PLANNING FOR SOLAR ENERGY IN HALIFAX NEIGHBOURHOODS

MASTER OF PLANNING
INDEPENDENT PROJECT

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DECEMBER 08, 2015
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ACKNOWLEDGEMENT

SUMMARY

Solar energy is the cleanest and most abundant energy resource that does not contribute to global warming (Zaidi, 2009, p. 3). Halifax has good resources of solar energy and high energy demand (Natural Resources Canada, 2014; Halifax, 2007, pp. 38-40). Halifax Regional Municipal Planning Strategy 2015 places emphasis on energy planning including using solar energy (Halifax, 2015a, p. 39). Solar City, Solar Hot Water and Solar Hot Air are three ongoing programs related to solar energy in Halifax, which implement rooftop solar collectors. Building forms largely determine the amount of solar radiation received on roofs.

In this study, I examined impacts of seven building form factors: layout organization, average roof area, building coverage, floor to area ratio (FAR), average building height, roof orientation and roof shape on rooftop solar suitability in select residential blocks in Halifax Peninsula using ArcGIS. Rooftop solar suitability value (Wh/m²/day) is the total amount of solar radiation energy received on building rooftops during a given time, obtained from the Solar Suitability Map provided by Halifax Regional Municipality.

At block level, building form factors affect solar access on roofs in various degrees. One building form factor can either reduce or enhance others' impacts. I found:

- Average roof area positively correlates with rooftop solar suitability.
- Low-rise blocks with higher building coverage receive more solar radiation on rooftops.
- Blocks receive less solar radiation on rooftops if they have higher building coverage and larger building height.
- Vertical randomness is less favorable in high site coverage.
- High site coverage and uniform layout is more favorable than randomness in blocks with relatively large buiding height.
- FAR and building coverage have similar impacts on rooftop solar suitability; however, blocks with smaller FAR and higher building coverage are likely to have higher solar energy potential.
- Roof area plays a key role in maximizing the solar energy potential with similar FAR.
- Flatter roofs receive more solar radiation than pitched roofs.

The study is a good resource for researchers interested in the relationship between building forms and building solar radiation. Planners will be able to make more informed energy-efficient building design decisions. Policy-makers can incorporate these findings into future building codes.

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1. INTRODUCTION

Harnessed from sunlight, solar energy is often called "alternative energy" to fossil fuel sources such as oil and coal. It is the cleanest and most abundant energy resource that does not contribute to global warming (Zaidi, 2009, p. 3). There are passive and active ways to capture solar energy (Zaidi, 2009, pp. 3-6). Passive solar buildings store and distribute the heat energy from sunlight using walls, windows, floors and roofs. Active solar systems use mechanical or electrical devices that convert the sun's heat or light to another form of usable energy. Two common solar technologies are: 1) solar thermal collectors (STC); and 2) photovoltaic (PV) cells, which are usually mounted on roof surfaces (Groszko & Butler, 2014, p. 10). Figure 1 shows the Nova Scotia Solar Resource Map by Nova Scotia Community College (2012). Halifax has good solar resources compared to the rest of Canada and is well above global solar leaders such as Germany (Natural Resources Canada, 2014).
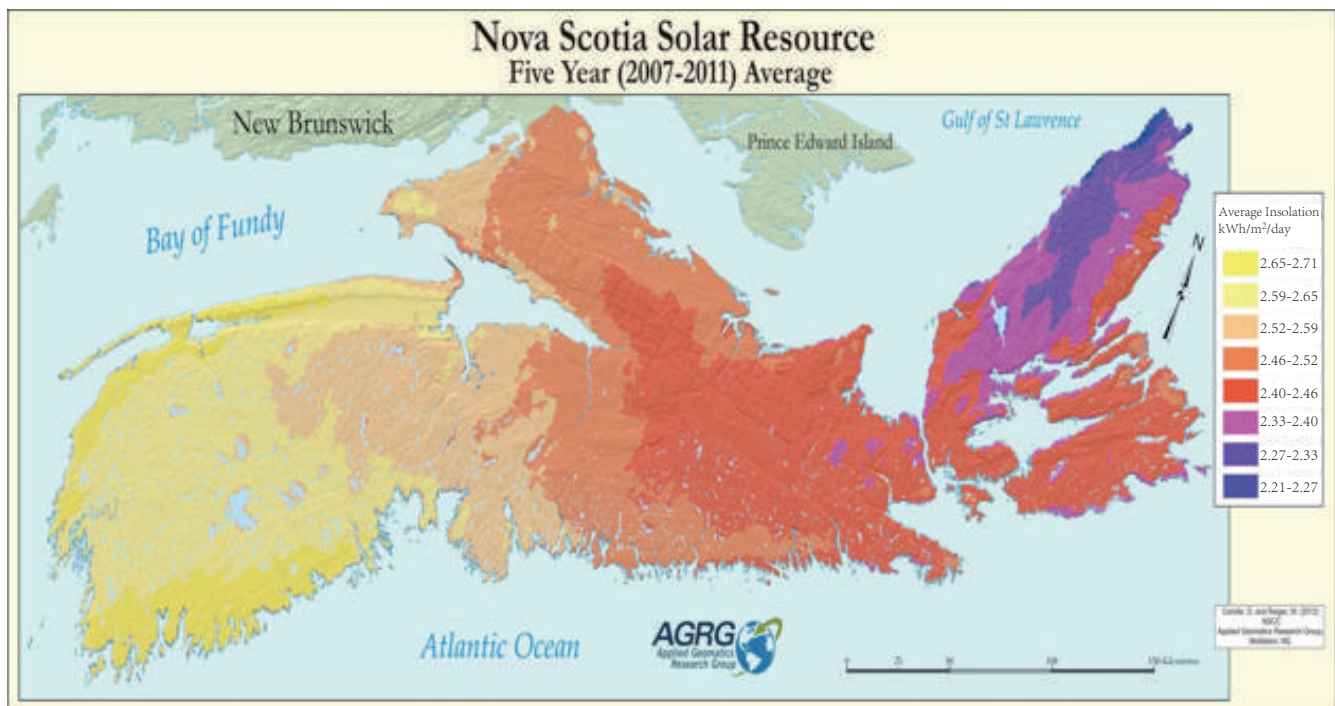
Figure 1. Nova Scotia Solar Resource Map (Colville & Reiger, 2012)

According to the Summary of Planning for Solar Report by Quality Urban Energy Systems of Tomorrow (QUEST), Halifax has the highest electricity per energy cost in Canada (QUEST Solar Subcommittee, 2013b). Halifax Community Energy Plan also shows an increase in the trend of energy use up to year 2026. The residential sector has the highest electrical energy consumption among all sectors (Halifax, 2007, pp. 38-40). Good resources of solar energy and high energy demand indicate opportunity for solar energy technology in Halifax.

The US Department of Energy expects the costs of solar power in North America to fall by 75% between 2010 and 2020 (QUEST, 2013a, p.3). Encouraging the use of solar energy technology, particularly solar PV (which generates electricity), can bring economic, social and environmental opportunities to Halifax in the future.

Halifax Regional Municipal Planning Strategy 2015 has set a goal of reducing corporate and community energy consumption by using integrated and systematic approaches to energy planning with a particular emphasis on the using renewable energy including solar energy (Halifax, 2015a, p. 39). Some of the goals in the Halifax Community Energy Plan are to improve energy efficiency of buildings and encourage energy efficient land use planning and neighbourhood site planning (Halifax, 2007, p. 6). The website of Halifax Energy and Environment identifies three ongoing programs related to solar energy: Solar City, Solar Hot Water and Solar Hot Air. All of these programs implement rooftop solar collectors to capture the sun's energy and transfer it to heat energy (Halifax Energy and Environment, 2014). The Solar City program offers homeowners a water heating option that can be financed through a new solar collector account with the city. The program aims to reduce average greenhouse gas emissions by 1,700 kg per year and create average yearly savings of $425 per household (Halifax, 2015c).

Planning for future energy-efficient and energy-producing buildings requires specific knowledge during the design process. Many design decisions such as building height, roof type and orientation have a significant effect on conditions for solar energy access on such buildings, although urban planners might not always be aware of the effect of their design. The role of urban planners is critical in achieving successful solar energy planning and increasing the use of solar technology and solar energy access. Planners need to understand impacts of various building form factors on building solar access to make recommendations for sustainable community development.

2. BACKGROUND

Building forms largely determine the amount of solar radiation received on roofs, which controls how much energy rooftop solar collectors can capture from the sun. I reviewed literature that studied impacts of building form factors on building solar radiation, particularly on rooftops to identify possible building form factors.

Košir et al. (2014) analyzed the amount of radiation at the block level/neighbourhood scale and identified several influencing factors: 1) density of the layout (distance between buildings and their height), 2) geometry of the site layout, 3) building shape, and 4) building orientation. They found the influence of the roof area size decreases proportionally to the height and increases proportionally to the length of the building. Another study by Kanters & Wall (2014) showed the effect of shape of building blocks, density, roof shape and orientation on the active solar potential of buildings, among which density is the most sensitive parameter.

Zeng (2011) found a relationship between floor area ratio (FAR) and solar PV potential. The larger the FAR, the smaller the potential energy supply per built area that PV integration could provide. The author suggested keeping FAR within a specified range and changing other building form factors to improve solar energy potential (Figure 2). The study showed that low-rise, large roof area, or high building coverage building blocks receive more solar radiation (Figure 3).

Building Cluster Type	A	B	C
Building Form			
The Solar Energy Potential (kwh/sq m/year)	101.2	74.9	64.1
The Building Surface Volume Ratio	0.399	0.347	0.434
Roof Area over the surface area ratio	71.6%	47.1%	12.3%
Average Building height (meter)	6	9	21

Figure 2. The Relationship between Floor Area Ratio and Solar Energy Potential (Zeng, 2011, p. 79)
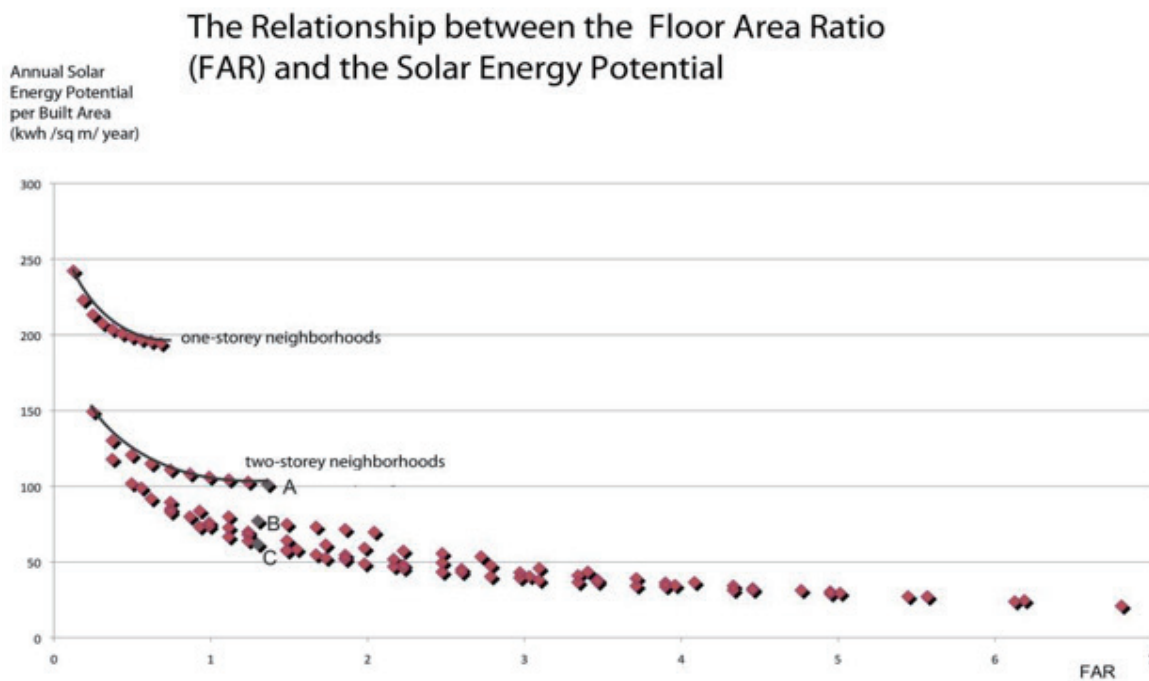

Figure 3. Solar Energy Potential Comparison among Model A, B and C (Zeng, 2011, p.81)

Zeng (2014) found that buildings with one-sloped roof, with the entire roof area tilting at the optimum angle equivalent to local latitude towards the sun, can utilize the entire roof area to collect solar radiation. Asymmetrical double sloping roofs with the sunward-facing slope having a larger area can collect more sunlight than symmetrical double-slope roofs. Zeng (2014) concluded that orientation, spacing and height of buildings all impact the shading of solar PV on roofs. Building height planning could mitigate the negative impacts of shading. Arranging buildings with the same height together in clusters could ensure good access to sunlight on all the roofs. Also, placing tall buildings on the shady part of a site could be a useful design principle. Although larger spacing between buildings could mitigate the shading effect, it would decrease building coverage and roof area available for PV.

