are the tributary areas associated with each of the pressure taps. Each term in the above summation is the contribution to the normal force coming from one of the areas. Since some of the taps are situated on the bottom of the panels, they have negative signs applied to their areas, thus producing instantaneous net forces. Because of lack of correlation of the wind pressures over the area, the individual terms do not all reach their peak at the same instant in time. Therefore, to determine the true peak upward force, it is important to carry out the above summation on a continuous and instantaneous basis. The results are usually expressed in coefficient form. For example, in the case of the upward force, the force is divided by the reference wind pressure, q_g, and the tributary area, A, to obtain

$$\frac{L}{q_g A} = \frac{1}{q_g}\left(\frac{p_1 A_{1p}}{A} + \frac{p_2 A_{2p}}{A} + \frac{p_3 A_{3p}}{A}\right)$$

The summation in the brackets on the right hand side, obtained on an instantaneous basis from the wind tunnel, is the overall upward force divided by the surface area and so is an area-averaged pressure. It may also be evident that as the above summation is carried out over progressively larger areas, the area-averaged pressure will reduce. This effect is generally reflected in NBCC and ASCE 7 curves for pressures on components and cladding.

In this investigation, the primary concern of the design team was the ballast requirements to resist lift-off of the panels. Therefore, uplift force was the primary focus of the assessment, although forces in the downward and lateral (drag) directions were also examined. The uplift forces were predicted for several averaging (tributary) lengths/areas of the array. The first was for loads representing an individual PV module, assuming that an individual panel within the array is structurally separated from the adjacent panels and depends on its own ballasting system. This assumption is also applicable for the design of the panel supports. The rest were for progressively larger averaging areas representing 2 PV modules in the east-west direction by 1 row in the north-south direction, 1 module by 2 rows, and 2 modules by 2 rows. Each of these averaging areas assumes in its own case to be able to contribute to resisting the applied load through redistribution (i.e., sharing) of the wind load. This approach provides insight into the loading of an installation where the strong interconnection allows ballast and system weight of components further away to assist in holding the modules in place.

It is important to identify which averaging scenario is appropriate for a given installation. A test could be performed physically on a mock-up of a typical array of panels or the stiffness could be determined analytically. It is the responsibility of the design team to select the appropriate averaging area for the particular racking system that is being installed. The selection of the appropriate averaging areas and ballasting scheme assume that the ballast will remain in place during the design wind event.

2.2 Criteria

The recommendations for wind loads provided in this report are based on a knowledgebase of wind tunnel tests employing procedures that meet or exceed the requirements set out in Section 31.2 of the American Society of Civil Engineers (ASCE) 7-10 Standard and ASCE 49-12. The intent was to recommend simplified procedures for prescribing wind pressures on the panels, consistent with the following Standards/Codes:

- ASCE 7-05, and therefore the International Building Code (IBC) 2006 and 2009;
- ASCE 7-10, and therefore IBC versions 2012 and 2015 as well as State/county adoptions of these IBC versions, such as the California Building Code 2016 (which is based off IBC 2015);
- ASCE 7-16, and therefore IBC version 2018 as well as State/county adaptations of the 2018 IBC;
- National Building Code of Canada (NBCC) 2005, and therefore the Ontario Building Code (OBC) 2006;
- NBCC 2010 and therefore OBC 2012; and,
- NBCC 2015.

3 RESULTS AND DISCUSSION

3.1 Recommended Design Wind Pressures

Design recommendations are given in the form of GC_p values for use with the ASCE 7, and C_pC_g values for use with the NBCC. As described in Section 2.1.4, the provided GC_p and C_pC_g values are differential (net) pressure coefficients and as such do not need to be augmented by an internal pressure coefficient (GC_{pi} or $C_{pi}C_{gi}$). These pressure coefficients represent the worst-case wind directions and are the combination of data obtained for 36 wind directions modeled in the wind tunnel.

Note that the wind pressure coefficients provided in this report do not include the effects of the directionality in the local wind climate or the effects of the immediate surrounding terrain or topography. These coefficients do not contain safety or load factors and are to be applied to the solar arrays in the same manner as would wind loads calculated by code analytical methods. Hence it is suggested that appropriate load factors as required by the building official of jurisdiction should be applied to the wind pressures when determining ballasting schemes. Unless otherwise specified by the building official of jurisdiction, these load factors should be taken from Chapter 2 of ASCE 7 for U.S.A. installations and Section 4.1.3.2 of NBCC for Canadian installations.

It is recommended that the uplift, downward and drag wind pressure coefficients presented in Tables 2 through 5 be considered for buildings with SolarStrap Rooftop Solar Racking System installations based on the aerodynamic parameters in Section 3.2.3 for 5°, 10°, 15°, and 20° tilt angles respectively. Coefficients for the 15° system mounted higher off the roof are in Table 6. The data provided in Tables 2 through 6 are categorized into six aerodynamic zones of an array: North Corner, North Leading Edge, East and West Edges, Field, South Corner, and South Leading Edge. These are described further in Section 3.2.2 and in the Notes section following the tables. Pressure coefficients are tabulated for conditions of no parapet (less than 0.5 H_{array}). For parapet heights greater than 0.5 H_{array}, the coefficients presented in Tables 2 through 6 should be multiplied by the appropriate multiplication factor from the plot in Figure 2. These factors are the result of extensive research conducted by RWDI, both of the proprietary and published nature[1].

Pressures derived using the recommended coefficients may be applied to the area of all SolarStrap Rooftop Solar Racking System modules within the selected averaging area projected onto a horizontal plane for direct estimate of uplift/downforce force (i.e., directly accounting for the cosine of the tilt angle), or a vertical plane for determining drag force component.

[1] Wind loading on tilted roof-top solar arrays: The parapet effect. *Journal of Wind Engineering and Industrial Aerodynamics.* 2013 (123A). https://doi.org/10.1016/j.jweia.2013.08.013

3.2 Applicability of Results

3.2.1 Applicability of Wind Load Recommendations

The arrays are to be installed on typical horizontal or low-slope (≤ 1:8) flat roof commercial buildings. Other SolarStrap system designs/geometries than those considered in the scope of this investigation could produce different wind loads. If significant buildings deviating from standard terrain conditions, as defined by the governing building code or standard, are located near the project site, then some load changes could occur. System specific aerodynamic properties and tolerances are provided in Section 3.2.3. Wind load coefficients have been provided in Tables 2 through 4 for a parapet height less than 0.5 H_{array}. For installations with a parapet height greater than 0.5 H_{array}, a multiplication factor from Figure 2 should be applied.

The setback from the roof edge, *s*, is defined in Example 1. Mounting closer than 3 ft (1.0 m) to the roof edge could change the recommendations. The maximum permissible setback to use the tabulated coefficients is 0.5 *h*, where *h* is the building height. When the setback is greater than 0.5 *h*, a factor of 1.5 must be applied to the coefficients for the exposed, leading 2 modules in the east-west direction and 1 row in the north-south direction.

Mounting within a distance equal to the height of a large roof obstruction could change the recommendations, where a large roof obstruction has frontal area of dimensions greater than 5 H_{array} high and 5 H_{array} wide. If this is the case, then RWDI should be contacted to comment on the probable effects and possibly to determine additional appropriate design wind pressures. Where open areas on the roof that exceed 10 ft (3 m) in width, which are caused by clearance provided around objects or for access routes, new corner or edge zones are formed where the array meets them.

The coefficients in Tables 2 through 4 are applicable for modules with areas between 17 ft^2 (1.6 m^2) and 23.5 ft^2 (2.2 m^2). The provided coefficients apply to contiguous arrays and sub-arrays with minimum size equal to 4 modules in the east-west direction by 4 rows in the north-south direction. For smaller arrays or sub-arrays guidelines for selecting appropriate coefficients are presented in Appendix A. For arrays and sub-arrays equal to or greater than the minimums above, to use a given averaging area, the number of interconnected modules must be at least equal to the number of modules within the selected averaging area.

It is important to identify which averaging scenario is appropriate for a given installation. A test could be performed physically on a mock-up of a typical array of panels or the stiffness could be determined analytically. It is the responsibility of the design team to select the appropriate averaging area for the particular racking system that is being installed. The selection of the appropriate averaging areas and ballasting scheme assume that the ballast will remain in place during the design wind event.

3.2.2 Effect of Building Size

The pressure coefficients in Tables 2 through 6 are valid for a particular range of building sizes ranging in height and plan dimensions. Figure 3 provides factors to adjust the tabulated pressure coefficients for a much larger range of building sizes. These factors are based the pressure coefficient curves presented in the SEAOC PV2 document and are a function of L_b, evaluated based on building height and plan dimension.

