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Effect of external shading on household energy requirement for heating and cooling in Canada

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ABSTRACT

Shading by neighbouring buildings and trees impacts the energy requirement of a building by reducing the amount of radiant energy absorbed and stored by its thermal mass. This study intends to quantify the magnitude of the effect of site shading on the energy requirement of residential buildings in Canada using a representative two-storey detached house. Site shading effects of neighbouring buildings and trees on annual heating and cooling energy requirements are evaluated using a building energy simulation program. The effects of the orientation, distance and size of the neighbouring object on heating and cooling energy requirement are investigated for four major cities (Halifax, Toronto, Calgary, Vancouver) representing the major climatic regions in Canada (Atlantic, Central, Prairies, Pacific). It is found that the annual heating and cooling energy requirement of a house in Canada may be affected by as much as 10% and 90%, respectively, by the existence as well as the orientation, size and distance of a neighbouring obstruction. Therefore, it is recommended that in building energy simulation studies, external shading should be given due consideration.

1. Introduction

Shading may decrease or increase the energy requirement of a building depending on building characteristics and environmental conditions. A potential benefit of shading for adjacent structures is decreasing the cooling energy requirement. Negative consequences of shading include the loss of natural light for passive or active solar energy applications and the loss of warming influences, which increase the heating energy requirement during the cold season. Factors influencing the impact of shading are site-specific such as the latitude and climate, as well as the direction, number, size and distance of neighbouring structures. Although potentially significant, the impact of neighbouring structures on the heating and cooling energy requirement of houses is often neglected in building energy analysis.

Due to the potentially substantial effect of shading due to neighbouring structures on the energy requirement of buildings, numerous studies have been conducted to assess the effect of shading by neighbouring buildings and trees. Frank et al. [1] developed a program that calculates the view factors of a building and the alignment of obstructions to simulate the shading effect by trees and buildings in urban environments. A decade later, Ok [2] developed a model to calculate the effect of shading due to adjacent or nearby buildings on the cooling load taking into consideration settlement density, as well as the shape, distance and orientation of the obstruction. A multi-storey residential building located in Istanbul was simulated for July 21st as a case study. The results showed that the effect of shading is more significant for the west and east oriented surfaces primarily due to the lower angle of solar radiation in the afternoon that results in a significant heating effect. In a similar study, Lam [3] investigated the shading effects due to neighbouring buildings on commercial buildings in seven main business districts in Hong Kong using the building energy simulation software DOE-2.1E [4]. The results of this study showed that the reduction in cooling load due to shading is about two percent, which is not significant for commercial buildings.

Farrar-Nagy et al. [5] studied a residential building in Tucson, Arizona to evaluate the opportunities for reducing cooling energy requirement in a hot dry climate through the use of spectrally selective windows, architectural shading, and site shading from adjacent buildings. Building performance was modeled using the building energy simulation software DOE-2 [4] and was measured while the building was unoccupied for a period of 12 days. It was found that ignoring the shading effect due to neighbouring buildings could result in overestimating the annual cooling energy requirement by up to 24%, depending on the orientation of the building, existence of overhangs and the type of windows.

In a paper that studied the impact of a number of parameters on the heating energy requirement of Canadian houses, Purdy and

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Table 1
Characteristics of the test case house.

Built year	1955
Floor-area (m^2)	66
Width (m)	9.6
Depth (m)	6.9
Height (including attic) (m)	6.3
U-value above-grade walls (W/m^2 K)	0.55
U-value above-grade ceiling (W/m^2 K)	0.47
U-value basement walls (W/m^2 K)	2.89
U-value basement floor (W/m^2 K)	1.39
U-value windows (W/m^2 K)	2.00
Number of windows	4 (one each side)
Dimensions of windows (m)	3 × 2
Front side	South

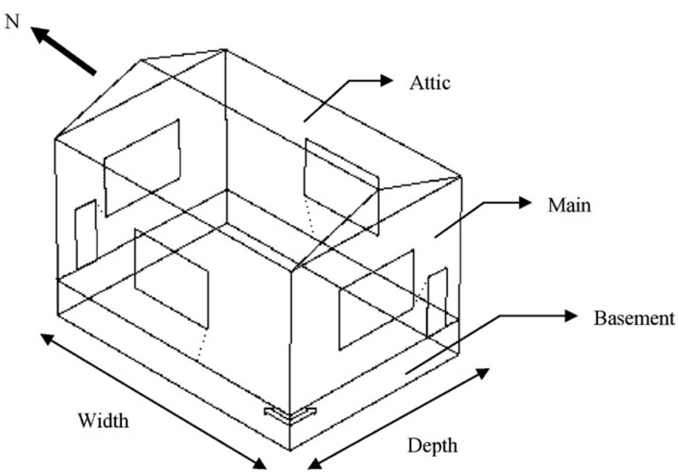

Fig. 1. Test case house.

Table 2
Climatic characteristics of selected cities.

City	Latitude	Longitude	HDD (based on 18 °C)	CDD (based on 18 °C)
Halifax	44° 54′ N	63° 34′ W	4031	105
Toronto	43° 41′ N	79° 24′ W	3570	359
Calgary	51° 6′ N	114° W	5108	40
Vancouver	49° 11′ N	123° 10′ W	2926	44

Beausoleil-Morrison [6] assessed the shading effect of surrounding objects. The study was conducted using a developmental version of the HOT3000 building simulation software [7], which uses the comprehensive building energy simulation software ESP-r [8] as its simulation engine. A two-storey research house at the Canadian Center for Housing Technology in Ottawa was selected as the base case house for this study. It was found that the shading caused by the neighbouring houses increases the annual heating load requirement by up to 5%. It was also found that the results are sensitive to the location of the neighbouring house. Furthermore, the results demonstrated that the solar shading caused by surrounding buildings, and by extension other large objects such as trees, have more impact than the shading caused by a typical roof overhang.