3. Purpose Statement, Research Question & Objectives

Urban planners make design decisions about building density, roof type and orientation that have a significant effect on solar energy access of buildings. In this study, I investigated impacts of seven building form factors: layout organization, average roof area, building coverage, floor to area ratio (FAR), average building height, roof orientation and roof shape on rooftop solar suitability (the total amount of solar radiation energy received on building rooftops during a given time) in select residential blocks on the Halifax Peninsula. I aim to help planners make better-informed decisions in the future.

Households play an important role in Halifax's energy consumption, and residential energy demand will continue to increase as the city grows. Therefore, I focused on examining residential blocks. I explored solar radiation on rooftops instead of facades and other building parts for two reasons. The Solar Suitability Map provided by Halifax Regional Municipality (HRM) only shows rooftop solar suitability. Solar radiation on other parts of buildings is unknown. Halifax currently uses rooftop solar collectors as the main solar energy technology (Halifax Energy and Environment, 2014).

Suitability (Wh/m^2/day)
High : 7.96172
Low : 0
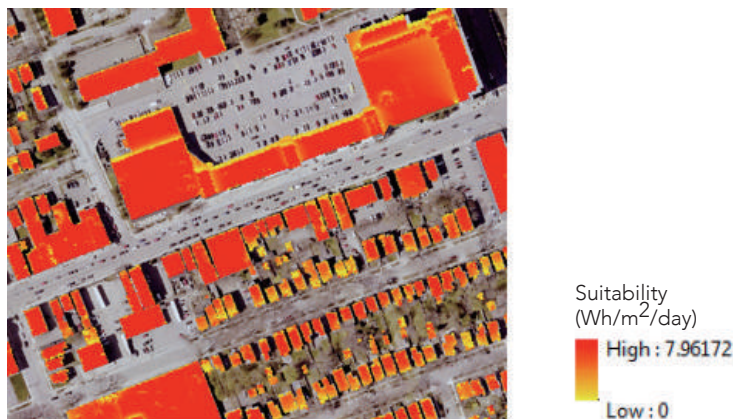
Figure 4. Solar Suitability Map based on HRM Solar City Project (Halifax, n.d.)

HRM collaborated with Dalhousie University to create the Solar Suitability Map using a digital surface model (DSM) based on LiDAR data from 2005, aerial photographs from 2006 and 2009 and a shadow-obstruction technique (Halifax, n.d.) (Figure 4). Appendix 1 contains more details about the map. To keep consistent with the information from the map, I used data from 2006 in preference to data from other years in the study.

To what extent does each building form factor contribute to rooftop solar suitability under locally specific conditions? To answer the research question, I accomplished two objectives:

1) To understand local contexts, building forms (layout organization, average roof area, building coverage, floor to area ratio (FAR), average building height, roof orientation and roof shape) and average rooftop solar suitability of a sample of residential blocks.

2) To assess the impact of each building form factor on rooftop solar suitability.

4. Methods and Analysis

I used quantitative approaches to explore the relationship between rooftop solar suitability and each building form factor: descriptive statistics (analyzing values such as mean and median to evaluate data dispersion) and correlation analysis (exploring linear relationships between two variables). I completed several information objectives to achieve each objective. The following subsections describe information objectives, strategies and the process of data collection and analysis.

4.1 Local Contexts, Building Forms & Rooftop Solar Suitability

4.1.1 Sample Blocks & Their Local Contexts

I developed and applied a sampling strategy to select residential blocks. Since residential zones define residential uses with various densities, heights and building forms, I first divided Halifax Peninsula into different residential zones: R-1 (single family dwelling), R-2 (general residential), R-2T (townhouse), R-2A (general residential conversion) and R-3 (multiple dwelling), using the zoning layer in ArcGIS (Halifax, 2015b, p. 43). Then, I examined residential blocks within each zone to look for blocks with typical and atypical layout organizations and various roof sizes using the HRM 2006 building polygon layer in ArcGIS. I also sought building blocks with various heights and roof types by using Google Street View and aerial photos. The Solar Radiation Map was created without removing the vegetation layer. Vegetation affects solar radiation on rooftops. For instance, larger roofs covered by more trees could receive less solar radiation than smaller roofs covered by fewer trees. I chose building blocks with less vegetation by observing the vegetation layer in ArcGIS. Data used in the selection process appear in Appendix 2. I selected nine residential blocks on the Halifax Peninsula (Figure 5).

I examined local contexts of sample blocks from various aspects including census information, zoning by-law requirements and surroundings. Appendix 2 summarizes data used in understanding the local contexts. A dissemination area is a small area composed of one or more neighbouring dissemination blocks, with a population of 400 to 700 persons. All of Canada is divided into dissemination areas (Statistics Canada, 2015). Figure 6-14 show the dissemination area of each block, the pictometry imagery photo, building polygons and street view of each block.

Figure 5. Sample Block Locations (Feng, 2015)

Block 1

This residential block is located in the North End Halifax Peninsula (bordered by Barrington Street, Duffus Street and Albert Street). It is zoned R-3 (multiple dwelling), where permitted residential uses include R-1, R-2, R-2T, R-2A (South End Area), boarding house, rooming house and apartment house (Halifax, 2015b, p. 72). The block contains 20 apartment buildings, most of which are two to three storeys high. Two are around eight storeys high. It is adjacent to Fort Needham Memorial Park and the Halifax Waterfront. Surroundings are mostly for residential R-2 and R-1 uses, containing many single-detached houses.

The block is within dissemination area DA12090847, where most of the land is for commercial uses (Halifax, 2014). The DA contains 270 private dwellings, of which 61% are in apartment buildings fewer than five storeys, and the rest are in apartment buildings with five or more storeys (Statistics Canada, 2012). They were constructed before 1980 (Statistics Canada, 2013).

Pictometry Imagery Photo (Feng, 2015)
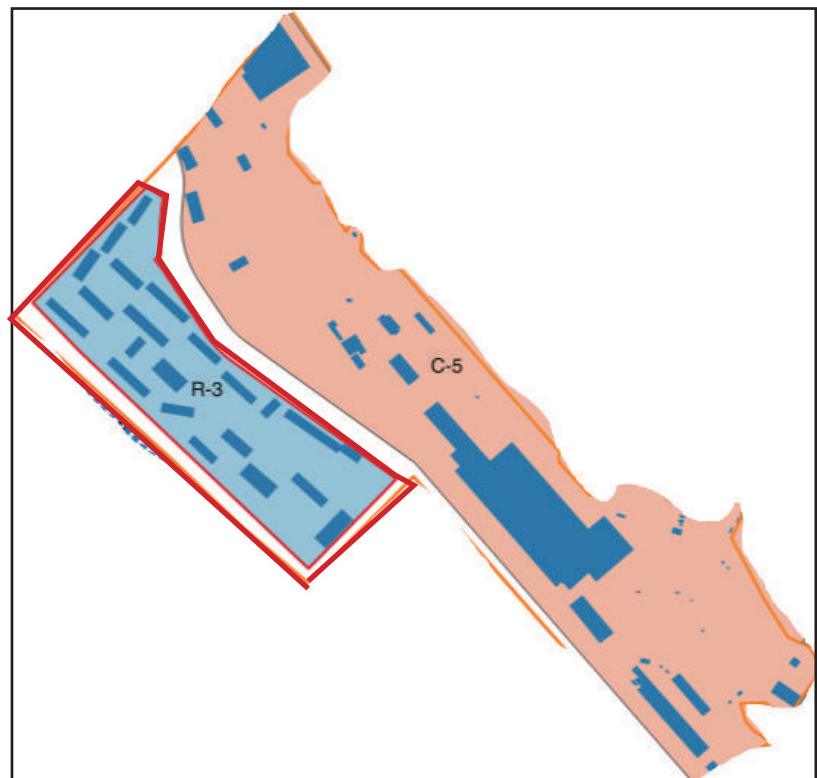
Dissemination Area (Feng, 2015)
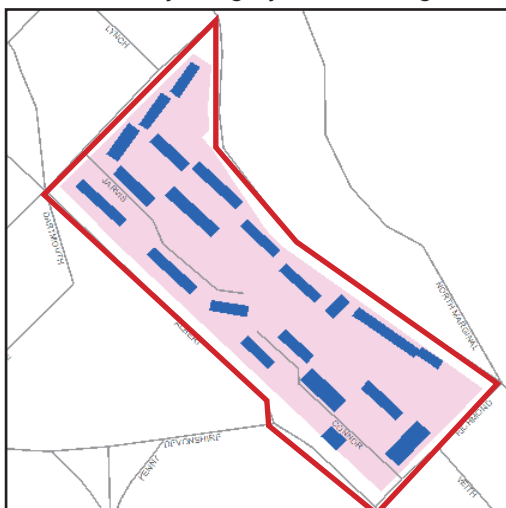
Building Polygons (Feng, 2015)

Site Vist (Feng, October 1st, 2015)

Figure 6. Block 1

Block 2

This residential block zoned R-3 (multiple dwelling) is located in the South End Halifax Peninsula (bordered by Queen Street, Kent Street and Tobin Street). The block contains 15 apartment buildings, mostly three to four storeys high, and only one is about eight storeys high. The block is adjacent to Dalhousie University Sexton Campus and the Halifax Waterfront. Surroundings are mainly for residential uses, commercial uses or mixed uses (Halifax, 2014). Buildings are mostly apartment buildings with similar heights.

The block is within DA12090297, mainly designated for residential uses, and only four or five buildings are mixed uses (Halifax, 2014). The DA contains 425 private dwellings, of which 65% are in apartment buildings fewer than five storeys, and the rest are in apartment buildings with five or more storeys or duplexes (Statistics Canada, 2012). Three fourths of the dwellings were constructed before 1980 (Statistics Canada, 2013).

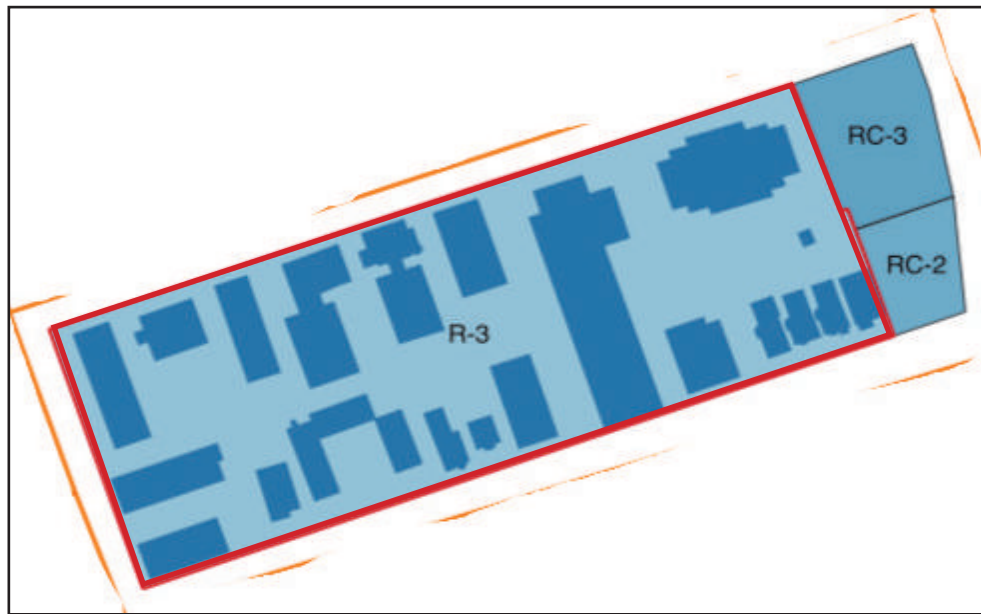Dissemination Area (Feng, 2015)

Building Polygons (Feng, 2015)

Pictometry Imagery Photo (Feng, 2015)
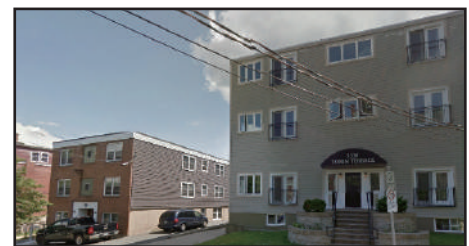
Site Vist (Feng, October 1st, 2015)

Figure 7. Block 2

Block 3

This residential block, located in the West End Halifax Peninsula (bordered by Olivet Street and Mumford Road) is zoned R-3. The block contains eight apartment buildings, mostly six storeys high. One is four storeys high, and another is approximately 12 storeys high. Surroundings are zoned residential R-1 and R-2, having many two storeys single-detached houses, and commercial C-2 and C-3 (Halifax, 2014). The block is next to Mt Olivet Cemetery and towards the southeast of Halifax Shopping Centre.