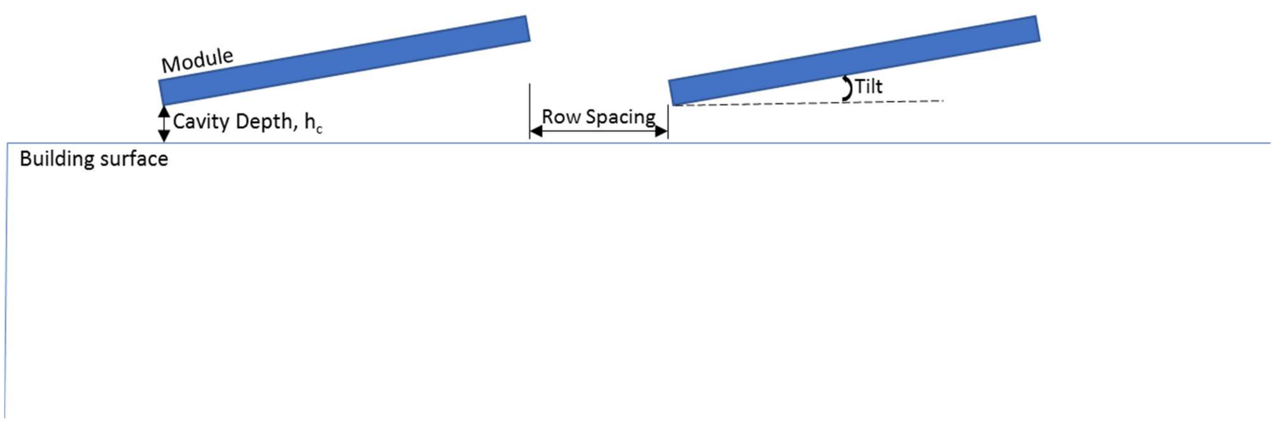
The effect of building size on the location of peak wind loading is less defined, although the limited published literature on the topic indicates that as the building height increases (within the range investigated) the location of the peak loading moves slightly inward from the array corner/edge zones. The peak wind loads are generated by corner vortices that affect the perimeter roof zone of a building, the size of which is dependent on building dimensions. A perimeter roof zone is defined with a width equal to the minimum of 0.6 h and 0.1 W_L from the building edge, where h is the building height and W_L is the width of the building on its longest side. Modules located within this perimeter roof zone will be subject to higher wind loading from the building aerodynamics and must be classified as corner or edge aerodynamic array zones.

Corner Zones are aerodynamic zones at the corners of an array produced by wind exposure of the leading modules and do not benefit from sheltering from adjacent modules on two sides. At a minimum, the Corner Zones encompass a roof area equaling three modules in the east-west direction and three rows in the north-south direction, with open roof on two sides. Edge Zones are aerodynamic zones along the North, South, East, or West edges of an array between Corner Zones produced by the wind exposure of leading modules and do not benefit from sheltering from adjacent modules on only one side. At a minimum, the Edge Zones encompass a roof area equaling three modules in the east-west direction, or three rows in the north-south direction, surrounded by open roof that do not fall in a Corner Zone. If there are modules within the perimeter roof zone that are not corner or edge at the minimum zone size, the size of the corner or edge zone must increase in size. This is shown graphically in the Key Plan and Examples and discussed in Appendix B.

3.2.3 Racking System Tolerances

The wind loading recommendations in this report are applicable for the design of the SolarStrap Rooftop Solar Racking System, based on the information received as of April 30, 2018 and October 23, 2019. The following table provides tolerances for the key dimensions (see schematic image below table) such that the coefficients in this report can still be used. Further wind tunnel research may be required to accurately define the relationship between the data in this report and those for other parameters, if outside the listed tolerances.

Parameter	Value	Applicability Tolerance / Range
Module Area	21 ft^2 (1.9 m^2)	17 ft^2 (1.6 m^2) through 23.5 ft^2 (2.2 m^2)
Setback from roof edge, *s*	3 ft (1m)	Tables 2 through 6: 3 ft (1 m) ≤ s ≤ half building height, ½*h* *See Section 3.2.1 for ½h ≤ s ≤ h*
Tilt, *θ*	5°, 10°, 15°, 20°	Table 2: 4° ≤ *θ* ≤ 6° Table 3: 9° ≤ *θ* ≤ 11° Table 4: 14° ≤ *θ* ≤ 16° Table 5: 19° ≤ *θ* ≤ 21° Linear interpolation permitted between Tables 2 through 5 Table 6: 14° ≤ *θ* ≤ 16°
Cavity Depth, h_c	Tables 2 through 5: 5.8" (14.7 cm) for 5°, 10°, 15° and 20° Table 6: 23.3" (59 cm)	Tables 2 through 5: ±⅝" (1.6 cm) Table 6: ±1" (2.2 cm)
Row Spacing	5°: 8" (20 cm) 10°: 13" (33 cm) 15°: 21" (53 cm) 20°: 26" (66 cm) Elevated 15°: 21" (53 cm)	±10%



4 DETERMINATION OF BALLAST

4.1 U.S.A. Installations

For U.S.A. installations using the ASCE 7-05, 7-10 or 7-16, the ballast required to resist uplift and sliding conditions may be determined using the following equations. The maximum value between these two scenarios should be used for design. **Note that the reduction factors provided apply to a single interconnected array.**

BALLAST (LB) TO RESIST UPLIFT

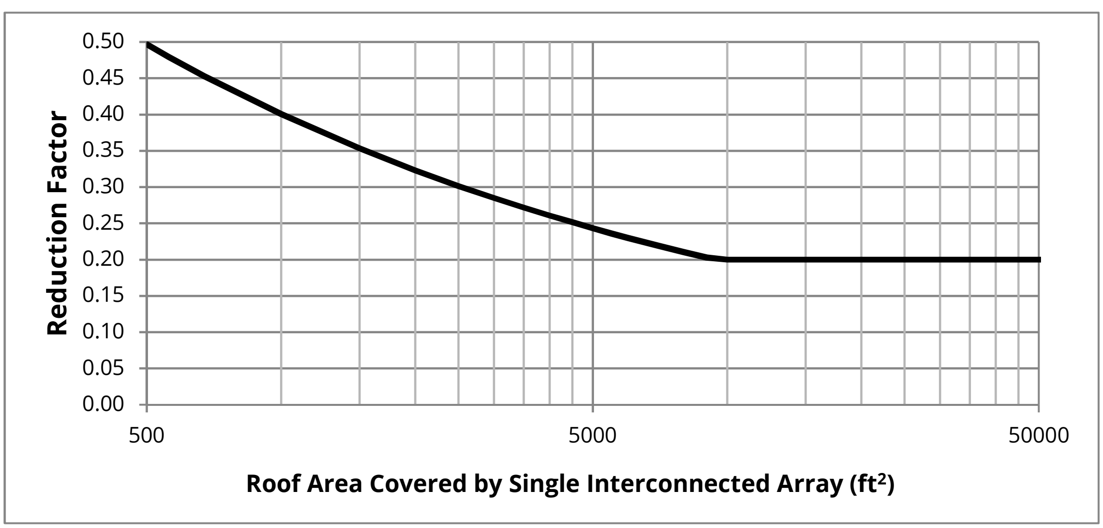
$$\alpha_D \cdot Ballast_{uplift} = \alpha_W \cdot q_z \cdot |GC_p|_{uplift} \cdot A_{uplift} - \alpha_D \cdot M \qquad (lb)$$

BALLAST (LB) TO RESIST SLIDING

$$\alpha_D \cdot Ballast_{drag} = \alpha_W \cdot q_z \cdot \left[(G\ \ _p)^*{}_{drag} \cdot A_{drag} \cdot \left(\frac{1}{f_n}\right) + |GC_p|^*{}_{uplift} \cdot A_{uplift} \right] - \alpha_D \cdot M \qquad (lb)$$

where

α_W	- factor on wind load from ASCE 7-05, 7-10 or 7-16 (Chapter 2)
α_D	- factor on dead load from ASCE 7-05, 7-10 or 7-16 (Chapter 2)
q_z	- 3-second gust wind pressure (lb/ft^2) for site location from ASCE 7-05, including exposure factor (Kz) and directionality factor (Kd = 0.85) as per 6.5.10 of ASCE 7-05 or 26.6 of ASCE 7-10 or 7-16
M	- self weight of assembled system (lb) for appropriate averaging area
f_n	- frictional coefficient
A_{uplift}	- area (ft^2) of panel(s) projected onto a horizontal plane
A_{drag}	- area (ft^2) of panel (s) projected onto a vertical plane
$\|GC_p\|_{uplift}$	- absolute value of uplift pressure coefficient from Tables 2 through 6 (as appropriate), for selected averaging area
$(GC_p)^*{}_{drag}$	- highest drag pressure coefficient from Tables 2 through 6 (as appropriate), multiplied by the appropriate area reduction factor from plot below
$\|GC_p\|^*{}_{uplift}$	- absolute value of highest uplift pressure coefficient from Tables 2 through 4 (as appropriate), multiplied by the appropriate area reduction factor from plot below



4.2 Canadian Installations

For Canadian installations using the NBCC 2005, 2010 or 2015, the ballast required to resist uplift and sliding conditions may be determined using the following equations. The maximum value between these two scenarios should be used for design. **Note that the reduction factors provided apply to a single interconnected array.**