Li and Wong [9] studied the daylighting performance and energy use of a commercial building shaded by nearby buildings in Hong Kong. A procedure involving computer simulation techniques was employed to evaluate the energy performance of office buildings with day-lighting controls shaded by neighbouring buildings. A detailed study of the shading effects showed that day-lighting is always an energy saver in the Hong Kong climate. Results from a regression analysis were used to establish a number of correlation equations, which could predict the energy savings due to shading by external obstructions.

Akbari and Taha [10] studied, among other parameters, the effect of shading by trees and the impact of painting the house white (high albedo) on residential heating and cooling energy use

Table 4
Orientation and number of neighbouring structures.

Number of neighbouring structures	2	3
Orientation	W/S	S/N/E
	E/S	S/N/W
	W/N	S/E/W
	S/N	N/E/W
	E/W	–
	E/N	–

Table 5
Size of neighbouring structures.

Orientation	Neighbouring house (H (m) × W (m))	Neighbouring tree (H (m) × W (m))
West	6.3 × 9.6	6 × 4
	6.3 × 19.2	6 × 8
	12.6 × 9.6	12 × 4
	12.6 × 19.2	12 × 8
South	6.3 × 6.9	6 × 4
	6.3 × 13.8	6 × 8
	12.6 × 6.9	12 × 4
	12.5 × 13.8	12 × 8

Table 6
Distance of neighbouring structures.

Orientation	Distance of neighbouring structures from the shaded house (m)
West or south	2.3
	4.7
	9.5
	14.2

Table 3
Size and orientation of neighbouring structures.

Obstruction type	Dimensions (m)	Orientation	Distance from the shaded house (m)	Shading period
House	Height = 6.3 Width = 9.6 Depth = 6.9	East or west	4.7	Whole year
House	Height = 6.3 Width = 6.9 Depth = 9.6	North or south	3.3	Whole year
Tree	Trunk height = 2 Crown height = 6 Crown width = 4 Crown depth = 4	All sides	4.7	Evergreen: whole year Deciduous: April 1st to October 1st

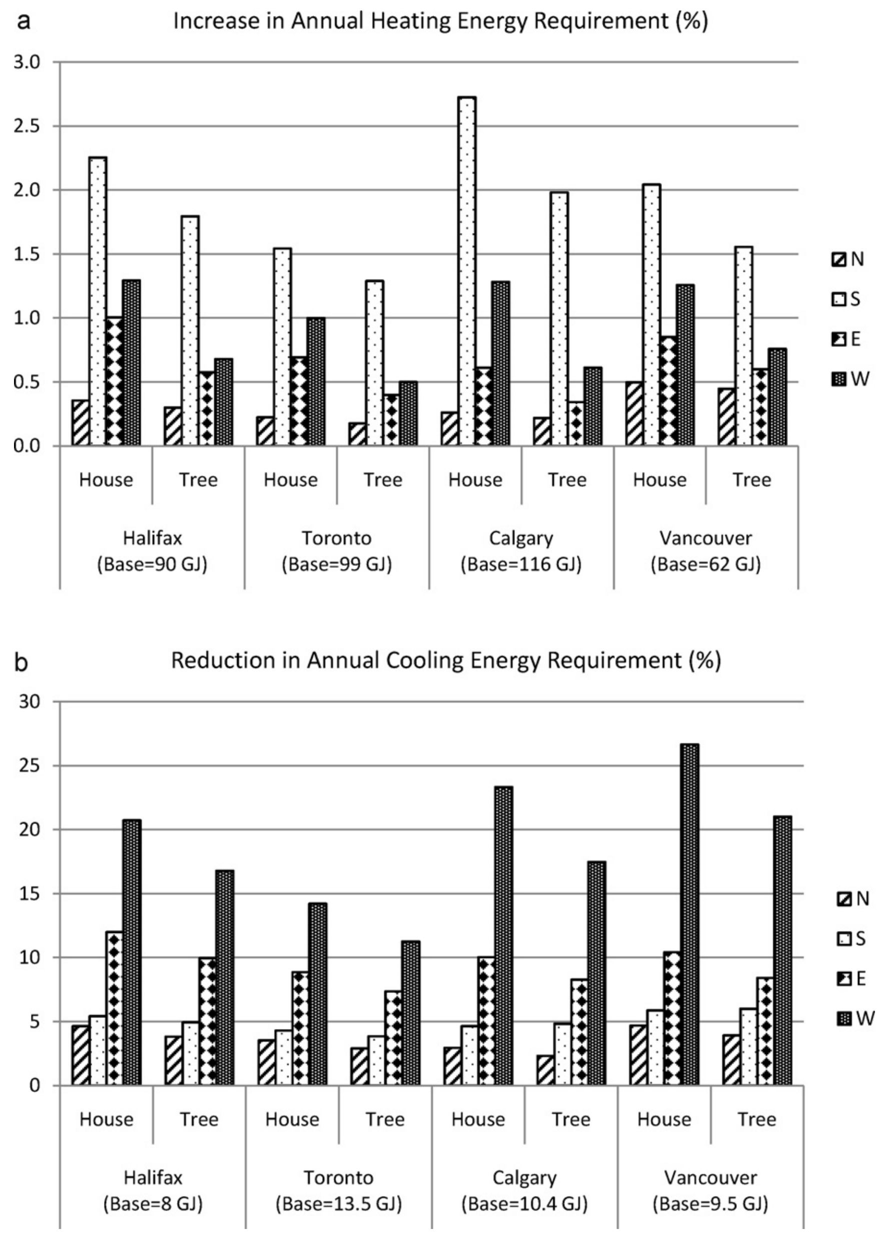

Fig. 2. Effect of orientation of neighbouring structures on the heating and cooling energy requirements.