The block is within DA12090565, where most of the land is for single-family dwellings, and some for commercial uses (Halifax, 2014). The DA contains 710 private dwellings, of which 77% are in apartment buildings with five or more storeys (Statistics Canada, 2012). Single-detached houses occupy 20% of the lots (Statistics Canada, 2013).
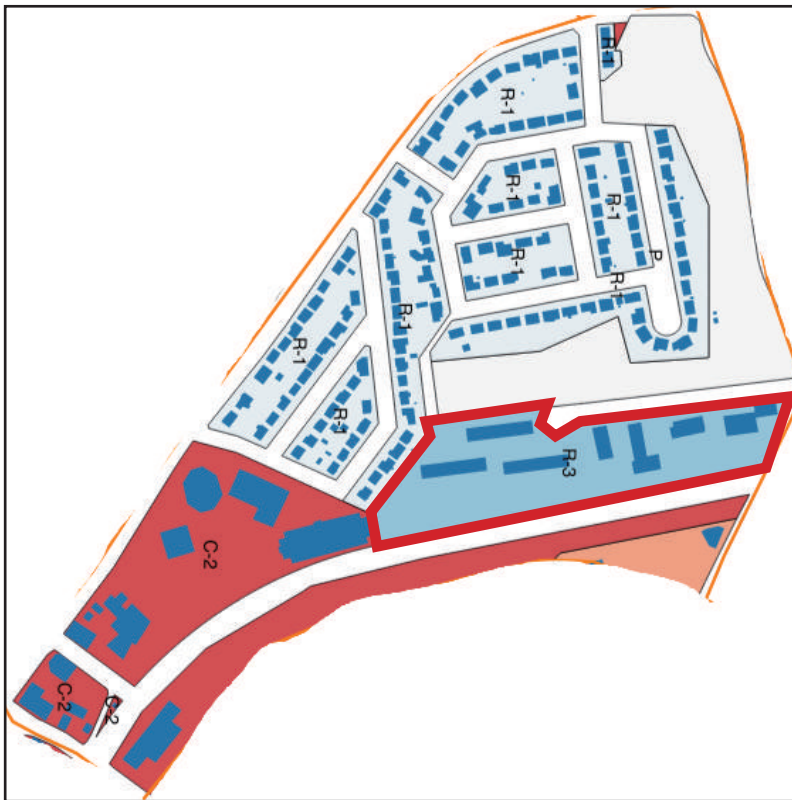
Dissemination Area (Feng, 2015)

Pictometry Imagery Photo (Feng, 2015)
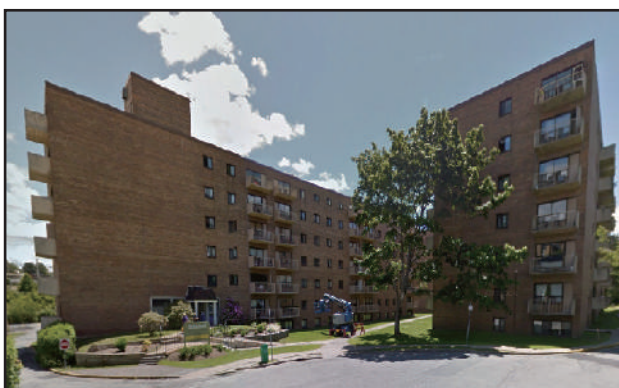
Street View (Google Maps, 2015a)
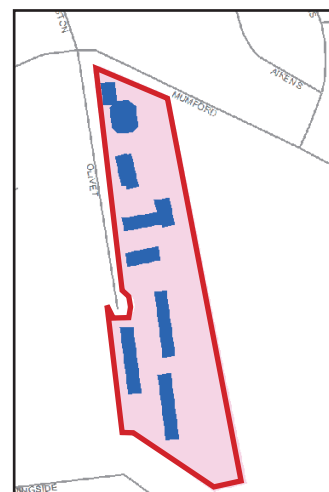
Building Polygons (Feng, 2015)

Figure 8. Block 3

Block 4

This residential block is located in the North End Halifax Peninsula (bordered by Novalea Drive and Sentinel Square). It is zoned R-2T (townhouse), and allows residential uses including R-1, R-2 and townhouse buildings (Halifax, 2015b, p. 63). The block contains three rows of three-storey townhouse buildings, built between 1970 and 1980 (ViewPoint Realty, 2015). It is adjacent to Merv Sullivan Park, Nova Scotia Community College and Circumferential Highway to the A. Murray MacKay Bridge. Surroundings are for residential (R-2), commercial, park and institutional uses, containing townhouses and two to three-storey single-detached houses.

The block is within DA12090224, zoned R-3, R-2T, R-2 and P (park and institutional) (Halifax, 2014). The DA contains 145 private dwellings, of which about 45% are in apartment buildings, 40% are in single or semi-detached houses, and about 15% are in row houses (Statistics Canada, 2012). They were constructed before 1980: over 50% were built before 1960 (Statistics Canada, 2013).
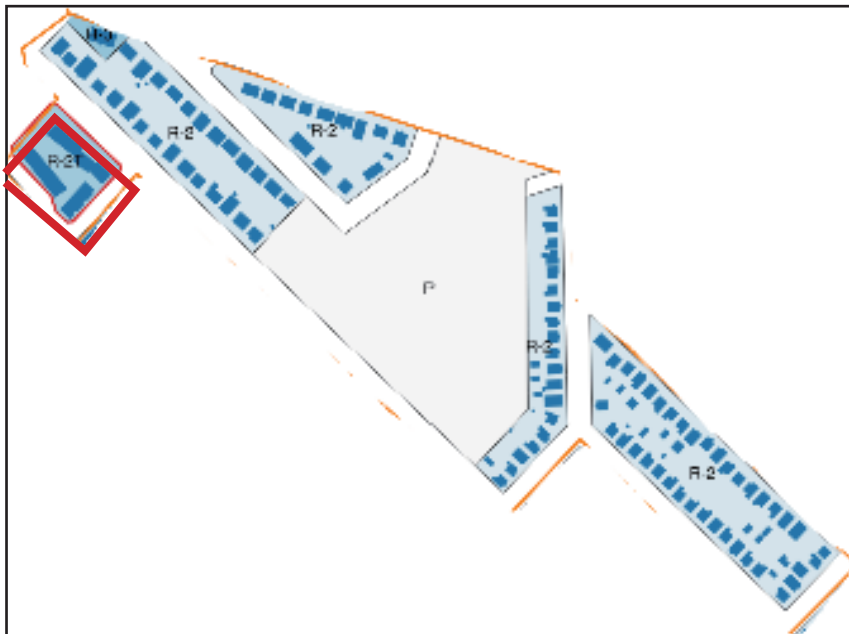
Dissemination Area (Feng, 2015)

Site Vist (Feng, October 1st, 2015)

Pictometry Imagery Photo (Feng, 2015)
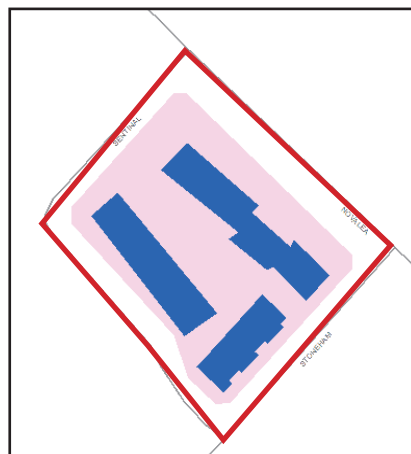
Building Polygons (Feng, 2015)

Figure 9. Block 4

Block 5

This residential block is located on Federal Avenue and Romans Avenue, close to Highway 102 and 111. It is zoned R-2 (general residential), and allows residential uses including R-1, semi-detached or duplex dwelling, buildings containing not more than four apartments (Halifax, 2015b, p. 57). The block contains 17 rows of two-storey row houses. The surrounding areas are for residential, park and institutional uses. It's next to St. Andrew's Community Centre, surrounded by two-storey similar row houses and single-detached houses.

The block is within DA12090883, zoned R-1 and R-2 (Halifax, 2014). The DA contains 145 private dwellings, of which about 90% are in row houses, and 7% are in single-detached houses (Statistics Canada, 2012). They were constructed before 1980: over 40% were built between 1946 and 1960 (Statistics Canada, 2013).

Dissemination Area (Feng, 2015)

Pictometry Imagery Photo (Feng, 2015)

Building Polygons (Feng, 2015)

Street View (Google Maps, 2015b)
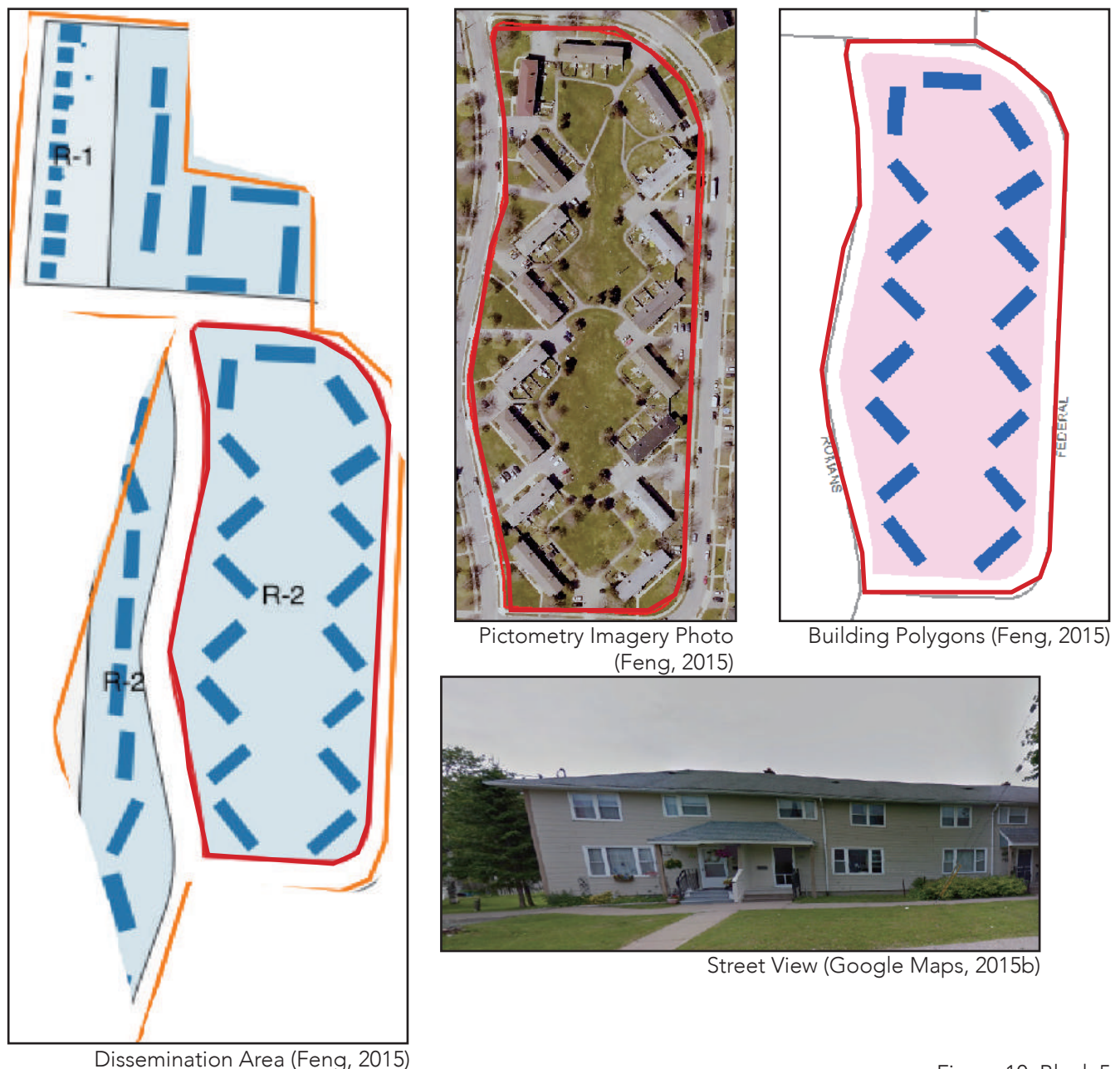
Figure 10. Block 5

Block 6

This residential block zoned R-2 is located close to block 4 and Robie Street. The block contains six three-storey townhouse condos, which were built in 1987 (Condo Company, 2015). It is adjacent to Nova Scotia Community College and Circumferential Highway to the A. Murray MacKay Bridge. The surroundings are for residential uses, where houses with large floor area are located.

