Review of Window Energy Rating Procedure in Canada

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Steering Committee and Technical Review

The following steering committee members provided technical direction and review for the project:

- Al Jaugelis, WDMA
- André Laperrière, Hydro-Québec
- Anil Parekh, Natural Resources Canada (NRCan)
- Catherine Lemieux, GCABC
- David Bruce, BC Ministry of Energy, Mines and Natural Gas
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- Gilbert Riopel, AIPVFQ
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- Jean-Francois Kogovsek, AIPVFQ
- Jean Marois, Fenestration Canada
- Jeff Baker, Fenestration Canada
- John Nicol, BC Ministry of Energy, Mines and Natural Gas
- Leonard Pianalto, CGA
- Lisa Bergeron, Fenestration Canada
- Morgan Hanam, Enermodal Engineering Ltd.
- Normand Bigras, Hydro-Québec
- Steve Hopwood, Natural Resources Canada (NRCan)
- Terry Adamson, WDMA-BC
- Voytek Gretka, BC Ministry of Energy, Mines and Natural Gas

Executive Summary

The Energy Rating (ER) is a Canadian energy efficiency metric defined in the CSA A440.2-09 Fenestration Energy Performance standard. The purpose of the ER is to help consumers compare the relative energy efficiency of windows and glazed sliding doors. The ER is a single number rating that evaluates the energy performance under winter heating conditions and takes into account the balance between heat loss through thermal transmittance and air leakage, and solar heat gain through the window or door. The ER was designed mainly for ranking products in a heating dominated climate and for windows and doors installed in low-rise residential buildings. The ER only applies to vertically installed fenestration; hence, a skylight does not have an ER. The ER is one of the metrics used to describe energy performance in the Canadian ENERGY STAR® technical specification for fenestration products and is also being incorporated into building codes and standards in certain jurisdictions.

Over the years some industry participants have questioned the usefulness of relying on the Energy Rating alone to select energy efficient windows and doors. It was observed that in certain regions, products with good ER ratings and high solar heat gain characteristics could result in overheating discomfort and customer complaints. In these regions, the market preferred products that achieved equally good ER ratings with lower solar heat gain characteristics. There was also concern that the ER formula does not contain a cooling component and, therefore, the ER does not give a complete picture of energy use and thermal comfort. It was felt that additional research was necessary to determine whether the ER was still a valid metric for use in all regions of Canada, given the many changes in house archetypes and advances in glass coating and window framing technology in the decades since 1989 when the ER was first developed.

This study was conducted to determine if the ER in its current form is still appropriate for selecting energy efficient windows and doors for all areas of Canada. The study also investigated the use of the ER as a ranking tool for doors, skylights and its applicability in larger multi-unit residential buildings.

Energy Analysis of Windows

Several parameters were established for use throughout the analysis work for this study. Archetypical houses, a range of geographic locations and a selection of window types defined by U-value and Solar Heat Gain Coefficient (SHGC) were selected through a review of codes and standards, climate data and the ENERGY STAR® database of windows. The goal of the analysis was to simulate a wide range of archetype house variables to assess how the ER ranks energy consumption for different types of windows in different Canadian climates.

The window energy analysis shows that in general, windows with a higher ER use less heating energy. However, a number of windows were simulated where a slightly higher ER results in higher heating energy consumption under certain conditions. Though the ER does not rank cooling energy appropriately (as expected), cooling energy consumption in houses is very low compared to heating energy in all Canadian locations under worst-case cooling conditions. In general, cooling energy is roughly 10% of overall space conditioning energy, in houses that have mechanical cooling. Therefore, when looking at space conditioning energy consumption alone, heating energy considerations far outweigh cooling. The same trends where a higher ER window generally uses less heating energy were seen for the majority of the geographic locations simulated. The exception to this finding is Yellowknife (i.e. the far north), where significant differences in heating energy trends are seen compared to the other locations. It is thought that this is due to the low amount of solar radiation that Yellowknife receives in the winter, resulting in less benefit from high SHGC windows.

The same trends, where higher ER correlates directly with lower heating energy consumption, are also seen for all of the archetype house parameters that were simulated (variables not directly related to the windows). This suggests that a representative archetype house is appropriate to use in the development of an ER to rank windows. However, the simulations of different window orientations, window to wall ratios, and shading strategies show varying trends. This analysis suggests that rating windows with a single ER number may not necessarily indicate lower energy consumption for houses with non-typical window orientations, window to wall ratios, and shading strategies.