in four Canadian cities. For this purpose, three different building prototypes were simulated for Vancouver, Edmonton, Toronto and Montreal using the building energy simulation program DOE-2.1D [4]. The building prototypes included a detached one-storey and a detached two-storey single-family house, and a row house. It was found that a 30% increase in the vegetative cover of an urban neighbourhood in Toronto (corresponding to about three trees per house), increases the annual heating energy consumption by up to 1%, while decreasing the cooling energy consumption by up to 30%. In urban neighbourhoods of Edmonton, Montreal and Vancouver, the predicted savings in heating energy use due to addition of trees and high albedo was about 10%. It was also found that the effect of shading and high albedo could totally offset the cooling energy in Edmonton and Vancouver, and average savings of 35% can be achieved in Montreal.

Simpson and McPherson [11] studied the shading effect of trees on the energy use of energy efficient, attic insulated and uninsulated houses in eleven California climate zones. Trees shading a west, southwest and east exposure were found to produce the largest annual energy savings for all climate zones and insulation levels considered. Depending on the climate zone, three mature trees (two on the west, one on the east side) reduced annual energy use for cooling up to 50%. Trees planted on the south and south-east exposures were found to be advantageous for cooling. It was however noted that increased heating loads due to reduced solar thermal gains in winter may substantially reduce or eliminate any savings from cooling energy reduction.

Akbari et al. [12] studied the impact of trees on cooling energy use. For this study, two houses in Sacramento, CA were instrumented for extensive data collection. The houses were shaded directly from the south and west with sixteen trees, eight tall (about 6 m high) and eight short (about 2.4 m high), and were simulated by DOE-2.1E building energy simulation program to compare the results of measurements and simulations. It was found that cooling energy savings for the house with a central air-conditioning system was 47% while the savings for the house with a heat pump system was 26%. In another study conducted for the Sacramento, California environment based on simulations of 254 residential properties,