Ballast (kg) to Resist Uplift

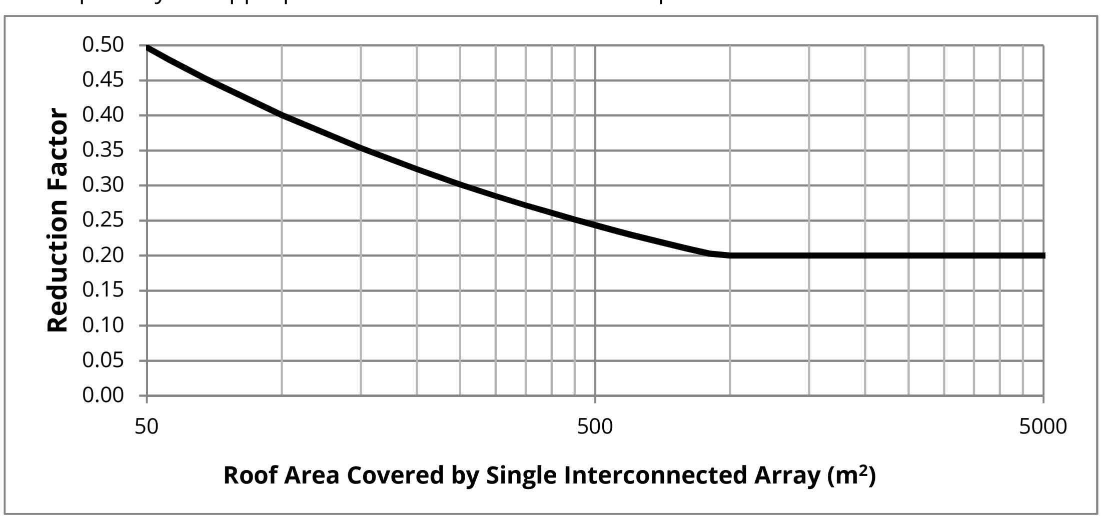
$$\alpha_D \cdot Ballast_{uplift} = \alpha_W \cdot q \cdot C_e \cdot |C_pC_g|_{uplift} \cdot A_{uplift} \cdot \left(\frac{1000}{9.81}\right) - \alpha_D \cdot M \qquad (kg)$$

Ballast (kg) to Resist Sliding

$$\alpha_D \cdot Ballast_{drag} = \alpha_W \cdot q \cdot C_e \cdot \left(\frac{1000}{9.81}\right) \cdot \left[(C_pC_g)^*{}_{drag} \cdot A_{drag} \cdot \left(\frac{1}{f_n}\right) + |C_pC_g|^*{}_{uplift} \cdot A_{uplift}\right] - \alpha_D \cdot M \qquad (kg)$$

where

α_W	- factor on wind load from NBCC 2005, 2010 or 2015 (Section 4.1.3.2)
α_D	- factor on dead load from NBCC 2005, 2010 or 2015 (Section 4.1.3.2)
q_z	- mean reference pressure (kPa) for site location from NBCC 2005, 2010 or 2015 (Section 4.1.7.1; Appendix C)
C_e	- exposure factor from NBCC 2005, 2010 or 2015 (Section 4.1.7.1)
M	- self mass of assembled system (kg) for appropriate averaging area
f_n	- frictional coefficient
A_{uplift}	- area (m²) of panel(s) projected onto a horizontal plane
A_{drag}	- area (m²) of panel(s) projected onto a vertical plane
$\|GC_p\|_{uplift}$	- absolute value of uplift pressure coefficient from Tables 2 through 6 (as appropriate), for selected averaging area
$(GC_p)^*{}_{drag}$	- highest drag pressure coefficient from Tables 2 through 6 (as appropriate), multiplied by the appropriate area reduction factor from plot below
$\|GC_p\|^*{}_{uplift}$	- absolute value of highest uplift pressure coefficient from Tables 2 through 4 (as appropriate), multiplied by the appropriate area reduction factor from plot below



4.3 Design of Array Penetrations

In some cases, the design team may choose to use penetrations, rather than ballast, to hold the array in position. The required wind loading acting on a given penetration should be determined using the pressure coefficients for an averaging area consistent with the tributary area of each penetration. For tributary areas greater than 100 ft^2 (10 m^2), the reduction factors given in the previous sections may be used in the same manner as described for ballast determination to resist sliding. For smaller areas, the coefficients given in Tables 2 through 6 (as appropriate) should be used.

Table 1: Conversions between Design Wind Speeds in ASCE 7 and NBCC

Basic 3-Second Gust Wind Speed (Vbasic) per ASCE 7		Mean Hourly Values per NBCC	
mph	m/s	$\bar{V}$ (m/s)[1]	q (kPa)[2]
85	38	25	0.41
90	40	26	0.46
100	45	29	0.56
110	49	32	0.68
120	54	35	0.81
130	58	38	0.95
140	63	41	1.10
150	67	44	1.27

Notes:

1. The factor to convert from a 3-second gust speed to mean hourly is 1/1.52, based on Figure C6-4 in the ASCE 7-05 (Figure C26.5-1 in ASCE 7-10 and 7-16).

2. Based on Equation (14) in Commentary I of the NBCC Structural Commentaries (Part 4 of Division B), the conversion from mean hourly wind speed to reference pressure is $\bar{\boldsymbol{V}} = \mathbf{3}\ \ .\mathbf{2} \cdot \sqrt{\boldsymbol{q}}$

Table 2: Recommended Pressure Coefficients, 5° Tilt Angle

Wind Force Averaging Area Number of Modules in EW Direction by Number of Rows in NS Direction	GCp Values (for use with ASCE)						CpCg Values (for use with NBCC)					
	Uplift				Downforce	Drag	Uplift				Downforce	Drag
	1 Module by 1 Row	2 Modules by 1 Row	1 Module by 2 Rows	2 Modules by 2 Rows	1 Module by 1 Row	1 Module by 1 Row	1 Module by 1 Row	2 Modules by 1 Row	1 Module by 2 Rows	2 Modules by 2 Rows	1 Module by 1 Row	1 Module by 1 Row
North Corner	-0.75	-0.60	-0.65	-0.50	1.00	1.00	-1.65	-1.30	-1.35	-1.05	1.70	1.70
North Leading Edge	-0.60	-0.45	-0.50	-0.40	1.00	1.00	-1.30	-1.00	-1.05	-0.85	1.70	1.70
East & West Edges	-0.70	-0.55	-0.60	-0.50	0.70	0.70	-1.55	-1.20	-1.35	-1.05	1.20	1.55
Field	-0.60	-0.45	-0.50	-0.40	0.65	0.65	-1.30	-1.00	-1.05	-0.85	1.15	1.30
South Corner	-0.80	-0.60	-0.65	-0.55	0.70	0.80	-1.70	-1.35	-1.45	-1.15	1.20	1.70
South Leading Edge	-0.65	-0.60	-0.55	-0.45	0.65	0.65	-1.40	-1.30	-1.15	-0.95	1.15	1.40

Table 3: Recommended Pressure Coefficients, 10° Tilt Angle

Wind Force Averaging Area Number of Modules in EW Direction by Number of Rows in NS Direction	GCp Values (for use with ASCE)						CpCg Values (for use with NBCC)					
	Uplift				Downforce	Drag	Uplift				Downforce	Drag
	1 Module by 1 Row	2 Modules by 1 Row	1 Module by 2 Rows	2 Modules by 2 Rows	1 Module by 1 Row	1 Module by 1 Row	1 Module by 1 Row	2 Modules by 1 Row	1 Module by 2 Rows	2 Modules by 2 Rows	1 Module by 1 Row	1 Module by 1 Row
North Corner	-0.95	-0.75	-0.80	-0.60	1.00	1.00	-2.10	-1.60	-1.70	-1.30	2.15	2.15
North Leading Edge	-0.75	-0.60	-0.60	-0.50	1.00	1.00	-1.60	-1.25	-1.30	-1.05	2.15	2.15
East & West Edges	-0.90	-0.70	-0.75	-0.60	0.70	0.90	-1.90	-1.50	-1.65	-1.30	1.50	1.90
Field	-0.75	-0.60	-0.60	-0.50	0.65	0.75	-1.60	-1.25	-1.30	-1.05	1.45	1.60
South Corner	-1.00	-0.75	-0.85	-0.65	0.70	1.00	-2.10	-1.65	-1.85	-1.45	1.50	2.10
South Leading Edge	-0.80	-0.75	-0.65	-0.55	0.65	0.80	-1.75	-1.60	-1.45	-1.20	1.45	1.75