Thermal Comfort Effects of Windows

Windows have a significant impact on the thermal comfort of a space, however, a quantitative analysis of thermal comfort is challenging since it is impacted by many occupant-dependent variables. ASHRAE Standard 55 "Thermal Environmental Conditions for Human Occupancy" was used as a guideline for this analysis. Two parameters were used to assess comfort: the operative temperature, the mean of the internal air and radiant temperatures; and the window surface temperature, a proxy for radiant asymmetry. A range of comfortable temperatures was established for both operative temperature and surface temperature, and the number of hours outside of this range were counted based on simulations. This allowed the comparison of various window types based on how many hours were outside of the comfort range for each window.

The assessment of operative temperature indicates that the number of "warm hours," or overheating hours recorded, is much greater than the number of "cold hours." Windows with a high SHGC had a greater number of overheating hours than windows with a low SHGC. The number of cold hours is relatively low for most locations except the far north. U-value has a greater impact on the number of cold hours, with low U-value windows performing best. The assessment of surface temperature, on the other hand, shows the number of cold hours was much higher than the number of warm hours. Windows with low U-values had a significantly lower number of cold hours than windows with higher U-values. SHGC has less of an impact on surface temperature than on operative temperature.

Several different variables were investigated relative to thermal comfort, including: natural ventilation, electric baseboard heating, house size, thermal mass, and orientation. The results for each variable typically follow the same trends for U-value and SHGC when compared in a single location across five representative window types. For natural ventilation (and no mechanical cooling), the locations examined indicate a direct relationship between the SHGC and the level of thermal discomfort, where a higher SHGC indicates more thermal discomfort hours. Rotating the building to investigate different orientations has the most significant impact on thermal comfort when evaluating either warm or cool hours of a specific room, since the orientation of that room changes. As expected, when a room is located on a south and/or west exposure, it experiences the most solar gain, and therefore, the highest number of warm discomfort hours, and the fewest number of cool discomfort hours.

Broadly speaking, the correlation between ER and comfort was not as clear as the correlation between SHGC and operative temperature discomfort, or the correlation between U-value and surface temperature discomfort. However, if the ER is used to select windows for a typical single family dwelling, additional measures may need to be taken to prevent overheating, particularly for windows oriented south and west, and where very high window to wall ratios are present.

Doors and Skylights

An analysis was completed to investigate the potential application of the ER to doors and skylights. The ER applies to fenestration systems installed in a vertical orientation; therefore, the ER applies to doors but not skylights. Several door and skylight products were selected for energy analysis using the NRCan ENERGY STAR® database of doors and skylights. For doors, the results indicate that the ER does not appropriately compare opaque doors with glazed doors. However, when comparing door products that are the same type (e.g. opaque doors to opaque doors, or fully glazed doors to fully glazed doors), products with a higher ER generally have a lower heating and total energy consumption. This is consistent with the findings for windows. It is anticipated that if a larger number of doors were simulated, with ER values that are close together, some small anomalies would be seen as with the window findings. Therefore, the ER is an appropriate metric to rank fully glazed doors.

For skylights (flat glazed and tubular daylighting device products), a number of anomalies are evident where a product with a much higher ER value results in greater heating energy consumption than a product with a lower ER value. This means that the ER does not appropriately rank skylights.

Multi-Unit Residential Buildings

This analysis was completed to assess the potential use of the ER to rate windows in multi-unit residential buildings. Three types of buildings were investigated: a row house, a four-storey building and a 20-storey building. The ER is said to apply to low-rise residential buildings (three storeys or less, with an area less than 600 m^2), which would include the row house archetype. Energy simulations were completed in the same manner as houses using the same 23 window types to allow for comparison.

The results of the row house simulations are consistent with the results for the single detached house, where the ER generally provides a good ranking of heating and total energy consumption, with a few small anomalies. The low-rise and high-rise multi-unit residential buildings show the same trend for heating, however, the plots for total energy result in a greater number of cases where a higher ER results in higher total energy. These buildings have higher window to wall ratios, and therefore require more cooling energy, which has a greater impact on the total energy consumption of the building. Based on these findings, the ER is appropriate for row houses, but not for larger low-rise and high-rise buildings. Factors related to shading, orientation and window to wall ratio have a greater impact in these building types. By extension, thermal comfort concerns would also be greater in such buildings.