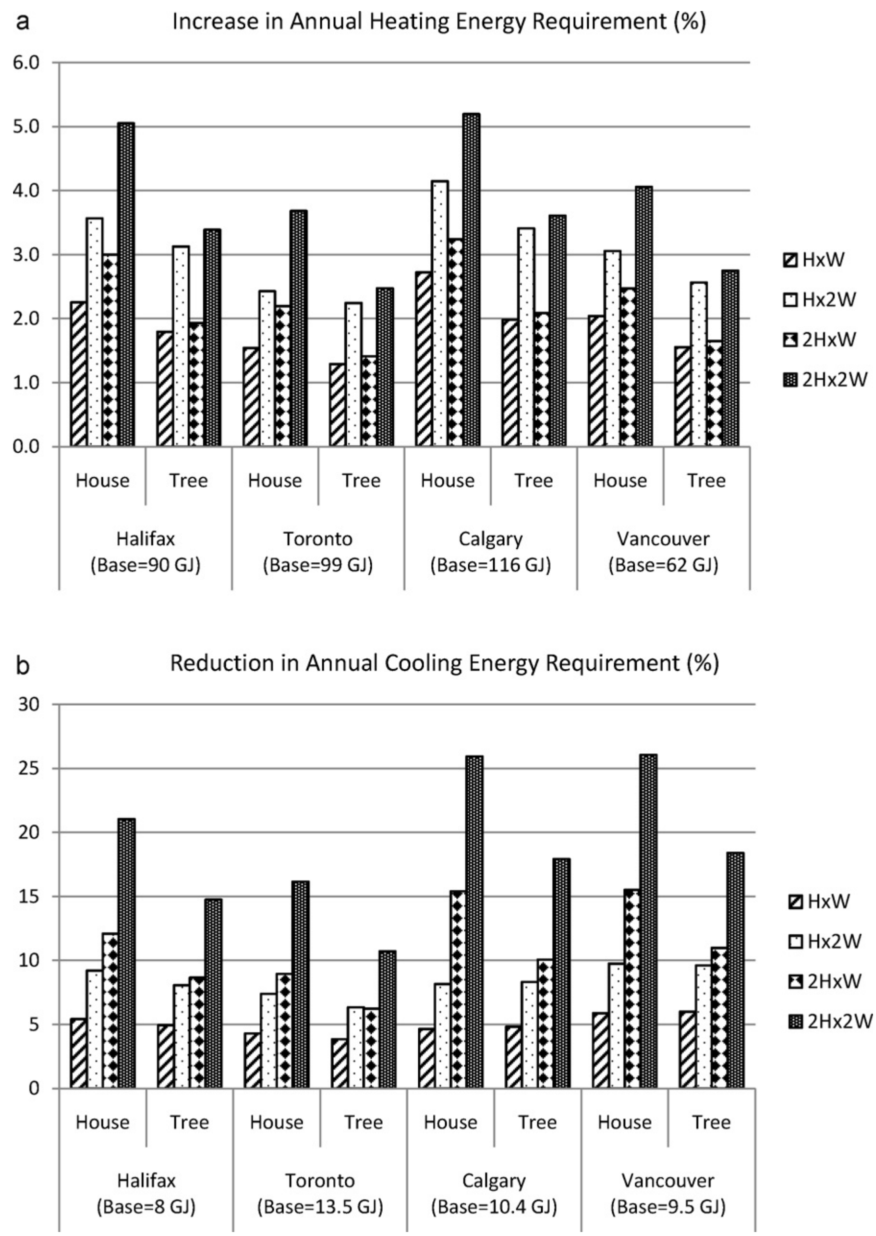

Fig. 3. Effect of the size of southerly neighbouring structures on the heating and cooling energy requirements.

by Simpson and McPherson [13] found that planting an average of three trees per property reduces the annual and peak cooling energy use by 7.1% and 2.3%, respectively.

Higuchi and Udagawa [14] studied the shading effect of broad leaved evergreen and deciduous trees. A two storey house was simulated using the simulation program EESLISM (Udagawa and Makoto [15,16]). Simulations were carried out for five cases, which consist of a base case with no trees, and two types of trees and two kinds of tree planting arrangements. It was found that the annual cooling load reduced by up to 20% and the heating load increased by 5% when two evergreen trees exist on the south and one on the west side.

Hongbing et al. [17] studied the effect of location and height of evergreen and deciduous trees on daylighting of multi-storey (four to six stories) residential buildings in Shanghai. Two typical layouts of the green space between buildings (GSBB) were selected and their daylighting models were built with AutoCAD and Sketchup 5 on the basis of local solar altitude and azimuth angle. Four equations to calculate the optimum height of deciduous trees for the vernal equinox and evergreen trees for the winter solstice for 12:00 and 13:00 pm were recommended. They concluded that the type, size, number and pattern of trees have a substantial impact on daylighting, and therefore site specific studies are needed to determine optimal building and shading configurations.

This review of the literature shows that shading caused by neighbouring structures can have a significant impact on the energy consumption of a building. The objective of this work is therefore to quantify the effect of shading from neighbouring structures on the heating and cooling energy requirements of Canadian houses.

2. Methodology

A two-storey detached house commonly found in Canada is used as the “test case house”, which was first modeled and simulated without any external shading to provide the “base case” energy requirement. Then, external shading, in the form of neighbouring houses and trees, was added to the model and simulated to assess the effect of external shading in a variety of forms. The test case

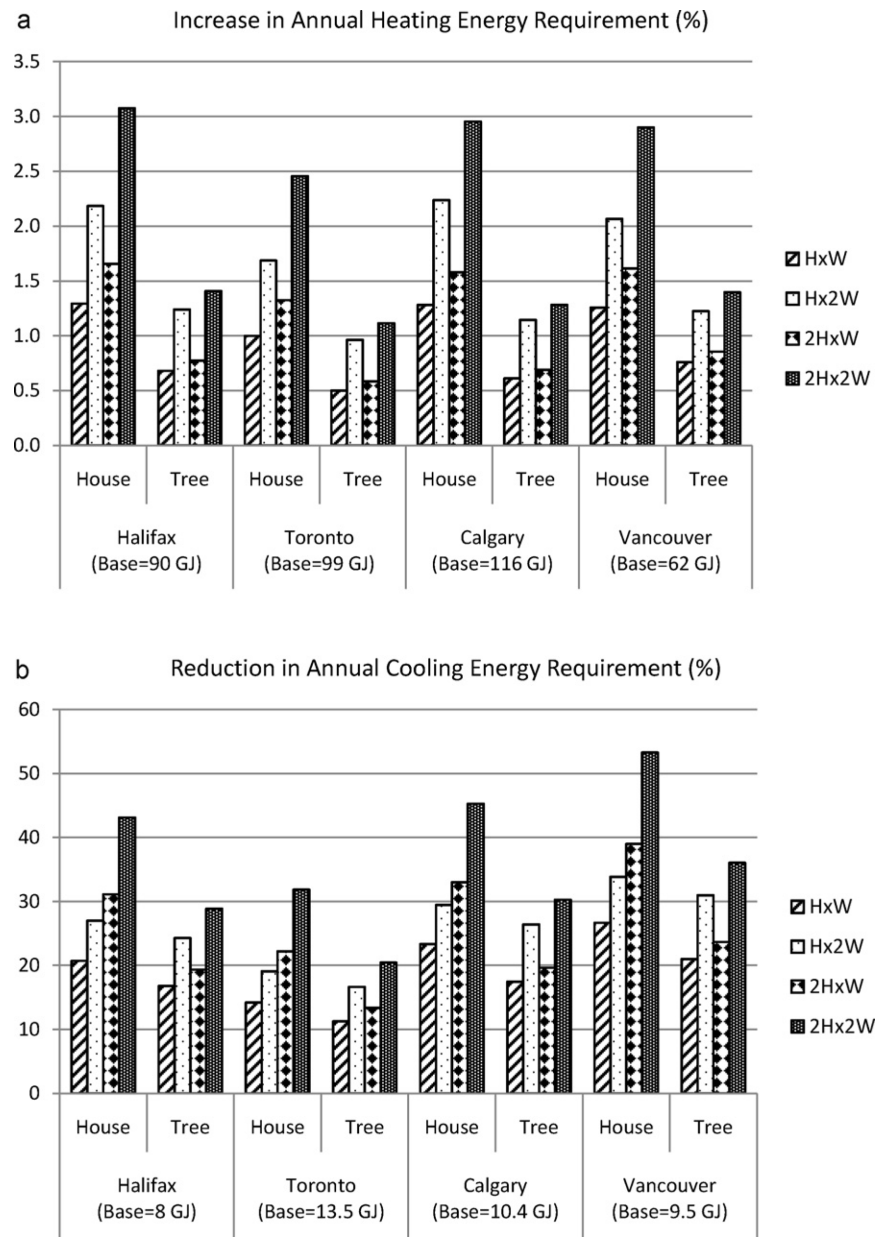

Fig. 4. Effect of the size of westerly neighbouring structures on the heating and cooling energy requirements.