Table 4: Recommended Pressure Coefficients, 15° Tilt Angle

Wind Force Averaging Area Number of Modules in EW Direction by Number of Rows in NS Direction	GCp Values (for use with ASCE)						CpCg Values (for use with NBCC)					
	Uplift				Downforce	Drag	Uplift				Downforce	Drag
	1 Module by 1 Row	2 Modules by 1 Row	1 Module by 2 Rows	2 Modules by 2 Rows	1 Module by 1 Row	1 Module by 1 Row	1 Module by 1 Row	2 Modules by 1 Row	1 Module by 2 Rows	2 Modules by 2 Rows	1 Module by 1 Row	1 Module by 1 Row
North Corner	-1.10	-0.85	-0.90	-0.70	1.10	1.10	-2.40	-1.85	-1.95	-1.50	2.45	2.45
North Leading Edge	-0.85	-0.65	-0.70	-0.55	1.10	1.10	-1.85	-1.45	-1.50	-1.20	2.45	2.45
East & West Edges	-1.00	-0.80	-0.90	-0.70	0.75	1.00	-2.20	-1.75	-1.90	-1.50	1.75	2.20
Field	-0.85	-0.65	-0.70	-0.55	0.75	0.85	-1.85	-1.45	-1.50	-1.20	1.65	1.85
South Corner	-1.15	-0.90	-0.95	-0.75	0.75	1.15	-2.45	-1.90	-2.10	-1.65	1.75	2.45
South Leading Edge	-0.95	-0.85	-0.75	-0.65	0.75	0.95	-2.05	-1.85	-1.65	-1.35	1.65	2.05

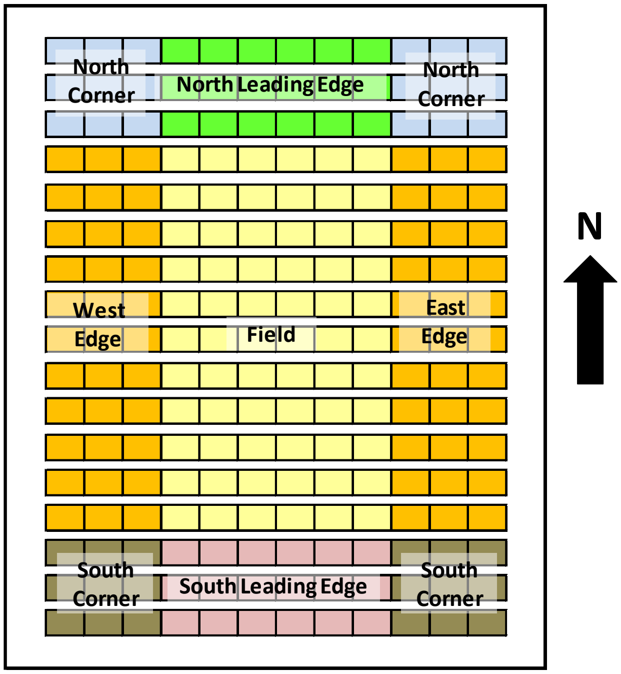
Table 5: Recommended Pressure Coefficients, 20° Tilt Angle

Wind Force Averaging Area Number of Modules in EW Direction by Number of Rows in NS Direction	GCp Values (for use with ASCE)						CpCg Values (for use with NBCC)					
	Uplift				Downforce	Drag	Uplift				Downforce	Drag
	1 Module by 1 Row	2 Modules by 1 Row	1 Module by 2 Rows	2 Modules by 2 Rows	1 Module by 1 Row	1 Module by 1 Row	1 Module by 1 Row	2 Modules by 1 Row	1 Module by 2 Rows	2 Modules by 2 Rows	1 Module by 1 Row	1 Module by 1 Row
North Corner	-1.35	-1.05	-1.10	-0.85	1.35	1.35	-2.90	-2.25	-2.35	-1.80	2.95	2.95
North Leading Edge	-105	-0.80	-0.85	-0.65	1.35	1.35	-2.25	-1.75	-1.80	-1.45	2.95	2.95
East & West Edges	-1.20	-0.95	-1.10	-0.85	0.90	1.20	-2.65	-2.15	-2.30	-1.80	2.10	2.65
Field	-1.05	-0.80	-0.85	-0.65	0.90	1.05	-2.25	-1.75	-1.80	-1.45	2.00	2.25
South Corner	-1.40	-1.10	-1.15	-0.90	0.90	1.40	-2.95	-2.30	-2.55	-2.00	2.10	2.95
South Leading Edge	-1.15	-1.05	-0.90	-0.80	0.90	1.15	-2.50	-2.25	-2.00	-1.65	2.00	2.50

Table 6: Recommended Pressure Coefficients, Elevated 15° Tilt Angle

Wind Force Averaging Area Number of Modules in EW Direction by Number of Rows in NS Direction	GCp Values (for use with ASCE)						CpCg Values (for use with NBCC)					
	Uplift				Downforce	Drag	Uplift				Downforce	Drag
	1 Module by 1 Row	2 Modules by 1 Row	1 Module by 2 Rows	2 Modules by 2 Rows	1 Module by 1 Row	1 Module by 1 Row	1 Module by 1 Row	2 Modules by 1 Row	1 Module by 2 Rows	2 Modules by 2 Rows	1 Module by 1 Row	1 Module by 1 Row
North Corner	-1.55	-1.20	-1.25	-1.00	1.50	1.55	-3.35	-2.60	-2.70	-2.15	3.25	3.35
North Leading Edge	-1.20	-0.90	-1.00	-0.75	1.50	1.50	-2.60	-1.95	-2.15	-1.60	3.25	3.25
East & West Edges	-1.40	-1.10	-1.25	-1.00	1.00	1.40	-3.00	-2.40	-2.70	-2.15	2.15	3.00
Field	-1.10	-0.85	-0.90	-0.70	1.00	1.10	-2.40	-1.85	-1.95	-1.50	2.15	2.40
South Corner	-1.55	-1.20	-1.30	-1.00	1.05	1.55	-3.35	-2.60	-2.80	-2.15	2.25	3.35
South Leading Edge	-1.30	-1.15	-1.00	-0.90	1.05	1.30	-2.80	-2.50	-2.15	-1.95	2.25	2.80

Key Plan



Notes:

1. Pressures derived using the above coefficients may be applied to the area of all SolarStrap modules within the selected averaging area projected onto a horizontal plane for the purpose of determining uplift/downforce force components, or a vertical plane for determining drag force component. For U.S.A. installations, the GCp values are to be used in conjunction with 3-second gust wind pressure qz, from the ASCE 7-05, ASCE 7-10 or ASCE 7-16. For Canadian installations, the CpCg values are to be used in conjunction with mean-hourly wind pressure q, from the NBCC 2005, NBCC 2010 or NBCC 2015.

2. The tabulated coefficients in Tables 2 through 6 should be factored by the appropriate factors from Figure 2 for the parapet height and Figure 3 for the specific building dimensions.

3. Downforce and drag coefficients for larger averaging areas may be obtained by multiplying the single module coefficient by the appropriate area reduction factor obtained from the curves presented in Section 4. These reductions only apply to averaging areas extending across at least 3 rows of the array.

4. North and South Corner Zones are aerodynamic zones at the corners of an array produced by wind exposure of the leading modules and do not benefit from sheltering from adjacent modules on two sides. Modules within the corner of the perimeter roof zone, defined as the minimum of 0.6 h and 0.1 W_L, shall be classified as corner. At a minimum, the North and South Corner Zones encompass a roof area equaling three modules in the east-west direction and three rows in the north-south direction, with open roof on two sides. Refer to the Key Plan, Application Examples and Section 3.2.2 for further information.

5. North Leading Edge, South Leading Edge and East & West Edges are aerodynamic zones along the perimeter of an array between North and South Corners produced by the wind exposure of leading modules and do not benefit from sheltering from adjacent modules on only one side. All non-corner, modules within the perimeter roof zone shall be treated as edge. At a minimum, the North Leading Edge, South Leading Edge and East & West Edges encompass a roof area equaling three modules in the east-west direction, or three rows in the north-south direction, surrounded by open roof that do not fall in a Corner Zone. Refer to the Key Plan, Application Examples and Section 3.2.2 for further information.

6. Where open areas of the roof that exceed 10 ft (3 m) in width are caused by clearance provided around objects or for access routes, new corner or edge zones are formed where the array meets them.

7. The coefficients presented for the various averaging lengths/areas are based on the assumption that the load applied can be resisted by, or shared over, this much of the array. The determination of an appropriate averaging strategy is based on the stiffness and interconnection details of the system as deemed appropriate by the design team. If requested RWDI can comment on the results of array stiffness testing. The selection of the appropriate averaging areas and ballasting scheme assume that the ballast will remain in place during the design wind event.

8. The coefficients provided in Tables 2 through 6, along with the multiplication factors in Figures 1 and 2, are applicable to a large range of building sizes with horizontal or low-slope (≤ 1:8) flat roofs.

9. The tabulated coefficients are valid for setbacks values between 3 ft (1 m) and 0.5 *h*, where *h* is the roof height.

10. Load factors as required by the building official of jurisdiction should be applied when determining required ballast.

11. The above coefficients are applicable to the SolarStrap Rooftop Solar Racking System for modules ranging from 17 ft^2 (1.6 m^2) through 23.5 ft^2 (2.2 m^2). SolarStrap designs/geometries other than those considered in the scope of this investigation could produce different wind loads.