The block is within DA12090231, zoned mostly as commercial land (Halifax, 2014). The DA contains 375 private dwellings, of which about 45% are in apartment buildings, and over 40% are in row houses (Statistics Canada, 2012). About 70% of the dwellings were constructed between 1971 and 1990, and 17% were built between 2001 and 2006 (Statistics Canada, 2013).
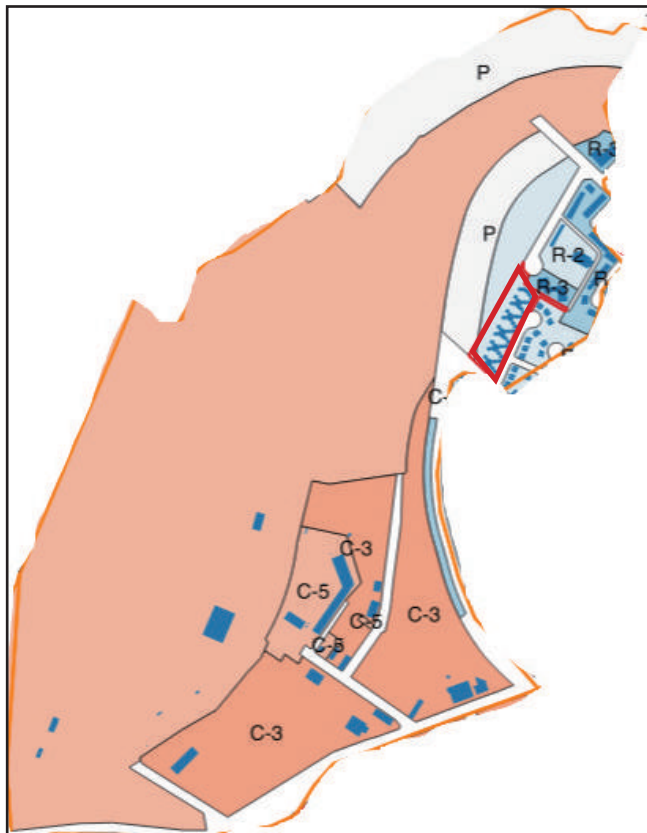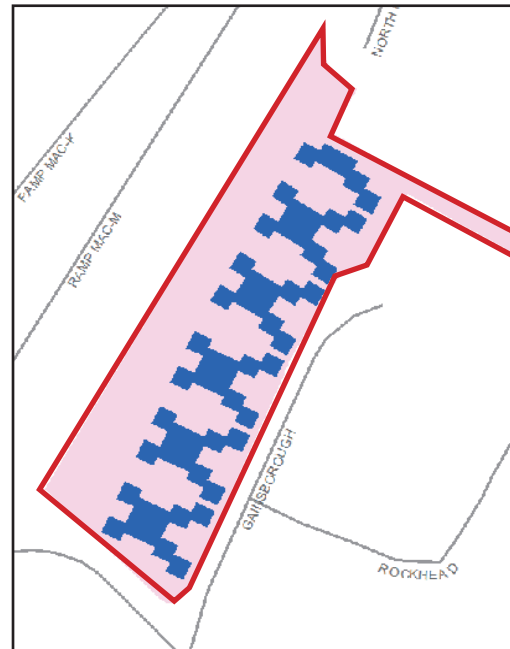
Dissemination Area (Feng, 2015)

Building Polygons (Feng, 2015)

Site Vist (Feng, October 1st, 2015)

Pictometry Imagery Photo (Feng, 2015)

Figure 11. Block 6

Block 7

This residential block is located at the corner of Queen Street and Morris Street in the South End Halifax Peninsula. It is zoned R- 2A (general residential conversion) and R-3 (multiple dwelling). In R-2A zone, R-1, R-2, R-2T and converted multiple dwelling houses are allowed (Halifax, 2015b, p. 65). The block contains various types of buildings including two apartment buildings approximately eight storeys high, 26 two to three-storey single and semi-detached houses. The block is adjacent to Holy Cross Cemetery and Dalhousie Sexton Campus, surrounded by similar types of residential buildings.

The block is within DA12090298, zoned mostly as R-2A (Halifax, 2014). The DA contains 355 private dwellings in the DA, of which about 60% are in apartment buildings with fewer than five storeys, and over 35% are in apartment buildings with five or more storeys (Statistics Canada, 2012). About 35% of the dwellings were constructed before 1946 (Statistics Canada, 2013).
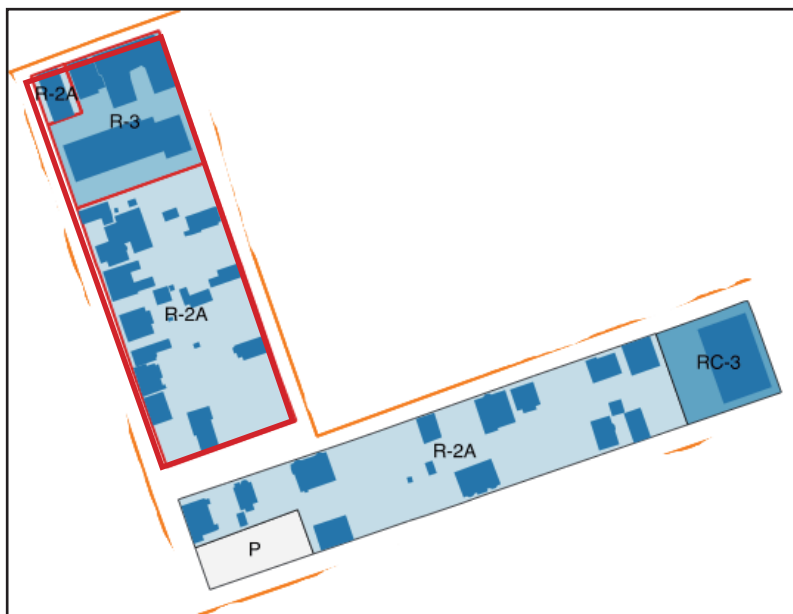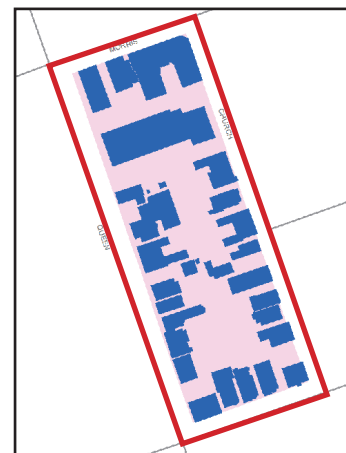
Dissemination Area (Feng, 2015)

Building Polygons (Feng, 2015)
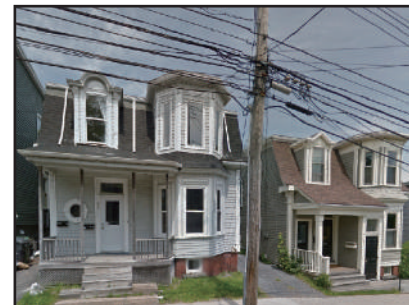
Site Vist (Feng, October 1st, 2015)

Pictometry Imagery Photo
(Feng, 2015)

Figure 12. Block 7

Block 8

This residential block zoned R-2 (general residential) is located at the corner of Cunard Street and Robie Street. The block contains over 15 single-detached houses, surrounded by residential and commercial uses with similar building types. An eight-storey apartment building is on the east side of the block, and Halifax Commons is at the opposite corner of the street.

The block is located within DA12090878, zoned mostly as R-2, some of the land is for minor commercial, C-2A (Halifax, 2014). The DA has 355 private dwellings. Over 70% are in duplex apartment buildings and apartment buildings with five or fewer storeys. About 20% are in single-detached houses (Statistics Canada, 2012). Almost 90% of the dwellings were constructed before 1970: 45% were built before 1946; about 5% were built between 2001 and 2006 (Statistics Canada, 2013).

Dissemination Area (Feng, 2015)

Pictometry Imagery Photo
(Feng, 2015)
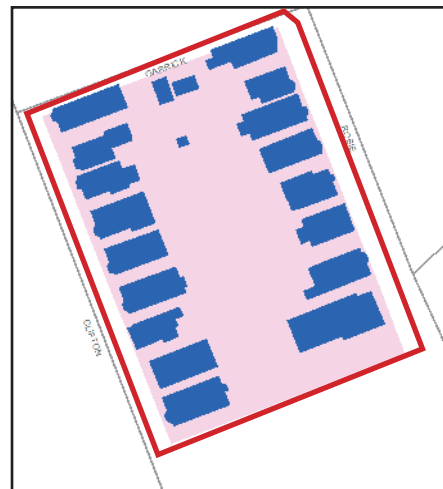
Building Polygons (Feng, 2015)

Site Vist (Feng, October 1st, 2015)

Figure 13. Block 8

Block 9

This residential block is located at the corner of Quinpool Road and Connaught Avenue. It is zoned single family, R-1, where detached one-family dwelling houses are the only allowed residential uses (Halifax, 2015b, p. 48). The block contains about ten fewer than four-storey single-detached houses, surrounded by R-1 residential uses with similar building types.