house was selected from the Canadian Single-Detached and Double/Row Database (CSDDRD) (Swan et al. [18]) and modeled using the building energy simulation program, ESP-r, a comprehensive building modeling tool based on the finite volume technique [9].

The CSDDRD contains detailed data from 16,952 actual houses in Canada and is statistically representative of the Canadian housing stock. It is a subset of the EnerGuide for Houses Database (EGHD) of Natural Resources Canada, and contains detailed data on house type, location and orientation, geometry, envelope, occupancy and air infiltration, as well as data on domestic hot water and space heating/cooling systems [19]. The EGHD data were collected from over 200,000 requested home energy audits from 1997 to 2006 conducted by specially trained energy auditors.

The test case house was selected from the CSDDRD based on its main features (i.e. number of storeys, floor area, envelope characteristics, and space heating/cooling equipment) such that the design of the test case house is one that is commonly encountered across the country. The level of thermal insulation in the test case house is in conformance to the building code.

The parameters examined in this work include the orientation, size and distance of the shading objects.

2.1. Test case house

The two-storey test case house is composed of two above-grade storeys, a conditioned basement and a non-conditioned attic. It is occupied by two adults and two children, and has a set of appliances including a refrigerator, washer and dryer, dishwasher and TV. The thermal characteristics of the house are given in Table 1, while Fig. 1 shows the geometry.

Three thermal zones representing the basement, the attic and the two-storey living space were used to model the house in the ESP-r energy simulations. In the thermal model, the living space and basement are conditioned by the HVAC system while the attic is “free floating” in response to the thermal contact with the other zones and the outdoors. The contact between the basement zone and the ground is modeled with the BASESIMP model (Beausoleil-Morrison and Mitalas [20]) and the air infiltration is modeled

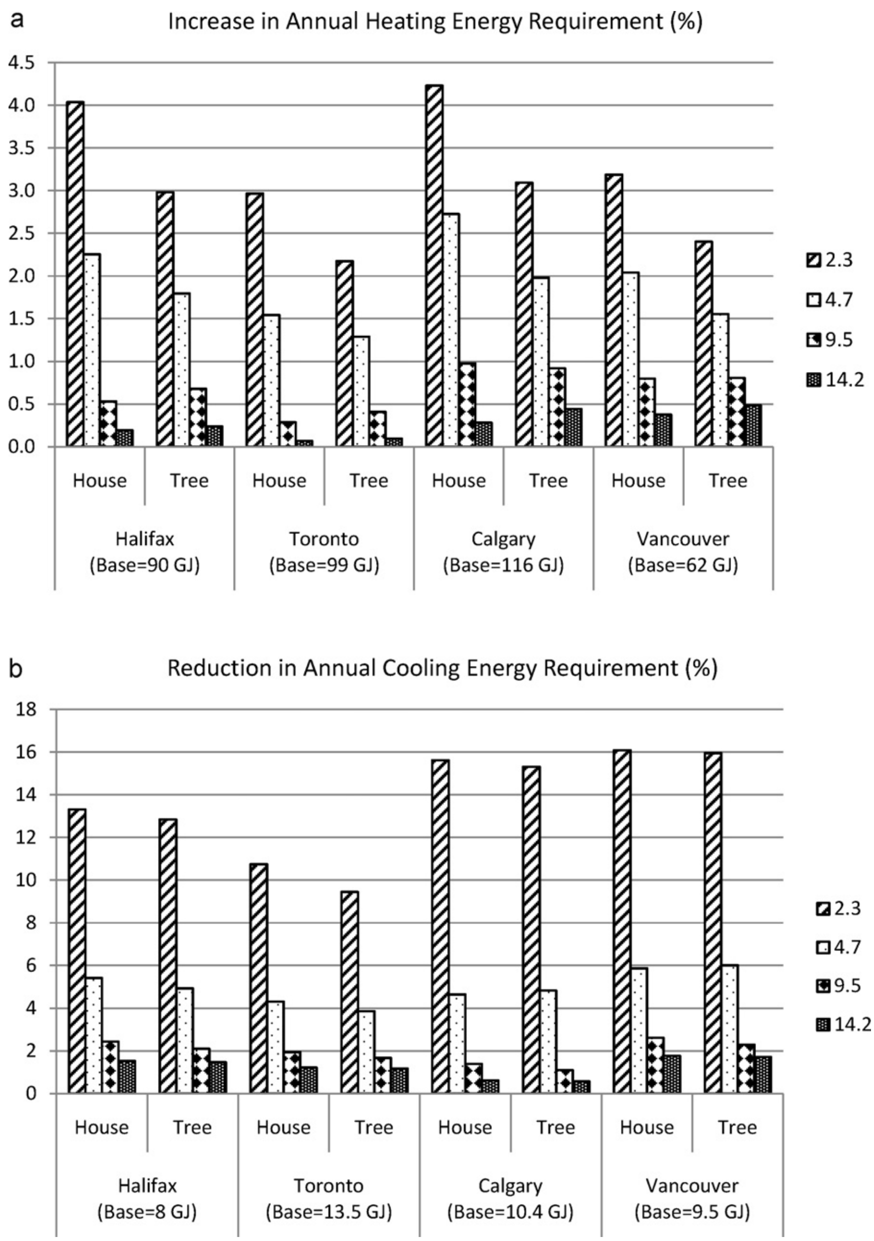

Fig. 5. Effect of the distance of southerly neighbouring structures on the heating and cooling energy requirements.