Conclusions

The ER is an appropriate tool for comparing windows on the basis of energy consumption for typical Canadian houses. The ER provides a better ranking of window energy consumption than U-value alone. Where anomalies occur (i.e. a window with a higher ER uses more energy), the differences in both the ER value and energy consumption are small. The ER however is not the only metric one may want to consider when choosing windows for a specific home, in a specific location, with a specific orientation. In particular, the ER on its own is not an appropriate measure to compare windows under the following non-typical conditions for houses and low-rise residential buildings:

- Far north locations, including the Canadian Territories
- Windows with significant winter exterior shading
- A house with windows oriented primarily in one direction

Despite these exceptions, the current ER formula works in most common house situations, in most locations, and therefore it is an appropriate metric for rating the relative energy performance of windows. However, for houses that are non-typical, have more site-specific design or energy efficient design, it would be best to select windows based on its U-value and SHGC rather than only the ER. If the ER is incorporated into standards then it should be accompanied by explanatory text regarding when it is appropriate and when it is not appropriate. Likewise, if the U-value alone is used to select energy efficient windows, explanatory text regarding the potential energy savings of a high or a moderate SHGC should also be provided. While the ER should be maintained, provisions to keep the alternate U-value compliance path are necessary because of these non-typical conditions.

Sommaire exécutif[1]

Le rendement énergétique (RE) est un indice de performance énergétique canadien tel que défini dans la norme CSA A440.2-09 «Rendement énergétique des systèmes de fenêtrage». Le RE a pour but d'aider les consommateurs à comparer l'efficacité énergétique relative des fenêtres et portes coulissantes vitrées. Le RE est un indice à valeur unique qui évalue la performance énergétique dans des conditions de chauffage hivernales et qui prend en compte l'équilibre entre les pertes par transmission thermique, les fuites d'air et le gain de chaleur solaire obtenus par la fenêtre ou la porte. Le RE a été conçu principalement pour les produits de fenestration installés sur des bâtiments résidentiels de faible hauteur et situés dans des régions dominées par des besoins énergétiques alloués au chauffage. Le RE, comme défini, ne s'applique qu'aux portes et fenêtres installées à la verticale; pour cette raison, un lanterneau ne peut obtenir un indice RE. Le RE est l'un des indices utilisés comme spécification technique par le programme ENERGY STAR® du Canada afin d'évaluer la performance énergétique des différents produits de fenestration. Il est également spécifié dans différents codes et normes de construction de certaines juridictions canadiennes.

Au fil des ans, certains participants de l'industrie ont mis en doute la pertinence de s'appuyer uniquement sur le RE pour évaluer l'efficacité énergétique des différents produits de fenestration. Dans certaines régions, il a été observé que des produits de fenestration ayant un RE supérieur et un coefficient de gain de chaleur solaire (CGCS) élevé peuvent causer une surchauffe du bâtiment, créant ainsi un inconfort dont les occupants se plaindraient. Dans ces régions, le marché a préféré des produits qui ont obtenu des indices RE équivalents, mais qui présentaient des CGCS moins élevés. Ils craignaient également que la formule du RE, ne contenant pas de variable qui tienne compte de la climatisation (refroidissement mécanique), ne donne pas une image complète de la consommation énergétique et du confort thermique. Il a donc été suggéré que des recherches supplémentaires seraient nécessaires pour déterminer si le RE est toujours un indice valable pour une utilisation uniforme dans toutes les régions du Canada, compte tenu des nombreux changements dans les types d'habitations et des progrès obtenus pour les verres énergétiques et les systèmes de fenêtres depuis 1989, lorsque la formule du RE a d'abord été mise au point.

Cette étude a été réalisée afin de déterminer si cet indice, dans sa forme actuelle, est toujours approprié pour évaluer l'efficacité énergétique des fenêtres et des portes, de façon uniforme, pour toutes les régions du Canada. L'étude analyse également l'utilisation du RE comme outil d'évaluation de l'efficacité énergétique pour les portes d'entrée et les lanterneaux ainsi que son applicabilité pour des immeubles multi-résidentiels de plus grandes dimensions.

Analyse énergétique des fenêtres

Plusieurs paramètres ont été mis en place pour le travail d'analyse de cette étude. Différents types d'habitations, lieux géographiques et modèles de fenêtres définies par la valeur U et CGCS, sélectionnées en se référant aux codes et normes du bâtiment, aux données climatiques et à la base de données des fenêtres homologuées ENERGY STAR®. Le but de l'analyse était de simuler un large éventail de variables pour différents types d'habitations afin de mesurer la façon dont le RE permet d'évaluer la consommation d'énergie pour différents modèles de fenêtres, dans les différentes zones climatiques canadiennes.