The block is within DA12090325 zoned mostly as R-1 (Halifax, 2014). The DA contains 355 private dwellings. Over 90% are in single-detached houses, and the rest are in apartment buildings with five or fewer storeys (Statistics Canada, 2012). They were constructed before 1980: 71% were built before 1946 (Statistics Canada, 2013).
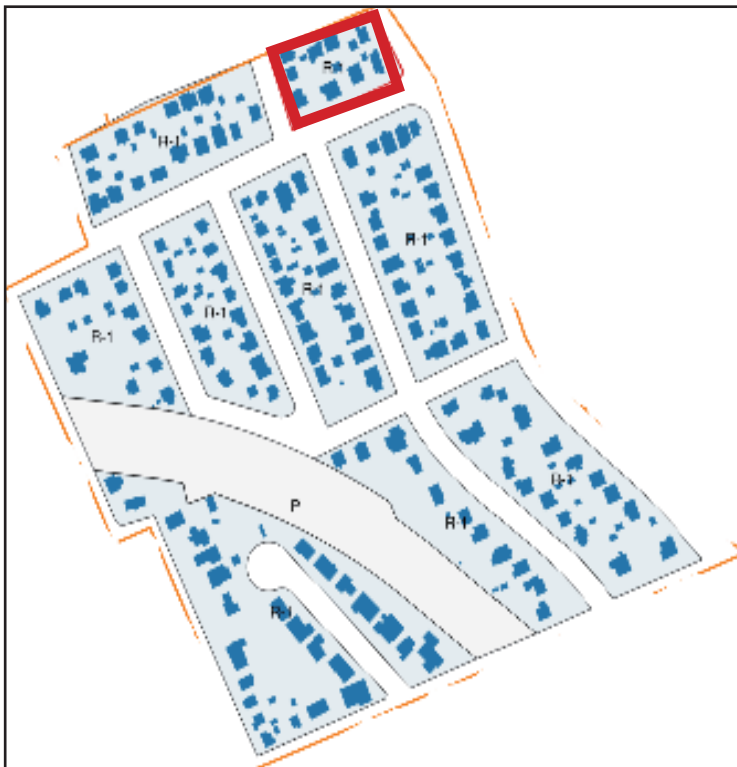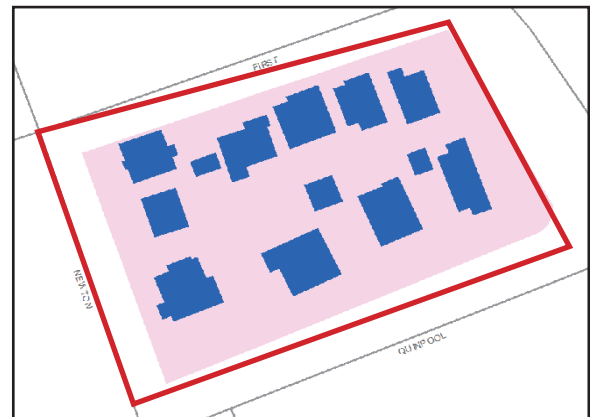
Dissemination Area (Feng, 2015)

Building Polygons (Feng, 2015)

Pictometry Imagery Photo (Feng, 2015)

Street View (Google Maps, 2015c)

Figure 14. Block 9

4.1.2 Building Form Factors and Rooftop Solar Suitability

After an extensive literature review, I selected seven building form factors to examine: layout organization, average roof area, building coverage, floor to area ratio (FAR), average building height, roof shape and roof orientation. The following introduces how I evaluated the building form factors and rooftop solar suitability. Table 1 summarizes the results, and Appendix 3 contains more detailed results including standard deviation values. Appendix 2 shows the data I used to conduct the analysis.

Layout organization directly affects the spacing between buildings, and thus influences the solar radiation on a building envelope (Košir et al., 2014, p. 453). I examined layout organization qualitatively by studying the building polygon layer of each sample block. For example, block 5 has the most unique layout organization, in which buildings are long, narrow and arranged in a zigzag shape (Figure 10). I obtained average roof area of each block by applying the statistical tool "mean" in ArcGIS to the building polygon layer.

I evaluated building coverage and FAR to examine layout density, as done by Cheng et al. (2006). For building coverage, I used the statistical tool "sum" in ArcGIS to estimate the total roof area of each sample block from the building polygon layer. I estimated the area of each sample block from the zoning layer. Each sample block has a well-defined boundary in the zoning layer except for block 6, which shares a large block with other buildings. I created a new block using the boundary defined in the parcel layer. Then, I divided the block area by the block's total roof area to estimate the building coverage. Floor to Area Ratio (FAR) is obtained through dividing the gross floor area of a building by the total area of the lot. I considered FAR as the ratio of the gross floor area of all buildings in a block over the block area (Zeng, 2011, p. 75). To assess the gross floor area, I first estimated the gross floor area of each building, and then summed them. I examined the number of floors of each building through Google Street View and site visits, and multiplied it by the area of the building polygon. I counted half-basements and attics as half floors and did not consider basements under the ground in the estimation.

I obtained building height using raster data by subtracting Digital Elevation Model (DEM) data from Digital Surface Model (DSM) data using the "raster calculator" tool in ArcGIS. Then, I converted the raster data into point features (vector data) using the "raster to point" tool (Figure 15). I used the statistical tool "mean" in ArcGIS to estimate the average building height for each sample block.

Figure 15. Converting Height Raster Data into Vector Data (Feng, 2015)

I examined roof shape in each sample block through site visits and 2014 pictometry imagery photos. For each block, I calculated average slope value to investigate roof steepness. To achieve that, I extracted slope raster data from the DSM data, and converted them to point features (vector data) using the "raster to point" tool in ArcGIS. In all building blocks, the slope value increases suddenly close to the edge of the roof (Figure 16). I considered points with slope value larger than 60 degrees as outliers and removed them from statistical calculation.
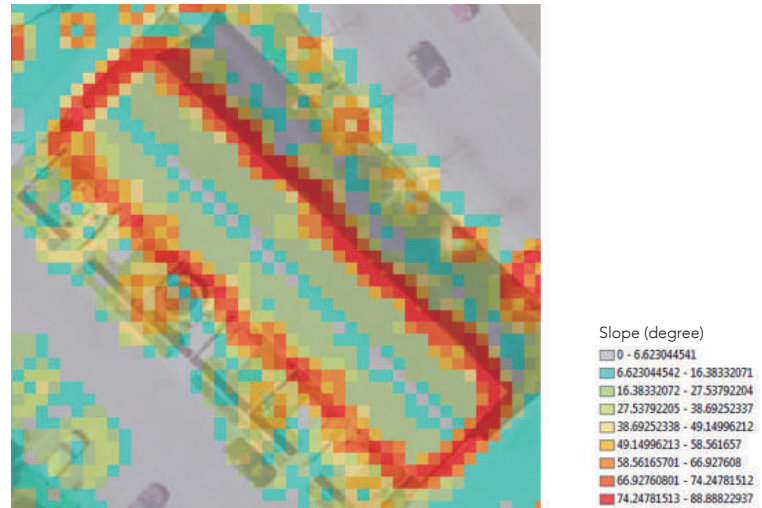
Figure 16. Slope Raster Data (Feng, 2015)

Roof orientation not only determines exposed surfaces, but also affects the duration of exposure (Košir et al., 2014, p. 453). To examine roof orientation, I extracted aspect raster data from DSM data. However, the aspect data did not appear to correspond with the actual orientation of the rooftop surfaces. Flat roofs have various aspect values (Figure 17). Research by Carl (2014, p.11) showed that topographic effects on the ground such as elevation, slope, and orientation influence the amount of radiation reaching a surface. Thus, elevation could cause different aspect values on flat roofs. Elevation is not a building form factor, and is not considered in the study, though it can affect the analysis. I did not examine roof orientation in the study.
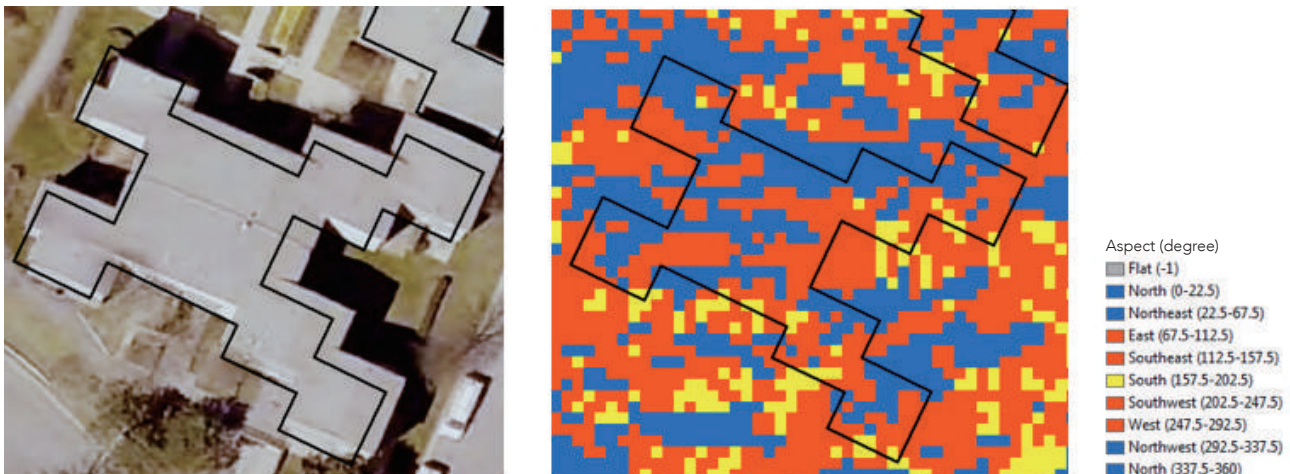
Figure 17. Aspect Data Inconsistency (Feng, 2015)

Since building polygons of each sample block in 2014 pictometry imagery photo are the same as those in the 2006 aerial photo, I used 2014 pictometry imagery photo that has a higher resolution. The boundaries of 2012 building polygons match well with the boundaries of the solar radiation layer. Therefore, I used building polygon layer from 2012 HRM Geodatabase instead of re-digitizing the 2014 pictometry imagery photo. However, some of the building polygons did not match well with the pictometry imagery photo, slope layer or height layer (Figure 18). Re-digitizing might cause missing data, so I kept the original data in the study. I also removed building polygons that were sheds from the polygon layer to improve accuracy.

Figure 18. Data Offset (Feng, 2015)

In terms of the rooftop solar suitability, I clipped the solar radiation raster data by residential block layers and converted the raster data into point features (vector data) in ArcGIS. I removed point features with zero solar radiation value. Finally, I calculated the average solar radiation value (Wh/m^2/day) of each residential block by the statistical tool "mean" in ArcGIS.

Table 1. Summary of Building Forms and Rooftop Solar Suitability (Source: Author, 2015)

Block	No. of Buildings	Layout Organization	Average Roof Area (m²)	Building Coverage	FAR	Average Building Height (m)	Roof Shape	Average Slope (degree)	Average Rooftop Solar Suitability (Wh/m²/day)
1	20	Buildings with long and narrow footprints locate on a large block, relatively separated from each other, and cover the entire block.	432.26	18.52%	0.663	10.750	Majority pitched; two flat roofs; the rest are gable and hip roofs	22.308	6.139266
2	21	Building footprints have various sizes and shapes, located farther from each other compared to block 7.	413.74	42.48%	1.696	11.000	Majority flat; the rest are a mix of gable and mansard roofs; some roofs have attic dormers on top	13.702	5.976890
3	8	Buildings with long and narrow footprints, most-separated from each other.	766.99	16.08%	1.095	19.520	All flat roofs	8.600	6.667679
4	3	The block has the smallest number of buildings, which occupy the whole block and are relatively separated from each other.	483.45	35.06%	0.905	6.700	All flat roofs	9.001	6.648035
5	17	Buildings with long and narrow footprints locate on a large block, having zigzag-shaped layout geometry.	248.07	13.81%	0.276	6.150	All gable roofs	26.849	6.398703
6	6	Buildings are placed in a line, with large and unique footprints.	436.05	25.25%	0.757	8.370	Mixed with gable and flat roofs	16.981	6.599400

7	28	Building footprints have various sizes and shapes, located closer from each other compared to block 2.	196.76	47.37%	2.000	12.180	Majority pitched, mixed with mansard roofs and gable roofs; some roofs have attic dormers on top (Figure 19)	21.930	5.156709
8	17	Typical R-2 layout; buildings have almost equal and small distance to each other, with a bit long and narrow footprints.	109.77	34.71%	0.696	7.571	Mixed with flat and gable roofs; some roofs have attic dormers on top	21.012	4.942662
9	10	Typical R-1 layout; square building polygons are relatively separated from each other	137.85	25.63%	0.550	6.880	All pitched roofs; five out of ten are gable roofs; two are pyramid hip roofs; one cross hipped roof, one cross gable roof, one is a combination of flat and gable roofs	31.432	5.316863

Note: *Appendix 4 shows how each roof type look like.*

Figure 19. Attic Dormers on the Rooftop in Block 7 (Feng, Oct. 1st, 2015)

4.2 Impact of Building Form Factors on Rooftop Solar Suitability

Different building form factors can affect rooftop solar suitability to varying degrees. In the next subsection, I further examined the data in Table 1. Then, I conducted correlation analysis to explore how closely five building form factors (average roof area, building coverage, floor to area ratio (FAR), average building height and roof shape) are related to each other and rooftop solar suitability based on specific conditions of sample blocks. I did not examine layout organization quantitatively, but it helps explain the results of my analysis.

4.2.1 Analysis of GIS Data

Layout Organization

In terms of layout organization, block 1, 3 and 4 have similar block geometry, having buildings with long and narrow footprints. Block 2, 7, 8 and 9 have buildings located along every street forming the blocks; buildings in block 2 and 7 have various height and footprints because of their various building types (Figure 7&12).