with the AIM-2 model (Walker and Wilson [21]). To simplify the model, windows are placed at the geometric center of the walls. This is a reasonable assumption based on the findings of Purdy and Beausoleil-Morrison [6]. It is also assumed that windows are always closed and they have no blinds to isolate the effect of external shading.

Neighbouring structures are modeled in ESP-r by adding one or more obstructions to the test case house. In this work trees are assumed to be fully opaque. The shading and insolation module of ESP-r was used to calculate the temporal distribution of shading patterns on exterior surfaces and the distribution of insolation within zones [9].

2.2. Case studies conducted

The effect of shading due to neighbouring obstructions is assessed by conducting simulations with different orientations, sizes and distances of shading. The space heating and cooling energy requirements predicted for each case are compared to those for the base case house. Since the effect of shading on heating and cooling energy requirement varies substantially based on the climate and the geographical location of a house, four cities, Halifax, Toronto, Calgary and Vancouver, were selected to represent the four major climatic regions in Canada, namely Atlantic, Central, Prairies and Pacific.

The weather data files used in the simulations are from the Canadian Weather Year for Energy Calculation (CWEC) files [22]. These files are 'typical year' weather files which are obtained by concatenating twelve Typical Meteorological Months selected from a database of, in most cases, 30 years of data. The months are chosen based on statistical criteria (representing mostly solar and dry bulb temperature).

The climatic characteristics of selected cities are summarized in Table 2.

The type, size, orientation and distance of shading obstructions considered are summarized in Table 3. The neighbouring house

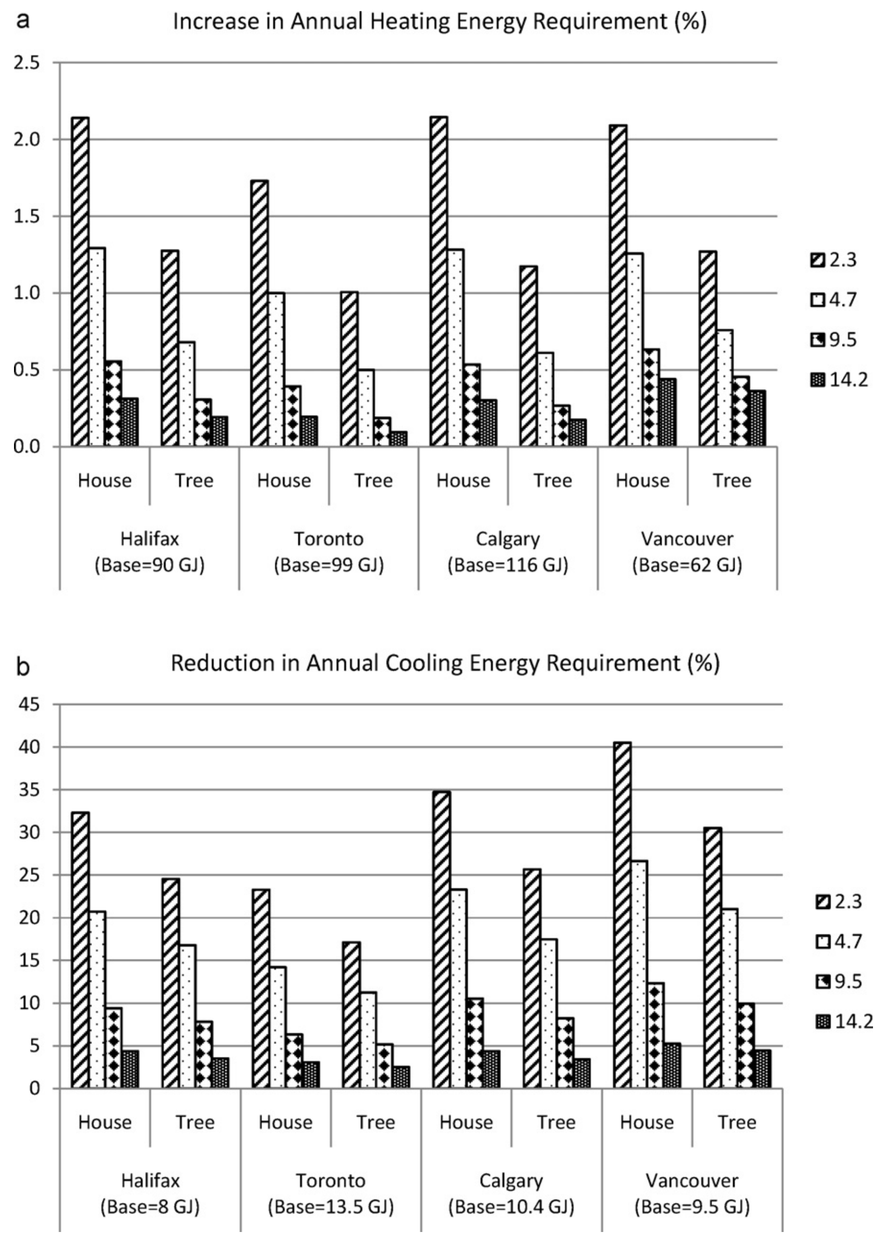

Fig. 6. Effect of the distance of westerly neighbouring structures on the heating and cooling energy requirements.