L'analyse énergétique des fenêtres montre que, en général, des fenêtres avec un indice RE plus élevé utilisent moins d'énergie allouée au chauffage. Cependant, quelques simulations ont démontré que, dans certaines conditions, des fenêtres avec un RE légèrement supérieur ont obtenu une consommation d'énergie de chauffage plus élevée. Bien que le RE n'évalue pas de façon appropriée la consommation d'énergie de refroidissement (comme prévu), la consommation d'énergie de refroidissement dans les habitations est très faible par rapport à la consommation d'énergie de chauffage, et ce, même pour les régions canadiennes qui font face aux besoins de refroidissement les plus élevés. En général, la consommation d'énergie de refroidissement représente environ 10% de l'énergie totale consommée pour des espaces à température contrôlée, situés dans des habitations qui utilisent un système de refroidissement mécanique. Par conséquent, lorsque l'on regarde la consommation d'énergie utilisée pour le contrôle de la température, la consommation énergétique de chauffage dépasse de loin la consommation énergétique de refroidissement. On a constaté les mêmes tendances, soit une consommation d'énergie de chauffage moindre, lors des simulations de fenêtres avec un RE plus élevé, dans la majorité des régions canadiennes. La seule exception est

[1] In case of discrepancies please refer to the English version.

Yellowknife (à l'extrême nord du territoire), où des différences significatives dans les tendances de consommation d'énergie de chauffage ont été constatées en comparaison aux autres régions canadiennes. On pense que cela est attribuable à la faible quantité de rayonnement solaire que reçoit Yellowknife en hiver, entrainant ainsi moins de gains reliés à des fenêtres avec un CGCS élevé.

Les mêmes tendances, quand un RE plus élevé est en corrélation directe avec une consommation inférieure d'énergie de chauffage, ont également été constatées pour l'ensemble des différents types d'habitations simulés (variables non directement reliés aux fenêtres). Ceci suggère qu'il est approprié d'utiliser un seul type d'habitation spécifique pour le développement d'un RE qui permet d'évaluer et de comparer adéquatement les fenêtres. Cependant, les simulations de différentes orientations, de divers ratios de surface fenêtre/mur, et des différentes stratégies d'ombragement ont démontrés des tendances différentes. Cette analyse suggère que l'évaluation des fenêtres par le seul indice RE n'indique pas automatiquement une plus faible consommation d'énergie pour les habitations avec des orientations, un ratio de surface fenêtre/mur et des facteurs d'ombragement atypiques.

Effets des fenêtres sur le confort thermique

Les fenêtres ont un impact significatif sur le confort thermique d'un espace à température contrôlée, cependant une analyse quantitative du confort thermique est difficile à réaliser, car elle est influencée par plusieurs variables dépendantes des occupants. La norme ASHRAE 55 "Thermal Environmental Conditions for Human Occupancy " a été utilisée comme un guide pour cette analyse. Deux paramètres ont servi à évaluer le confort thermique: la température ambiante effective, soit la moyenne de la température de l'air intérieur et de la température de rayonnement ; et la température sur la surface de la fenêtre, un indicateur de l'asymétrie de rayonnement. Une échelle de températures confortables pour les occupants a été créée à la fois pour la température ambiante effective et pour la température de la surface de la fenêtre. Le calcul du nombre d'heures pour lesquelles la température se situait en dehors de cette échelle a été réalisé par simulation. Cela a permis de comparer les différents types de fenêtres en se basant sur le nombre d'heures pour lesquelles chaque type de fenêtre se situait à l'extérieur de cette zone de confort.

La mesure de la température ambiante effective indique que le nombre d'«heures chaudes» (heures de surchauffe enregistrées) est beaucoup plus élevé que le nombre d' «heures froides» (heures de refroidissement enregistrées). Les fenêtres avec un CGCS supérieur ont obtenu un plus grand nombre d'«heures chaudes», que les fenêtres avec un CGCS inférieur. Le nombre d'«heures froides» est relativement faible pour la plupart des régions, sauf pour l'extrême nord du Canada. La Valeur-U a un impact plus important sur le nombre d'«heures froides», les fenêtres avec une faible Valeur-U obtenant de meilleures performances. Cependant, la mesure de la température sur la surface de la fenêtre a démontré que le nombre d'«heures froides» était tout de même beaucoup plus élevé que le nombre d'«heures chaudes». Les fenêtres avec de faibles Valeur-U ont obtenu un nombre significativement plus faible d'«heures froides» que les fenêtres avec des Valeur-U plus élevées. Le CGCS a moins d'impact sur la température de surface de la fenêtre que sur la température ambiante effective.