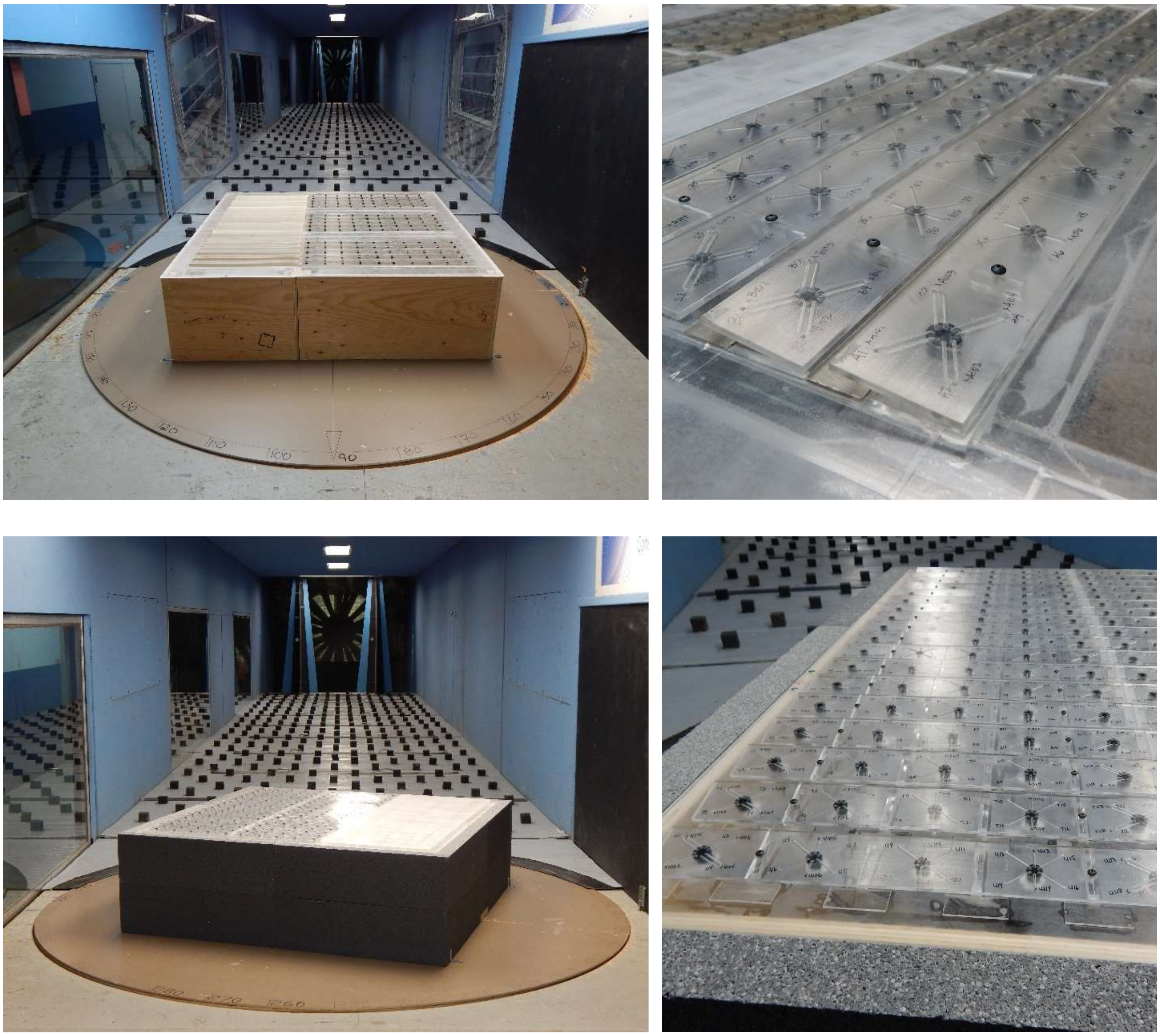
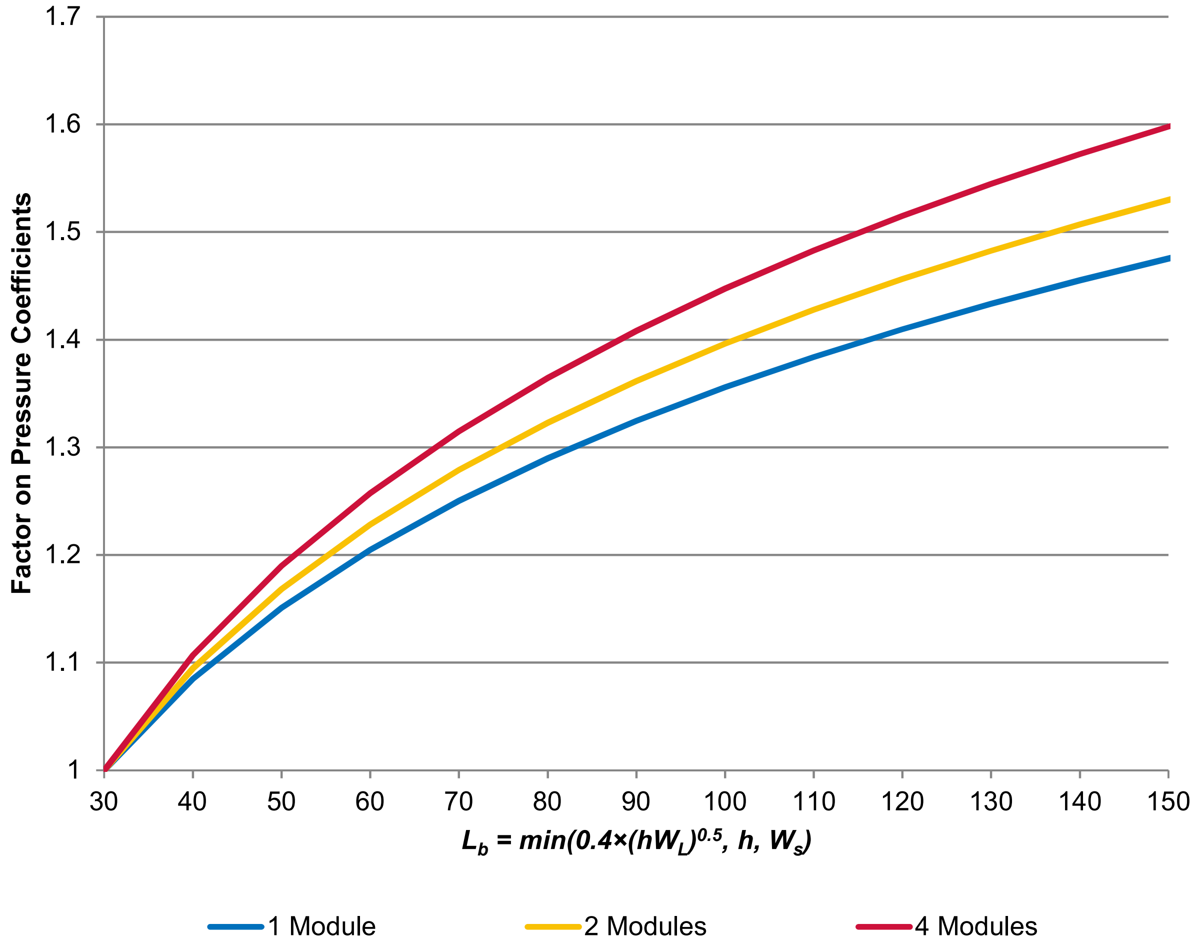


Figure 1 – Representative Wind Tunnel Models

Figure 2 - Parapet Height Factor Curve



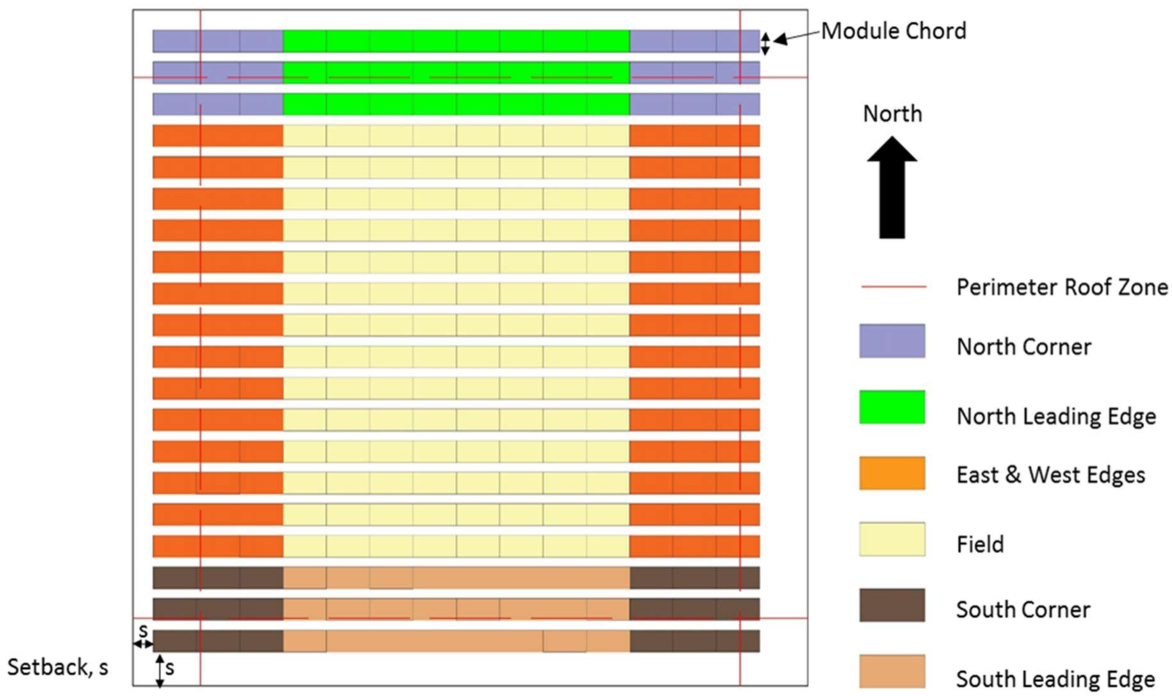
This curve is based on the curves presented in Figure 29.9-1 of SEAOC PV-2. *h* is the height of the building (in feet), W_L and W_s are the longest and shortest lengths of the building, respectively, (in feet).