is assumed to be the same size as the base case house to reflect the pattern of houses in suburban neighbourhoods. In all cases, the obstructions are assumed to be located at the centerline of the house. The effect of shading by trees is examined for evergreen and deciduous trees. It is assumed that deciduous trees provide shading only during the April 1 to October 1 period, while evergreen trees provide shading throughout the year. Due to the vast landmass of Canada, a tree that is common in one area may be completely absent or unable to grow in another area. Therefore, an average size for both types of trees is assumed.

The orientation and number of shading obstructions, as well as the obstruction combinations considered are given in Table 4. To assess the effect of the size of the shading obstructions, the width and height of the obstructions located on the south and west side of the base case house were doubled as shown in Table 5. To assess the distance of neighbouring obstructions, their distance from the base case house was changed as shown in Table 6.

3. Results and discussion

The results are summarized in Figs. 2–6. In every figure, the changes in the heating and cooling energy requirement are given as a percentage of the heating and cooling energy requirement of the base case house with no external shading. Since the base case house energy requirement varies from location to location, the base case house energy requirement values are included in each figure.

As seen in Fig. 2a, shading from a neighbouring house located on the south side of the test case house results in the largest increase in heating energy requirement, which varies from 2.7% for the house located in Calgary to 1.5% in Toronto, representing 3.2 GJ/year and 1.5 GJ/year, respectively. On the other hand, shading caused by a house located on the west side decreases cooling energy requirement the most, by more than 25% in Vancouver (representing 2.5 GJ/year), as shown in Fig. 2b. The results are sensitive to the orientation of the neighbouring structure, which confirms Purdy's

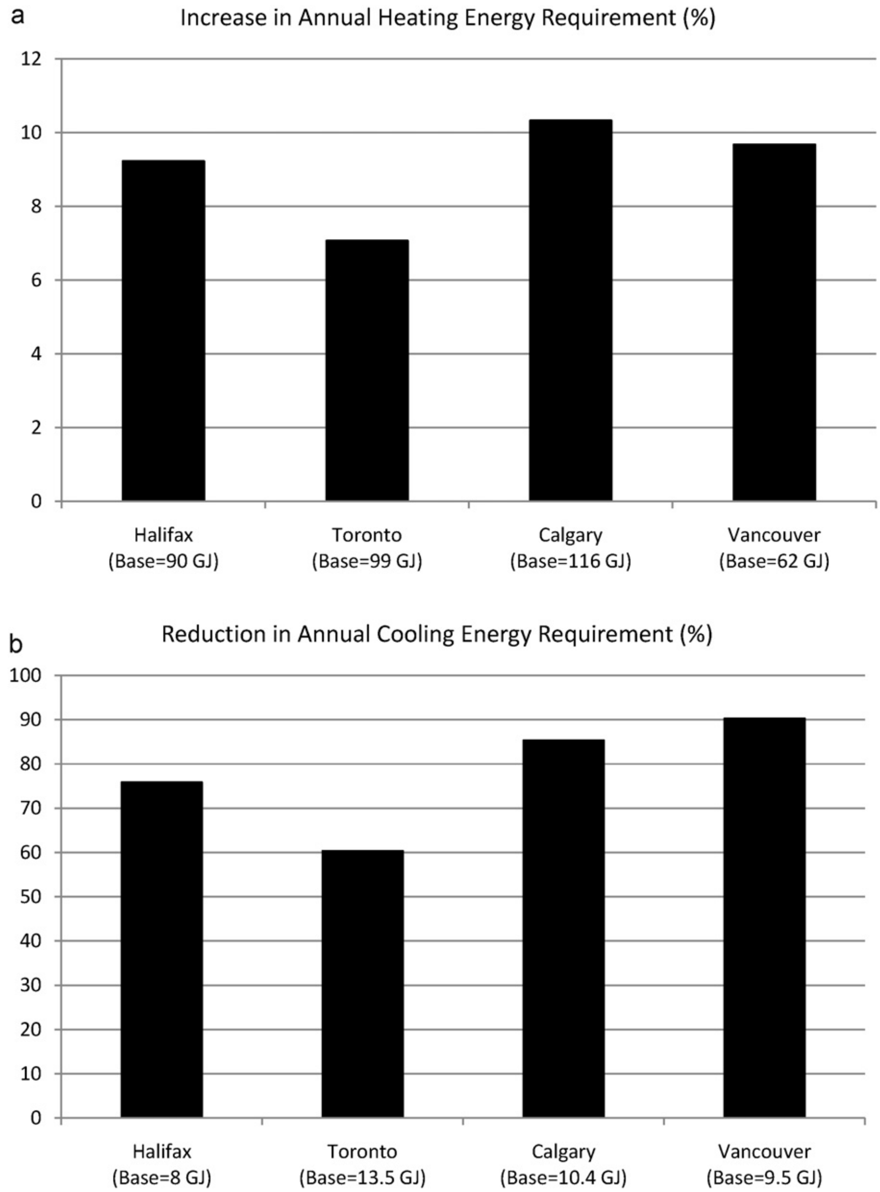

Fig. 7. Worst case results.

results on shading by surrounding objects (Purdy and Beausoleil-Morrison [6]). The effect of shading caused by a tree is smaller than that of a house, as shown in Fig. 2a and b, due to the smaller size of the shade produced. However, while a deciduous or an evergreen tree has the same effect on the cooling energy requirement, the increase in the heating energy requirement due to the shade of a deciduous tree was found to be negligible (less than 0.5%) because deciduous trees shed their leaves in the winter.