Average Roof Area

Among all the blocks, buildings in block 3 have the largest average roof area, almost 300 m^2 larger than the second largest one, block 4; data points spread out over a wide range of values (standard deviation $\approx$ 226 m^2). Buildings in block 8 and 9 have smaller average roof area compared to others, and data points vary slightly (standard deviation $\approx$ 28 m^2). Roofs of buildings in block 5 have relatively similar sizes (standard deviation $\approx$ 25 m^2). Buildings in block 2 and 7 have various roof sizes. The largest roof area in block 2 is about 1600 m^2 (largest among all sample points), and the smallest is about 75 m^2. In block 7, the largest roof area is about 950 m^2, and the smallest is about 50 m^2. Buildings in block 1 and 6 have almost the same average roof area around 430 m^2, but block 6 has less variation (standard deviation (1) $\approx$ 132 m^2, standard deviation (6) $\approx$ 82 m^2). In blocks 3, 4, 5, 6 and 9, the average roof area is smaller than the median. There could be two reasons. First, the block has more roofs with area smaller than the average roof area; second, some roof areas are very small. For example, five out of six buildings in block 6 have roofs with similar shapes and sized around 400 m^2. The building at the corner of the block has the smallest sized roof (253 m^2). The median (471 m^2) is larger than the average value (436 m^2).

Building Coverage

Block 7 has the highest building coverage value (47.37%), and block 5 has the lowest (13.81%) (Table 1). Blocks with relatively low building coverage (1, 3 and 5) contain only apartment buildings. Blocks having both houses and apartment buildings (2 and 7) are denser.

FAR

According to Table 1, block 7 has the largest FAR (2.000), and block 5 has the smallest FAR (0.276). However, some blocks have low building coverage but large FAR such as block 3. Buildings in these blocks are much taller and have larger gross floor area than those in other blocks. By contrast, block 9 consists of two to three-storey single-detached houses. It has smaller gross floor area, so the block has smaller FAR, even if it has higher building coverage. By comparing FAR and building coverage values, I found block 2 and 7 are the densest blocks; block 1 and 5 are the least dense blocks.

Average Building Height

Table 1 shows that block 3 has the largest average building height (19.52 m), which is more than seven meters taller than the second largest, block 7. Five blocks (4, 5, 6, 8 and 9) have average building height lower than ten meters, among which block 5 has the smallest value (6.15 m). Standard deviation values show that buildings in block 1, 2, 3 and 7 have varying heights compared to other blocks (Appendix 3). In most of the blocks, median building height is close to the average building height; however, the median height of block 7 is 9.26 m, about three meters smaller than the average height, 12.18 m. Block 7 contains apartment buildings much higher than its single-detached houses.

Roof Shape

Flat, gable, hip and mansard roofs are major types of roof observed (Table 1). Buildings in block 3 and 4 have all flat roofs; the average slope values are 8.60 degree and 9.00 degree, respectively. Block 5 and 9 have the largest average slope values: 26.85 degree and 31.43 degree, respectively, since their buildings have all pitched roofs. Other blocks have mixed types of roofs. Roofs in block 8 have the most various slope values (standard deviation ≈ 20.156 degree), followed by block 7 (standard deviation ≈ 18.473 degree) and block 2 (standard deviation ≈ 18.150 degree). Block 2 and 7 both contain apartment buildings and houses with various types of roof shape, and attic dormers on top. Most roofs in block 8 are relatively flat with attic dormers on top. Two houses have steep gable roofs and larger slope values than others in block 8, so the median slope value (10.41 degree) is much smaller than the average value (21.01 degree).

Rooftop Solar Suitability

Average solar radiation value ranges from 4.942662 Wh/m^2/day (block 8) to 6.667679 Wh/m^2/day (block 3). Rooftop solar suitability is more various in block 2, 7 and 8 than other blocks (standard deviation ≈ 2 Wh/m^2/day).

4.2.2 Relationship between Building Forms and Solar Radiation

I conducted a correlation analysis in Excel using data in Table 1, and summarized the results (values of correlation coefficients) in Table 2. More detailed results appear in Appendix 5, which includes p-values showing statistical significance. The correlation coefficient (R) can take a range of values from +1 to -1. Positive correlation coefficient means that one variable value increases as the other increases. Negative correlation coefficient means, one variable value increases as the other decreases. When correlation coefficient is close to zero, two variables have no linear relationship (Hinkle et al., 2003). Hinkle et al. (2003) classified strength of correlation by absolute value of correlation coefficient: very high (0.90-1.00), high (0.70-0.89), moderate (0.50-0.69), low (0.30-0.49) and little (0.00-0.29).

Table 2. Correlation Coefficients Showing the Relationships between Variables

	Average Roof Area (m²)	Building Coverage	FAR	Average Building Height (m)	Average Slope (degree)	Average Rooftop Solar Suitability (Wh/m²/day)
Average Roof Area (m²)	1					
Building Coverage	-0.34589	1				
FAR	0.12389	**0.77929**	1			
Average Building Height (m)	**0.69136**	-0.09138	0.48861	1		
Average Slope (degree)	**-0.7984**	-0.16415	-0.38483	-0.51137	1	
Average Rooftop Solar Suitability (Wh/m²/day)	**0.80937**	-0.52868	-0.23651	0.20308	-0.56971	1

Table 2 shows that among building form factors, building coverage and FAR, average roof area and average building height, average slope and average roof area are highly correlated with each other. Building coverage and FAR, as two variables measuring block density, have a positive correlation. Denser blocks have larger FAR and higher average building coverage such as block 2 and 7 (Table 1). Average roof area positively correlates with average building height; apartment buildings occupy larger area than houses. On the other hand, average roof area negatively correlates with average slope, which means smaller roofs are steeper, and larger roofs are relatively flat. Apartment buildings often have large and flat roofs. I then assumed a negative correlation between average building height and average slope. Table 2 proves the assumption correct, though the relationship is not statistically significant. FAR and average building height are positively correlated, but not statistically significant, either.

Table 2 also shows that average roof area is the only building form factor that has a statistically significant correlation with rooftop solar suitability. Roofs receive more solar radiation as roof size increases. According to Table 1, buildings in block 3 have the largest average roof area and rooftop solar suitability values among all blocks regardless of values of other building form factors; buildings in block 8 have the smallest average roof area and rooftop solar suitability values. Roof area has significant impacts on rooftop solar suitability. Carl (2014, p. 60) also found a positive relationship between roof area and solar radiation. Since average roof area positively correlates with average building height and negatively correlates with average slope, I assumed rooftop solar suitability positively correlates with average building height and negatively correlates with average slope. The values of correlation coefficients in Table 2 support the assumption: blocks with higher buildings or flatter roofs could receive more solar radiation on rooftops; however, the relationships are not statistically significant. Table 2 shows negative correlations between rooftop solar suitability and building coverage, FAR, i.e. denser blocks could receive more solar radiation on rooftops, which are not statistically significant, either.

Roof area has significant impacts on rooftop solar suitability. To analyze the impact of average building height on rooftop solar suitability with minimum influence of roof area, I examined block 1, 2, 4 and 6 with similar average roof area. The order of average building height in block 1, 2, 4 and 6 is 4<6<1<2, from smallest to largest, but the order is reversed for rooftop solar suitability (Table 3). Average building height negatively correlates with rooftop solar suitability, which contradicts my assumption. Research by Zeng (2014, p. 83) showed that low-rise blocks with higher building coverage can receive more solar radiation on rooftops. Compared with block 1 and 4, block 6 has higher building coverage, lower average height and higher rooftop solar suitability (Table 3). The conclusion also works for block 6 and 4, block 1 and 4. Among all sample blocks, block 4 has the third highest average building coverage and second lowest average building height. It receives average solar radiation of 6.65 Wh/m^2/day on rooftops, only 0.02 Wh/m^2/day less than the highest one, block 3, though the average roof area of block 3 is three times larger than block 4.

Table 3. Average Building Height and Building Coverage (Block 1, 2, 4 and 6)

Block	Average Building Height (m)	Building Coverage	Average Rooftop Solar Suitability (Wh/m^2/day)
1	10.75	18.52%	6.139266
2	11.00	42.48%	5.976890
4	6.70	35.06%	6.648035
6	8.37	25.25%	6.599400

Blocks with higher building coverage sometimes receive lower solar radiation on rooftops. Block 2 has larger average building coverage and average building height, but lower rooftop solar suitability than block 1, 4 and 6 (Table 3). Comparing other block pairs with similar average roof area (block 8 and 9, block 7 and 9, block 5 and 7), I found the same result: blocks receive less solar radiation on rooftops if they have higher building coverage and larger building height (Table 4).

Table 4. Average Building Height and Building Coverage (Block 5, 7, 8 and 9)

Block	Average Building Height (m)	Building Coverage	Average Rooftop Solar Suitability (Wh/m^2/day)
5	6.15	13.81%	6.398703
7	12.18	47.37%	5.156709
9	6.88	25.63%	5.316863
8	7.57	34.71%	4.942662

Layout organization can influence block's rooftop solar suitability. Cheng et al. (2006, p. 5) concluded that vertical randomness is less favorable in high site coverage. Randomly placed tall buildings cause overshadowing of adjacent roofs. Block 2 contains both apartment buildings and houses. Some tall buildings are inserted between two lower buildings (Figure 20). In contrast, in block 1, 4 and 6, distances between buildings are larger, and adjacent buildings have similar height (Figure 21). Roofs in block 2 receive more shadowing and less
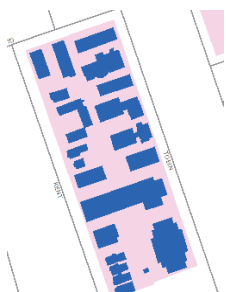
Figure 20. Building Polygons (Block 2) (Feng, 2015)
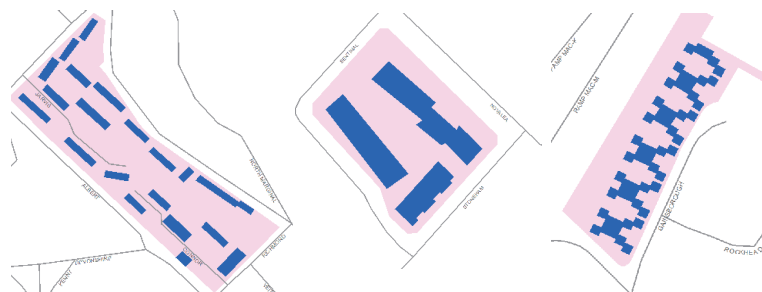
Figure 21. Building Polygons (Block 1, 4 & 6, from left to right) (Feng, 2015)

solar radiation. Block 7, having a similar layout organization as block 2 does, is more shaded than block 5 and 9 (Figure 22). Block 8 (typical R-2 layout) has more vertical randomness than block 9 (typical R-1 layout) (Figure 23).
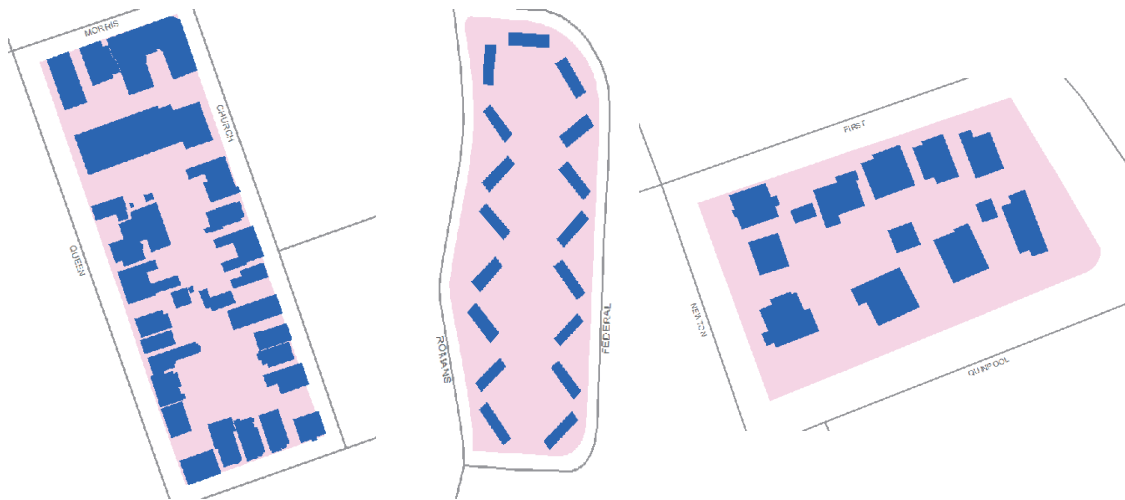
Figure 22. Building Polygons (Block 7, 5 & 9, from left to right) (Feng, 2015)
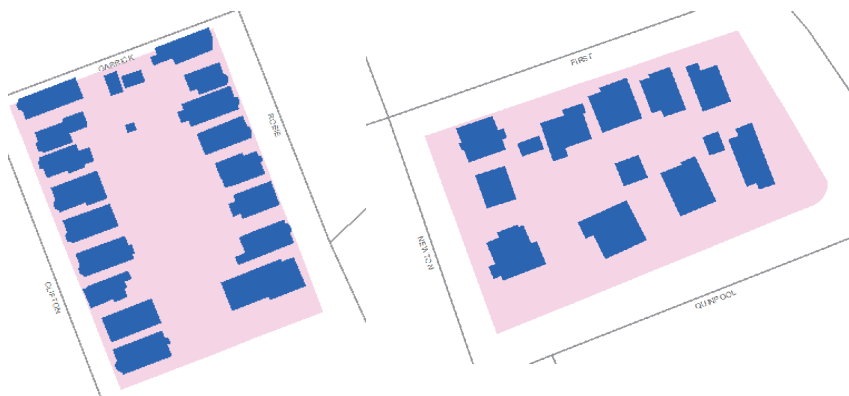
Figure 23. Building Polygons (Block 8 & 9, from left to right) (Feng, 2015)