Figure 3 - Building Height Factor Curve

Application Example 1 – Contiguous Array Covering Most of Roof

Colour coded to match Tables 2 though 4

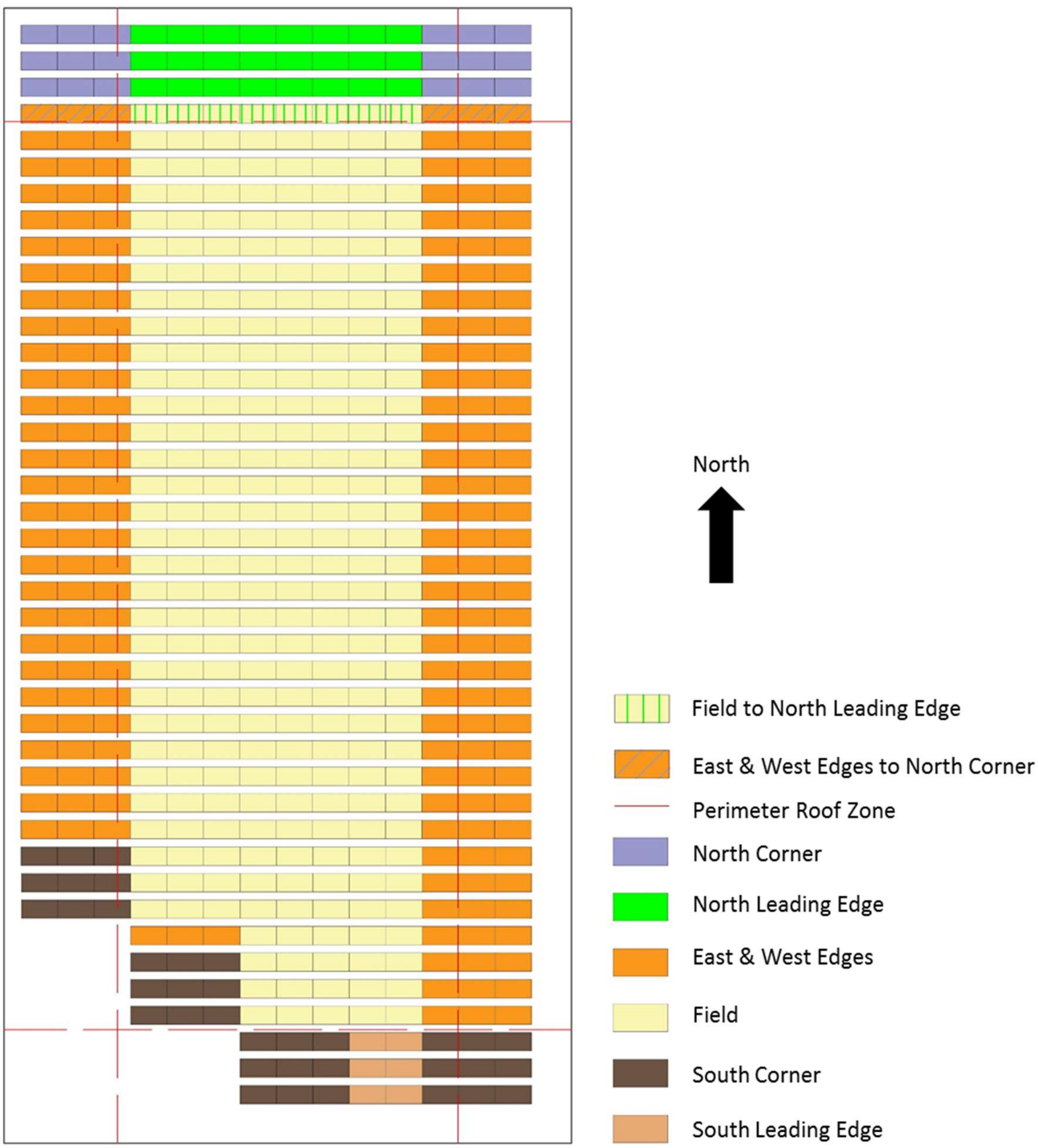
Building Dimensions	Nominally 100 ft North-South; 100 ft East-West; height 50 ft
Perimeter Roof Zone	10 ft
Setback	3 ft



Application Example 2 – Step Back Array Covering Most of Roof with Enlarged Aerodynamic Zones

Colour coded to match Tables 2 through 4

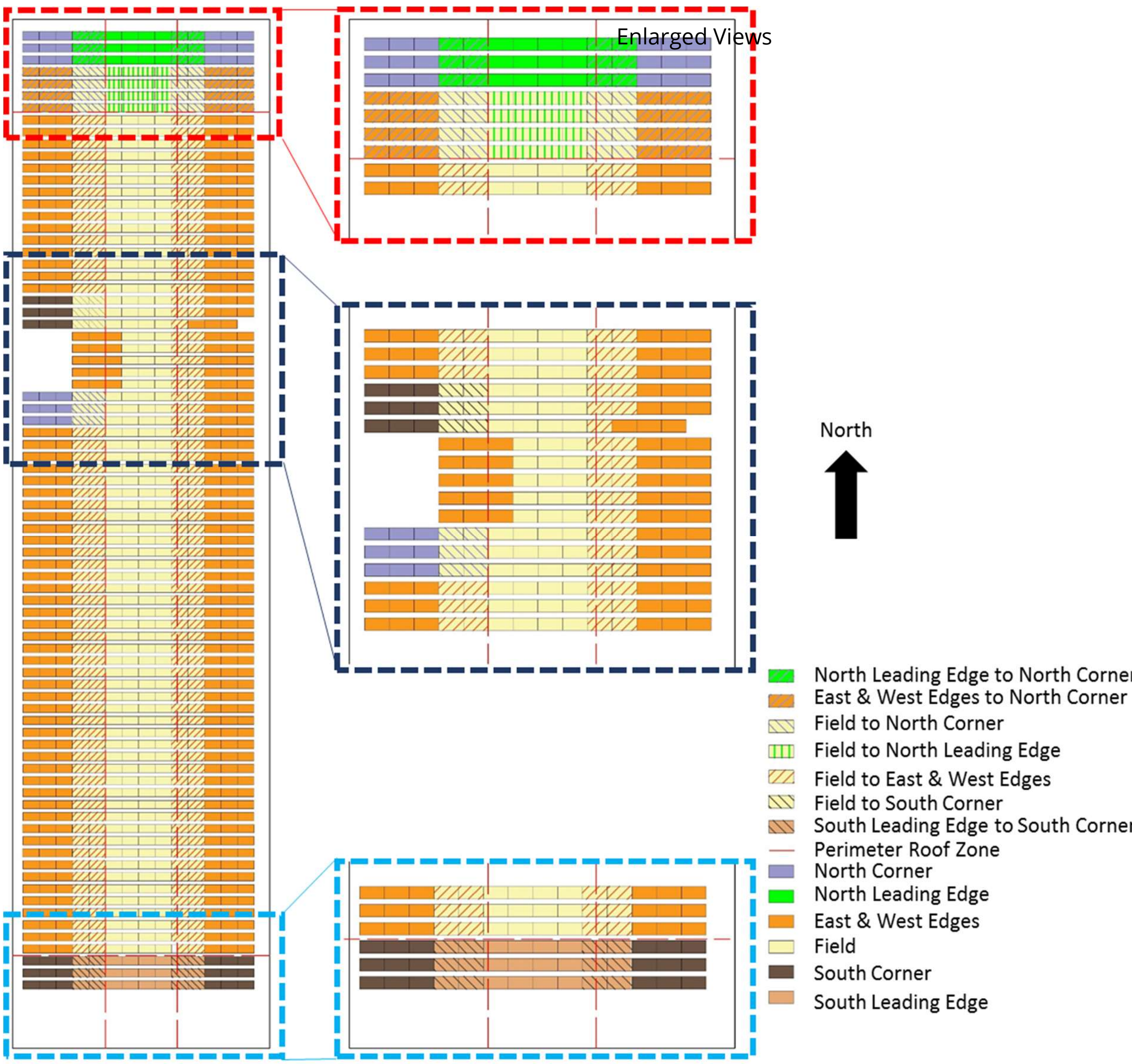
Building Dimensions	Nominally 100 ft North-South; 200 ft East-West; height 60 ft
Perimeter Roof Zone	20 ft
Setback	3 ft