Since the solar azimuth arc is longer in the summer than in winter, neighbouring structures on the east and west exposures cause more shade. Therefore, the cooling energy requirement decreases more if the neighbouring structure is on the east or west side as opposed to the south side as shown in Fig. 2. On the other hand, the heating energy requirement increases more if the neighbouring structure is on the south side, since the solar radiation is highest on the south exposure during the heating season.

The effect of having obstructions on more than one side was studied by adding obstructions to two and three sides of the base case house as shown in Table 4. It was found that the shading caused by two obstructions to the east and west sides decreases the cooling energy requirement more than the shading caused by two obstructions located on any other combination of directions. The decrease in cooling energy requirement is as high as 36% for the house located in Vancouver (3.4 GJ/year), and as low as 7% for the house in Toronto (0.9 GJ/year). On the other hand, adding two obstructions to the west and south sides results in the largest increase in the heating energy requirement, up to 4% increase for the house located in Calgary (4.6 GJ/year).

Three obstructions added to the south, east and west sides reduce the cooling energy requirement more than any other combination of directions, resulting in a reduction of 40% for the house located in Vancouver (3.8 GJ/year). The same combination also results in the highest increase in the heating energy requirement, up to 4.6% (5.3 GJ/year) for a house in Calgary.

The results obtained for shading from multiple directions also revealed that the changes in heating and cooling energy requirements due to obstructions located on two or three sides of the base case house can be estimated using results of single obstruction simulations with less than 5% error. For example, if two obstructions are added to the west and east sides of the house, the increase in heating energy requirement or reduction in cooling energy requirement can be estimated, with less than 5% error, as follows:

Change in the energy requirement with one easterly and one westerly obstruction = Change in the energy requirement with one easterly obstruction + Change in the energy requirement with one westerly obstruction

Using the same approach, the effect of obstructions on three sides can also be estimated with less than 5% error.

As shown in Figs. 3 and 4, increasing sizes of the neighbouring structure has a substantial impact on the heating and cooling energy requirements. As to be expected, due to the shorter azimuth arc of the sun during the winter months, an increase in the width of the obstruction creates a larger shadow and has a larger impact on the heating energy requirement than an increase in the height of the obstruction. Similarly, an increase in the height of the obstruction has a larger impact on the cooling energy requirement than an increase in the width due to the longer azimuth arc of the sun during the summer months.

The effect of the distance of the obstruction on the heating and cooling energy requirements are shown in Figs. 5 and 6. The results indicate that as the distance decreases, the effect of shading increases at an increasing rate. Thus, while there would be substantial reductions in the energy requirement for cooling in densely zoned neighbourhoods due to shading, the increase in heating energy requirements would likely be higher. For example, if the distance of a neighbouring house located on the south side is decreased from 14.2 m to 2.3 m in Calgary, the heating energy requirement would increase by about 5 GJ/year while the cooling energy requirement would decrease by 1.6 GJ/yr.

To explore the largest magnitude of the potential effect of shading by neighbouring buildings, an extreme case of shading was modeled where obstructions were added to the south, west and east side of the house, with each obstruction being 2.4 m away from and twice as big as the base case house. As can be seen in Fig. 7, in this extreme situation, the cooling energy requirement is reduced by 90% (8.6 GJ/year) for the house in Vancouver and heating energy requirement is increased by 10% (12 GJ/year) for the house in Calgary.

4. Conclusion

The findings of this study, which are in general agreement with the findings of other studies, indicate that the annual heating and cooling energy requirements of a house in Canada may be significantly affected due to the shading provided by neighbouring objects such as houses and trees. The orientation, size and distance of the neighbouring object determine the magnitude of the shading effect on the heating and cooling energy requirement. Shading caused by a neighbouring object reduces the solar heat gain, resulting in an increase in the energy requirement for heating while reducing the energy requirement for cooling. Due to the lower altitude of the sun and its shorter azimuth arc during the winter months, a neighbouring object located on the south side of a house was found to have a larger impact on the heating energy requirement than that of objects located on the other sides. Similarly, a neighbouring object on the west side has a larger impact on the cooling energy requirement compared to those on other sides due to the higher altitude and the longer azimuth arc of the sun during the summer months. In high density neighbourhoods with closely situated and larger houses on all three sides, the heating energy requirement may increase due to shading by as much as 10 percent, while the cooling energy requirement may decrease by as much as 90 percent compared to an unshaded house.

Planting deciduous trees around a house can give the advantage of reducing cooling energy requirement in summer and eliminate the disadvantage of increasing heating energy requirement in the winter.

Considering the potentially substantial impact of external shading by neighbouring objects on the annual energy requirement for heating and cooling in Canadian houses, it is recommended that external shading effects need to be accounted for in modeling residential energy consumption. For the same reason, shading effects need also be taken into consideration in planning new neighbourhood developments.

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