Cheng et al. (2006, p. 5) also found high site coverage and uniform layout is more favorable than randomness in blocks with relatively large building height. Block 6 has a uniform layout: buildings are placed in a line, and their footprints have similar shapes and sizes (Figure 24). Block 6's average building height and coverage values are approximately the mid-range of all blocks, but it has the third highest rooftop solar suitability, only 0.07 Wh/m^2/day less than the highest one, block 3. Overall, blocks where buildings are placed along streets forming the blocks such as block 2, 7, 8 and 9 receive less solar radiation on rooftops; blocks where buildings are more separated and have less shadowing from each other are more solar friendly.

Figure 24. Building Polygons (Block 6) (Feng, 2015)

The influence of building coverage on rooftop solar suitability varies as other building form factors vary. FAR is another variable that measures block density. Since FAR positively correlates with building coverage, and the correlation is statistically significant, FAR and building coverage have similar impacts on rooftop solar suitability. Blocks with low-rise buildings and larger FAR receive more solar radiation on rooftops; vertical randomness is less favorable in blocks with larger FAR. The overall patterns of average building coverage and FAR are similar; however, block 3 has the third largest FAR, but second lowest average building coverage (Figure 25). Zeng (2014, p. 76) noted that blocks with larger FAR and lower building coverage are likely to have lower solar energy potential. It can explain why the rooftop solar suitability of block 3 is only 0.02 Wh/m^2/day higher than the second highest block 4, even if block 3 has much larger average roof area. We can see from Figure 25 that block 2 and 7 are the densest, and block 1 and 5 are the least dense; however, their rooftop solar suitability is neither the highest nor the lowest among the blocks. The amount of solar radiation one block can receive on rooftops depends on various factors, and density is one of the factors.

| FAR | 0.663 | 1.696 | 1.095 | 0.905 | 0.276 | 0.757 | 2 | 0.696 | 0.55 |

| Building Coverage | 18.52% | 42.48% | 16.08% | 35.06% | 13.81% | 25.25% | 47.37% | 34.71% | 25.63% |
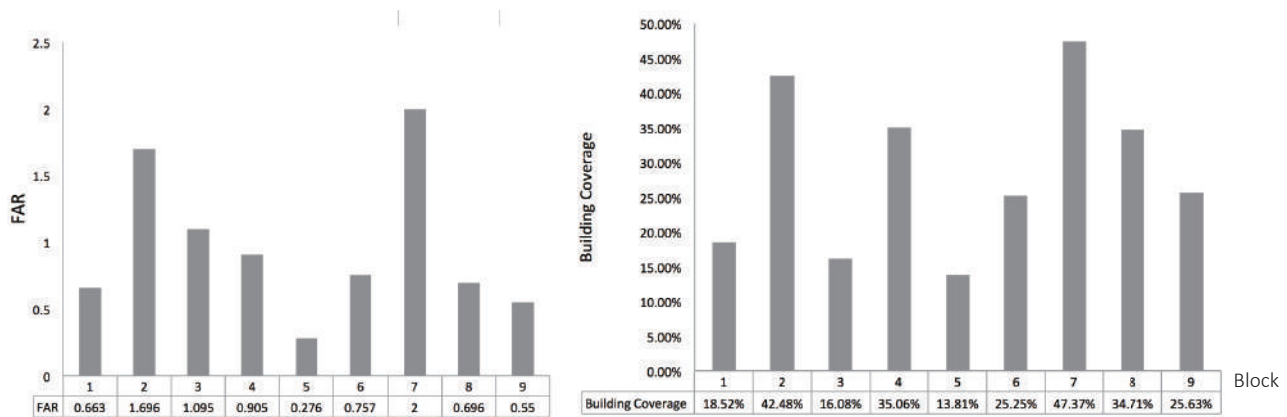
Figure 25. Building Coverage and FAR

Zeng (2014, p. 97) also concluded that roof area plays a key role in maximizing the solar energy potential with similar FAR. I compared block 6 and 8 in Table 5. They have relatively similar FAR, building coverage, average building height and average slope values. The average roof area of block 6 is four times larger than block 8, and block 6 receives much higher solar radiation. Nevertheless, their layout organizations are distinct, which can influence their rooftop solar suitability. I would need to examine more sample blocks to test Zeng's conclusion in further study.

Table 5. Building Form Factors and Rooftop Solar Suitability (Block 6 and 8)

Block	Average Roof Area (m^2)	Building Coverage	FAR	Average Building Height (m)	Average Slope (degree)	Average Rooftop Solar Suitability (Wh/m^2/day)
6	436.05	25.25%	0.757	8.37	16.981	6.599400
8	109.77	34.71%	0.696	7.57	21.012	4.942662

Table 2 shows a negative correlation between average slope and rooftop solar suitability, which is not statistically significant. Studies showed that flatter roofs receive more solar radiation than pitched roofs, since parts of pitched roofs receive a higher solar radiation while other parts are shaded (Carl, 2014; Kanters & Wall, 2014; Zeng, 2014). Comparing nine sample blocks in Table 6, I found block 3 and 4, which are the only two blocks with all flat roofs and the lowest average slope values, had the highest rooftop solar suitability values. Although block 5 and 9 have pitched roofs, their rooftop solar suitability values are not the lowest. Block 5 has zigzag-shaped uniform layout organization, which helps it receive more solar radiation (Figure 22). Block 2 has the third lowest average slope value, in which most of the roofs are flat, but it has relatively low rooftop solar suitability. Block 2 has relatively more random layout organization, higher building coverage, average building height and FAR values, as well as more various types of buildings, so roofs are more likely to be shaded (Figure 20). Roof shape affects how much solar radiation roofs can receive, but other building form factors can either enhance or reduce the effect.

Table 6. Roofs of Nine Blocks

Block	Roof Shape	Average Slope (degree)
1	Majority pitched; two flat roofs; the rest are gable and hip roofs	22.308
2	Majority flat; the rest are a mix of gable and mansard roofs; some roofs have attics on top	13.702
3	All flat roofs	8.600
4	All flat roofs	9.001
5	All gable roofs	26.849
6	Mixed with gable and flat roofs	16.981
7	Majority pitched, mixed with mansard roofs and gable roofs; some roofs have attics on top	21.930
8	Majority flat; two gable roofs	21.012
9	All pitched roofs; five out of ten are gable roofs; two are pyramid hip roofs; one cross hipped roof; one cross gable roof; one is a combination of flat and gable roofs	31.432

5. CONCLUSION

5.1 SUMMARY OF FINDINGS

I examined the local contexts, building forms and rooftop solar suitability of nine residential blocks on the Halifax Peninsula, and analyzed impacts of building form factors on rooftop solar suitability. At block level, building form factors affect solar access on roofs in various degrees. One building form factor can either reduce or enhance others' impacts. Average roof area is the only building form factor that has a statistically significant relationship with rooftop solar suitability. The following summarizes my findings regarding layout organization, average roof area, building coverage, FAR, average building height and roof shape:

- Average roof area positively correlates with rooftop solar suitability.
- Low-rise blocks with higher building coverage receive more solar radiation on rooftops.
- Blocks receive less solar radiation on rooftops if they have higher building coverage and larger building height.
- Vertical randomness is less favorable in high site coverage.
- High site coverage and uniform layout is more favorable than randomness in blocks with relatively large buiding height.
- FAR and building coverage have similar impacts on rooftop solar suitability; however, blocks with smaller FAR and higher building coverage are likely to have higher solar energy potential.
- Roof area plays a key role in maximizing the solar energy potential with similar FAR.
- Flatter roofs receive more solar radiation than pitched roofs.

I did not examine roof orientation in the study. Literature shows that roofs receive more solar radiation from the south; however, in regions using solar energy predominantly for heating, an east/south orientation is preferred, since it helps minimize heat loss in winter and heat exposure in summer (Erley & Jaffe, 1979, p. 52). The impact of roof orientation on blocks' solar access in active solar systems is not as important as in passive solar systems. The orientation of the soalr collector or the collector mounting is more significant than the roof orientation (Erley & Jaffe, 1979, p. 54).

5.2 IMPLICATIONS IN PLANNING

The findings of this study provide some helpful insights for the planning of residential blocks. First, low-rise blocks with high site coverage receive the most solar access on rooftops. Second, in high-rise blocks, lower site coverage and uniform layout organizations are preferred. Third, larger and flatter roofs receive more sunlight. In Halifax, including the Halifax Peninsula, most land zoned as residential uses is for low-density housing developments such as single-detached houses, duplexes and townhouses. Higher site coverage can improve the solar potential of these residential blocks. Increasing either the number of houses or the area of individual houses within one block can increase the site coverage. Since large surface area can cause unwanted heat gain or loss through the fabric of a building, adding houses with flatter roofs is preferred. Nevertheless, once too many houses occupy one block, poor sunlight access on vertical surfaces of houses might become a livability concern. In blocks

consisting of high-rise apartment buildings, it is better to have more open space and buildings scattered less randomly. In blocks mixed with low and high-rise buildings, arranging buildings with the same height together in clusters could ensure good solar access on roofs.

The study is a good resource for researchers interested in the relationship between building forms and building solar radiation. Planners will be able to make more informed energy-efficient building design decisions. Policy-makers can incorporate these findings into future building codes. The study contributes to the on-going solar energy programs in Halifax, which all implement rooftop solar collectors. Residents have more access to rooftop solar technologies, and solar energy can reduce household energy costs. The study assists Halifax in saving natural resources, decreasing GHG emissions, reducing energy costs and achieving more sustainable and innovative future.

5.3 FUTURE WORK

Due to the limited number of sample blocks, I was only able to conduct correlation analysis and descriptive statistics to explore impacts of building form factors. Future directions for further study can extend the scope of the study. I can use other statistical tools such as regression analysis to examine more types of residential blocks on the Halifax Peninsula and other areas in Halifax, which helps expand the scale of my analysis, by supporting or further testing the findings. I obtained rooftop solar suitability values from the Solar Suitability Map, which did not exclude the vegetation layer. HRM used the map to promote its Solar City program instead of for research purposes; data used to create the map are from various years, so the map lacks accuracy. In future work, I can either create a more accurate map or use other solar radiation simulation tools to estimate the amount of solar radiation on rooftops in a way that will enable me to explore roof orientation.

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7. APPENDIX

Appendix 1. Solar Suitability Map

HRM collaborated with Dalhousie University to create the Solar Suitability Map using a digital surface model (DSM) (see Note 2 in Appendix 2) based on LiDAR data from 2005, aerial photographs from 2006 and 2009 and a shadow-obstruction technique (Halifax, n.d.). LiDAR (Light Detection and Ranging), is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light (National Ocean Service, 2013). The shadow-obstruction technique uses the "hillshade" tool in ArcGIS, which draws shadows on a map to simulate the effect of the sun's rays over the varied terrain of the land (ESRI, n.d.).