Application Example 3 – Larger Building Dimensions with Enlarged Aerodynamic Zones

Colour coded to match Tables 2 through 4

Building Dimensions	Nominally 100 ft North-South; 400 ft East-West; height 60 ft
Perimeter Roof Zone	36 ft
Setback	Varies

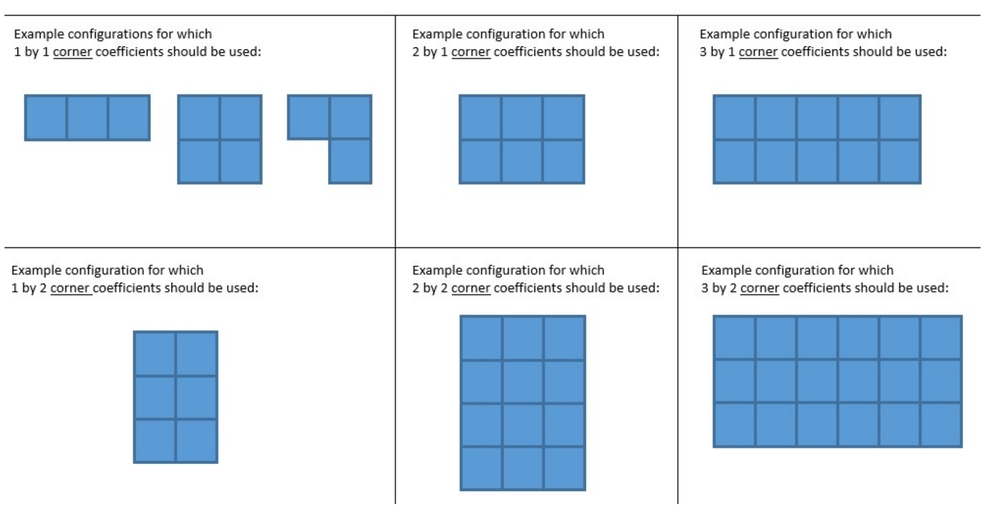


APPENDIX A: APPLICATION GUIDELINES TO SMALL ARRAYS OR SUB-ARRAYS

The provided coefficients are given for various averaging lengths/areas based on the assumption that the load applied can be resisted by, or shared over, this much of the array. As a result, the selection of an appropriate averaging length/area is based on the effective stiffness/load sharing of the array as determined by the designer. The following guidelines are intended to assist the designer in the application of the provided wind loading coefficients to various array layouts.

- To use a given averaging length/area, the minimum number of interconnected modules must be at least 3 times the number of modules within the selected averaging area. For example,
  - to use a 1 module by 1 row coefficient, there must be at least 3 interconnected modules in the array, sub-array, or array protrusion;
  - similarly, to use a 3 by 2 coefficient, there must be at least 18 interconnected modules.
- The contiguous array or sub-array must include at least one more module/row than the selected averaging length/area. For example,
  - to use a 2 modules by 1 row coefficient, there must be at least 3 interconnected modules along the row and 2 interconnected modules in the adjacent row;
  - similarly, to use a 3 by 2 coefficient, there must be at least 4 interconnected modules along the row and 3 interconnected modules in the adjacent row.
- A row is defined as interconnected modules in the east-west direction.
- There must be a minimum of 2 interconnected modules along a row within each contiguous array, sub-array, or array protrusion.
- Only corner zone coefficients may be used for contiguous arrays, sub-arrays, or array protrusions smaller than 4 modules along a row in the east-west direction in the by 4 rows in the north-south direction.

Several examples are provided below to illustrate the above guidelines for small arrays or sub-arrays.



APPENDIX B: EXAMPLES

Table B1: Dimensions for Application Example 1

Parameter	Value
(Short) Building Dimension, W_S	100 ft
(Long) Building Dimension, W_L	100 ft
Building Height, h	50 ft
Setback, *s*, North	3 ft
Setback, *s*, East	7.1 ft
Setback, *s*, South	5 ft
Setback, *s*, West	3 ft
Perimeter Roof Zone	10.3 ft
L_b	28 ft
Figure 3 Building Size Factor	1.0 for 1 module
	1.0 for 2 modules
	1.0 for 4 modules

In this example, the minimum corner and edge aerodynamic zones are larger than the perimeter roof zone and thus sufficiently large; they do not need to be enlarged.

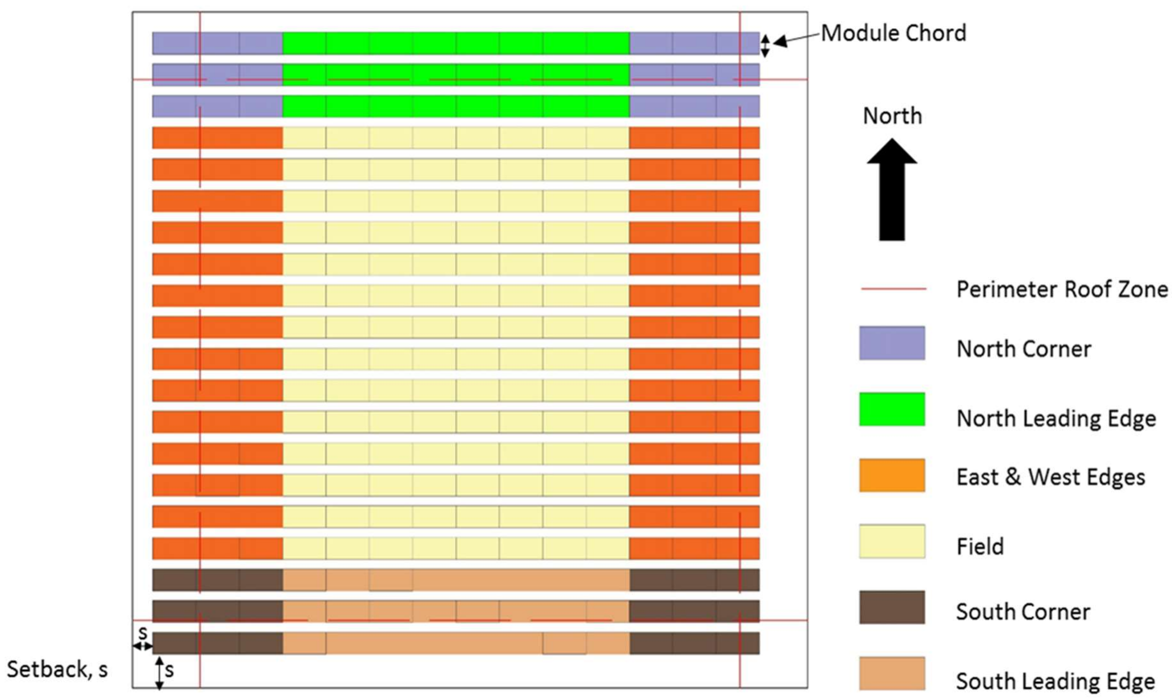


Table B2: Dimensions for Application Example 2

Parameter	Value
(Short) Building Dimension, W_S	99 ft
(Long) Building Dimension, W_L	200 ft
Building Height, h	60 ft
Setback, *s*, North	3 ft
Setback, *s*, East	7.1 ft
Setback, *s*, South	6.9 ft, 20.9 ft, 39.6 ft
Setback, *s*, West	6.9 ft, 22.3 ft, 41.6 ft
Perimeter Roof Zone	20 ft
L_b	44 ft
Figure 3 Building Size Factor	1.11 for 1 module
	1.12 for 2 modules
	1.14 for 4 modules

In this example, the minimum corner and edge aerodynamic zones on the north end of the building are smaller than the perimeter roof zone and thus they need to be enlarged. The additional modules that need to be classified as North Corner or North Leading Edge depends on the setback. The larger setback on the south end of the building is sufficiently large that the aerodynamic zones do not need to be enlarged.

Note that some of the setbacks for this example exceed the 0.5 *h* threshold for tabulated coefficients. The coefficients for the leading-edge modules will have to be factored by 1.5. Refer to Section 3.2.1 in the report for more details.

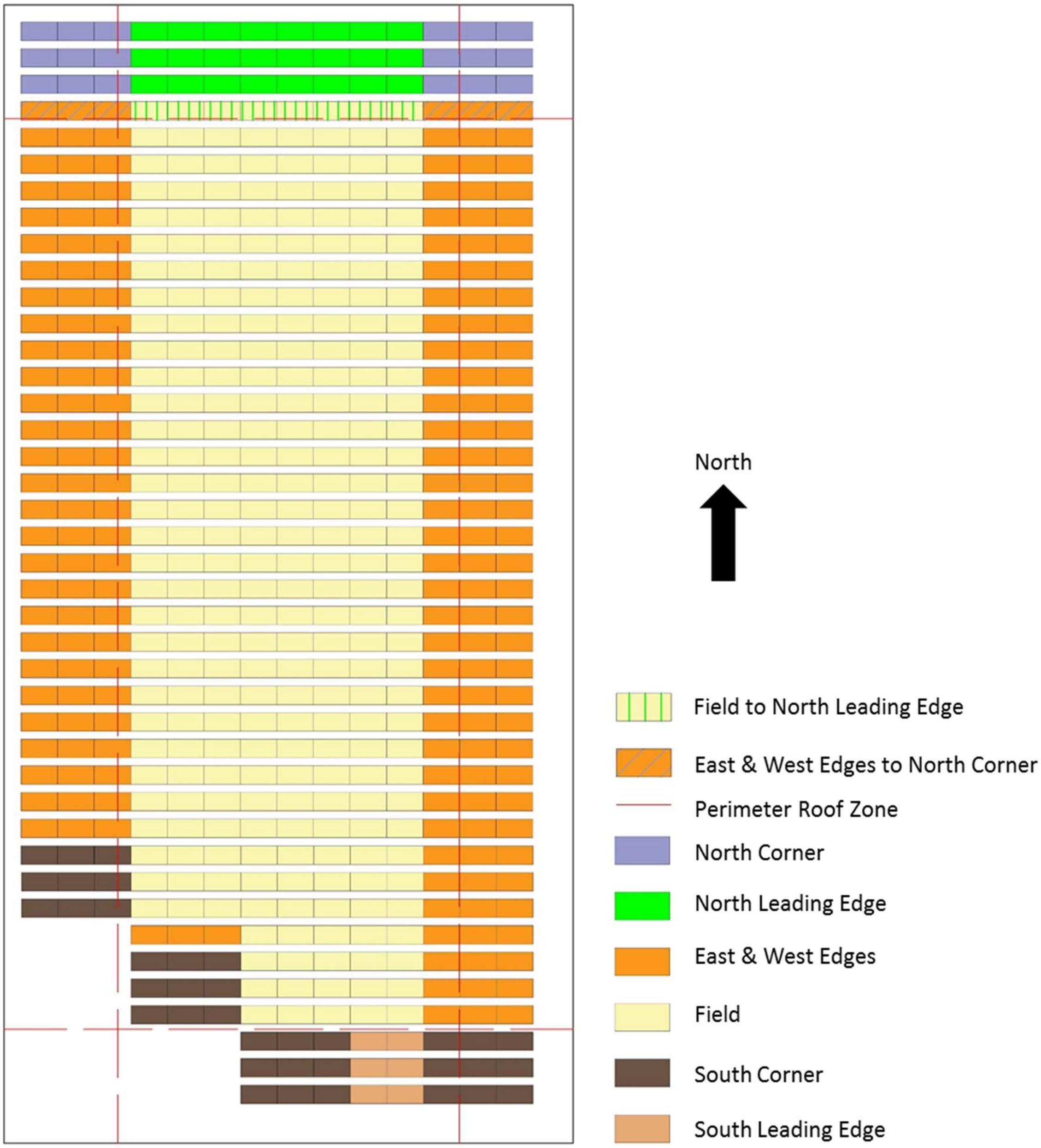

North
Field to North Leading Edge
East & West Edges to North Corner
Perimeter Roof Zone
North Corner
North Leading Edge
East & West Edges
Field
South Corner
South Leading Edge

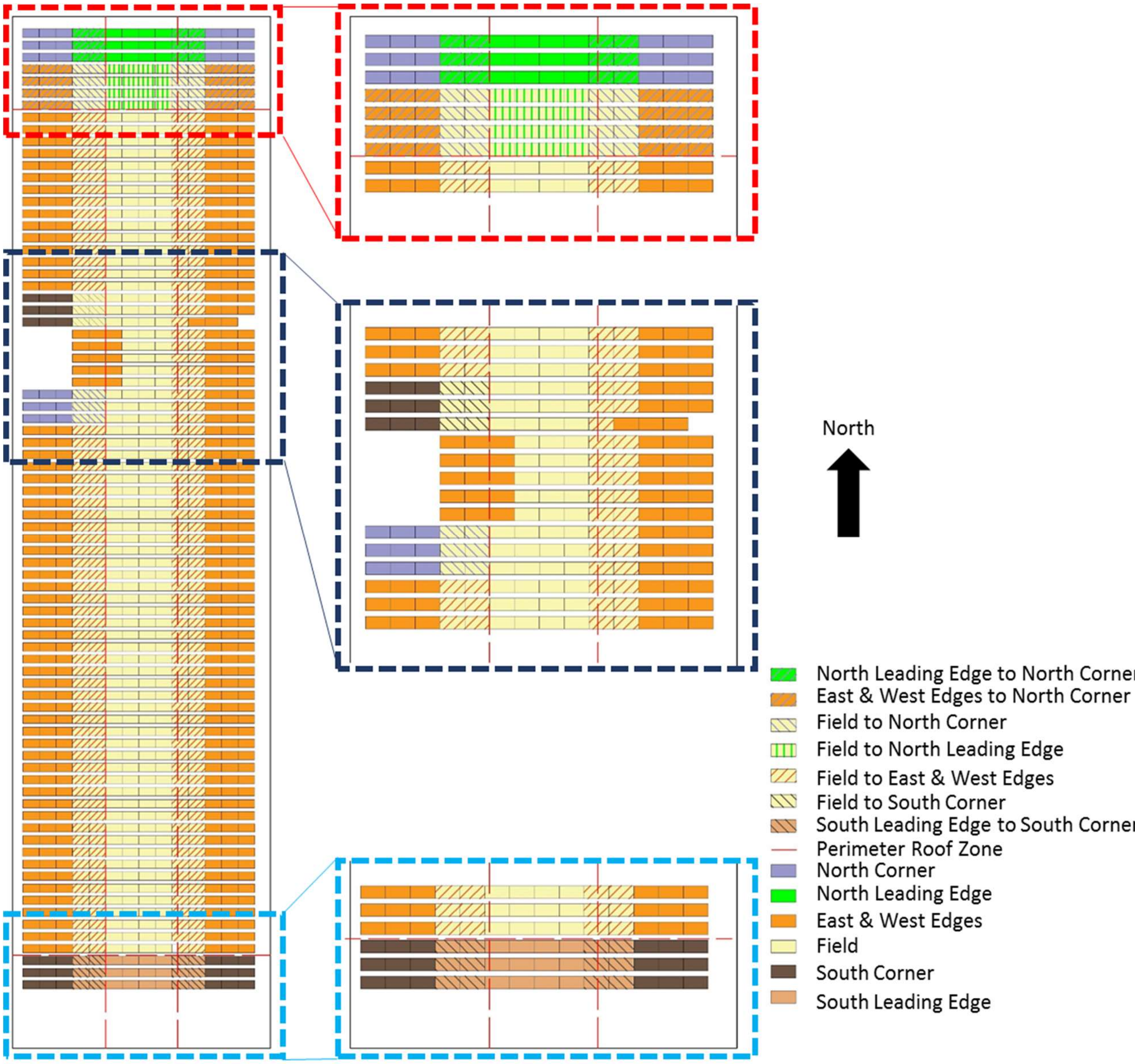
Table B3: Dimensions for Application Example 3

Parameter	Value
(Short) Building Dimension, W_s	99 ft
(Long) Building Dimension, W_L	400 ft
Building Height, h	60 ft
Setback, *s*, North	4.7 ft
Setback, *s*, East	6.2 ft, 12.6 ft
Setback, *s*, South	23 ft
Setback, *s*, West	4 ft, 23.2 ft
Perimeter Roof Zone	36 ft
L_b	60 ft
Figure 3 Building Size Factor	1.20 for 1 module
	1.23 for 2 modules
	1.26 for 4 modules

In this example, the minimum North Corner, North Leading Edge, East & West Edges, South Corner, South Leading Edge are smaller than the perimeter roof zone and thus they need to be enlarged. The additional modules that need to be classified as corner or edge depends on the setback. The full building is shown on the left, while enlarged views are shown on the right.

On the north edge of the example building, the North Corner and North Leading Edge zones are enlarged by 4 rows. Whereas, the south edge of the building has a larger set back and therefore the South Corner and South Leading Edge zones are enlarged by 3 rows. The larger North and South Corner zone do not apply when there is the larger setback of 23.2 ft (simulating an obstruction of some kind on the west edge, as seen in the central enlarged section). New Corner zones are required adjacent to this simulated obstruction as the void is greater than 10 ft. The simulated obstruction on the east edge of the building does not require new corner zones as it is less than 10 ft.

On the east and west edges of the example building the East & West Edge zones are enlarged by 2 modules.


North
North Leading Edge to North Corner
East & West Edges to North Corner
Field to North Corner
Field to North Leading Edge
Field to East & West Edges
Field to South Corner
South Leading Edge to South Corner
Perimeter Roof Zone
North Corner
North Leading Edge
East & West Edges
Field
South Corner
South Leading Edge