Solar position was calculated in 5-minute increments, from dawn to dusk, as it tracked through the sky for the equinoxes and solstices. Equinox is the time when the sun crosses the plane of the earth's equator, making night and day of approximately equal length all over the earth. It occurs usually on March 21st (spring equinox) and September 22nd (autumnal equinox) (Woodlands Junior School, n.d.a). The day of the solstice is either the longest day of the year (summer solstice) or the shortest day of the year (winter solstice) for any place outside of the tropics (Woodlands Junior School, n.d.b).The results of these four days are averaged to present a relative solar accessibility value on the rooftop surfaces. Each pixelated point in the solar layer in ArcGIS represents a solar suitability value ($Wh/m^2/day$). "Wh" stands for watt-hour, which is a unit of energy equivalent to one watt (1 W) of power expended for one hour (1 h) of time (The Encyclopedia of Earth, 2007).

Appendix 2. Data Used to Complete Objective One

Information objectives	Data
Determine reasonable sample size and sampling strategy	Halifax Peninsula Zoning By-Law
	Zoning layer from 2007 HRM Geodatabase[1]
	Building polygon layer from 2007 HRM Geodatabase
	2014 HRM pictometry imagery (resolution: 15cm)
	2006 HRM aerial photography (resolution: 60cm)
	Vegetation layer from 2005 LiDAR Data
Understand local contexts of the building blocks	Zoning layer from 2007 HRM Geodatabase
	Halifax Peninsula Zoning By-Law
	Dissemination Area (DA) layer from 2007 HRM Geodatabase
	Site Visit
	2006 Census data from Statistics Canada
	Other online sources
Examine building form factors of the building blocks	Building polygon layer from 2012 HRM Geodatabase
	Zoning layer from 2007 HRM Geodatabase
	Parcel layer from 2007 HRM Geodatabase
	Digital Surface Model (DSM)[2] from 2005 LiDAR data
	Digital Elevation Model (DEM)[2] from 2005 LiDAR data
	Aspect layer extracted from DSM
	Slope layer extracted from DSM
	2014 HRM pictometry imagery (resolution: 15cm)
	Site visit
	Other online sources
Determine rooftop solar suitability of the building blocks	Rooftop solar suitability (Wh/m^2/day) from Halifax solar suitability map
	Zoning layer from 2007 HRM Geodatabase

Note 1: *2007 HRM Geodatabase contains more complete 2006 GIS data than 2006 HRM Geodatabase.*

Note 2: *Surfaces represented by a Digital Surface Model (DSM) include buildings and other objects. Digital Terrain Models (DTM) represents the bare ground (Source: Li, Z., Zhu, Q., & Gold, C., 2005).*
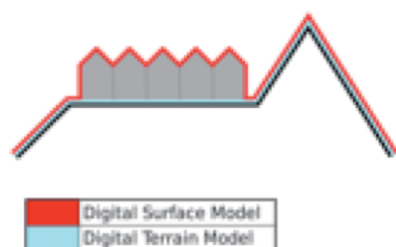
Appendix 3. Building Form Factors and Rooftop Solar Suitability

Variable	Block	Mean	Maximum	Minimum	Standard Deviation	Median
Roof Size (m²)	1	432.26	667.56	206.86	131.637	413.23
	2	413.74	1597.51	75.43	359.086	348.93
	3	766.99	985.36	350.4	225.606	862.85
	4	483.45	609.6	316.09	123.318	524.66
	5	248.07	296.81	191.88	24.986	249.84
	6	436.05	480.54	253.44	81.807	471.21
	7	196.76	952.17	49.71	188.94	141.54
	8	109.77	206.08	73.22	27.707	106.32
	9	137.85	182.86	91.19	27.348	138.57

Variable	Block	Total roof area (m²)	Block area (m²)	Building coverage
Building Coverage	1	8645.24	46673.48	18.52%
	2	8688.54	20452.17	42.48%
	3	6135.96	38170.68	16.08%
	4	1450.34	4136.3	35.06%
	5	4217.26	30527.45	13.81%
	6	2616.28	10362.38	25.25%
	7	5509.27	11672.53	47.37%
	8	1866.12	5530.43	34.71%
	9	1378.45	5798.56	25.63%

Variable	Block	Gross floor Area (m²)	Block area (m²)	FAR
FAR	1	30952	46673.48	0.663
	2	34693.3	20452.17	1.696
	3	41803.2	38170.68	1.095
	4	3741.43	4136.3	0.905
	5	8434.51	30527.45	0.276
	6	7848.83	10362.38	0.757
	7	23344.1	11672.53	2
	8	3848.07	5530.43	0.696
	9	3188.26	5798.56	0.55

Variable	Block	Mean	Maximum	Minimum	Standard Deviation	Median
Building height (m)	1	10.75	29.14	-0.16	5.809	9.22
	2	11	25.9	-0.54	4.438	10.56
	3	19.52	39.61	-0.05	6.379	19.45
	4	6.7	12.06	-0.18	1.355	6.46
	5	6.15	11.08	-0.36	1.913	6.66
	6	8.37	10.68	-0.06	1.46	8.64
	7	12.18	31.99	-0.3	6.963	9.26
	8	7.57	20.01	-0.09	2.391	7.55
	9	6.88	19.27	-0.22	2.517	7.12

Variable	Block	Mean	Maximum	Minimum	Standard Deviation	Median
Slope (degree)	1	22.31	59.99	0.09	13.161	21.4
	2	13.7	59.97	0	18.15	2.78
	3	8.6	59.98	0	13.608	1.95
	4	9	59.95	0.01	14.874	1.8
	5	26.85	59.96	0.43	13.251	25.36
	6	16.98	59.91	0.07	14.645	11.79
	7	21.93	59.97	0.1	18.473	17.38
	8	21.01	59.96	0.1	20.156	10.41
	9	31.43	59.93	0.98	15.135	30.34

Variable	Block	Mean	Maximum	Minimum	Standard Deviation	Median
Rooftop Solar Suitability (Wh/m²/day)	1	6.139266	7.934057	0.003727	1.59649	6.677176
	2	5.97689	7.896485	0.017176	2.007196	6.943829
	3	6.667679	7.958523	0.009893	1.692874	7.457425
	4	6.648035	7.824885	0.019261	1.37198	7.182305
	5	6.398703	7.944985	0.018777	1.409233	6.81425
	6	6.5994	7.949315	0.01284	1.925295	7.550839
	7	5.156709	7.925576	0.013579	1.987511	5.733602
	8	4.942662	7.839191	0.038486	2.005339	5.292233
	9	5.316863	7.889663	0.058129	1.842425	5.748861

Appendix 4. Roof Types (Source: M&M Construction Specialist, n.d.)

Cross Gable Roof

Cross Hipped Roof

Flat Roof

Gable Roof

Gambrel Roof

Hip Roof

Mansard Roof

Pyramid Hip Roof

Saltbox Roof
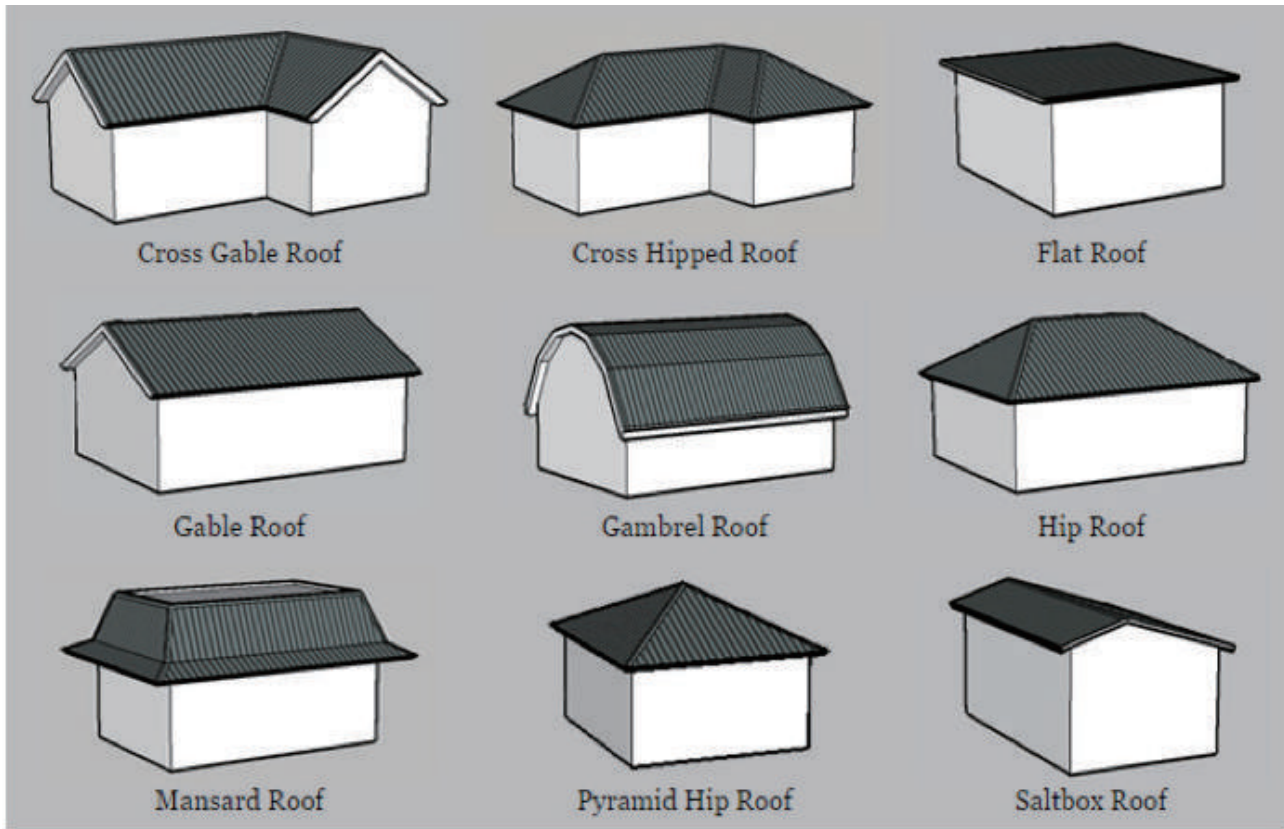
Appendix 5. Results of Correlation Analysis Showing Relationships between Variables (Source: Author, 2015)

		Average Roof Area (m^2)	Building Coverage	FAR	Average Roof Area (m^2)	Average Roof Area (m^2)	Average Rooftop Solar Suitability (Wh/m^2/day)
Average Roof Area (m^2)	R	1.					
	R Standard Error						
	t						
	p-value						
	H0 (5%)						
Building Coverage	R	-0.34589	1.				
	R Standard Error	0.12577					
	t	-0.97533					
	p-value	0.36189					
	H0 (5%)	accepted					
FAR	R	0.12389	0.77929	1.			
	R Standard Error	0.14066	0.0561				
	t	0.33033	3.29013				
	p-value	0.75082	0.0133				
	H0 (5%)	accepted	rejected				
Average Roof Area	R	0.69136	-0.09138	0.48861	1.		
	R Standard Error	0.07457	0.14166	0.10875			
	t	2.53167	-0.24278	1.48166			
	p-value	0.03914	0.81513	0.18198			
	H0 (5%)	rejected	accepted	accepted			
Average Roof Area	R	-0.7984	-0.16415	-0.38483	-0.51137	1.	
	R Standard Error	0.05179	0.13901	0.1217	0.1055		
	t	-3.50821	-0.44028	-1.10311	-1.57438		
	p-value	0.00988	0.67301	0.30645	0.1594		
	H0 (5%)	rejected	accepted	accepted	accepted		
Average Rooftop Solar Suitability (Wh/m^2/day)	R	0.80937	-0.52868	-0.23651	0.20308	-0.56971	1.
	R Standard Error	0.04928	0.10293	0.13487	0.13697	0.09649	
	t	3.64611	-1.64787	-0.64402	0.54872	-1.83405	
	p-value	0.00822	0.14337	0.54008	0.60025	0.10929	
	H0 (5%)	rejected	accepted	accepted	accepted	accepted	