Plusieurs variables différentes ont été étudiées par rapport au confort thermique, y compris la ventilation naturelle, le chauffage par plinthes électriques, la taille de l'habitation, la masse thermique et l'orientation. Les résultats obtenus pour chaque variable suivent généralement les mêmes tendances pour la Valeur-U et le CGCS quand la comparaison se fait au même endroit avec les cinq différents types de fenêtres témoins. Pour la ventilation naturelle (et non pour un système de refroidissement mécanique), les régions analysées ont démontré une relation directe entre la CGCS et le niveau d'inconfort thermique, où des fenêtres avec un CGCS plus élevé ont créé un nombre d'heures d'inconfort thermique plus élevé. La rotation du bâtiment, afin d'évaluer l'effet de différentes orientations sur une pièce spécifique, a eu l'impact le plus important sur le confort thermique, que ce soit sur le nombre d'«heures chaudes» ou d'«heures froides», selon les différentes orientations simulées pour cette pièce. Comme prévu, lorsqu'une pièce est exposée au sud et/ou à l'ouest, elle obtient un gain solaire plus élevé et par conséquent le nombre d'heures d'inconfort dû à la chaleur le plus élevé et le nombre d'heures d'inconfort dû au froid le moins élevé.

D'une manière générale, la corrélation entre le RE et le confort n'étaient pas aussi clairs que la corrélation entre le CGCS et l'inconfort dû à la température ambiante effective, ou la corrélation entre la Valeur-U et l'inconfort dû à la température de surface de la fenêtre. Toutefois, si le RE est utilisé pour choisir des fenêtres pour une habitation unifamiliale typique, des indices de mesure supplémentaires doivent être pris en considération pour éviter un effet de surchauffe, en particulier pour les fenêtres orientées vers le sud et l'ouest, où le ratio de surface fenêtre/mur est élevé.

Les portes et les lanterneaux

Une analyse a été effectuée pour étudier la pertinence d'appliquer l'indice RE aux portes et aux lanterneaux. Comme le RE s'applique aux systèmes de fenêtrage installés verticalement, il peut donc s'appliquer aux portes, mais non aux lanterneaux. Plusieurs produits de portes et de lanterneaux ont été sélectionnés pour effectuer cette analyse énergétique en utilisant la base de données des portes et des lanterneaux ENERGY STAR® de RNCan. Pour les portes, les résultats ont démontré que le RE n'est pas approprié pour comparer les rendements des portes sans vitrage avec des portes vitrées. Cependant, lorsque l'on compare des produits de portes qui sont du même type (par exemple des portes sans vitrage avec des portes sans vitrage, ou des portes entièrement vitrées avec des portes entièrement vitrées), les produits avec un RE plus élevé ont généralement une consommation énergétique liée au chauffage et totale plus faible. Ceci est cohérent avec les résultats obtenus pour les fenêtres. Nous pouvons anticiper que si on simulait un plus grand nombre de portes, avec des valeurs de RE qui se ressemblent, nous obtiendrions quelques petites incohérences, comme lors de l'analyse des fenêtres. Par conséquent, le RE est un indice approprié pour évaluer la performance énergétique des portes entièrement vitrées.

Pour les lanterneaux (verres plats et puits de lumière tubulaires), un certain nombre d'incohérences sont évidentes : où un produit avec un indice RE plus élevé obtient des consommations énergétiques de chauffage supérieures à un produit avec un indice RE moins élevé. Ce qui nous amène à conclure que l'indice RE n'est pas approprié pour évaluer les lanterneaux.

Immeubles multi-logements résidentiels

Cette analyse a été effectuée pour valider l'utilisation potentielle de l'indice RE dans l'évaluation des performances thermiques des fenêtres utilisées pour les multi-logements résidentiels. Trois types de bâtiments ont été étudiés: un immeuble d'habitations en rangée, un immeuble de quatre étages et un immeuble de 20 étages. Le RE est reconnu pour des évaluations de bâtiments d'habitations de faible hauteur (trois étages ou moins, d'une aire inférieure à 600 m^2), ce qui comprend les immeubles d'habitations en rangée. Pour permettre une comparaison fiable, des simulations énergétiques ont été réalisées de la même façon que pour les habitations unifamiliales détachées, en utilisant les mêmes 23 types de fenêtres.

Les résultats obtenus lors des simulations de bâtiments d'habitations en rangée sont cohérents avec les résultats obtenus lors des simulations des habitations unifamiliales détachées, où le RE fournit généralement une bonne évaluation de la consommation d'énergie de chauffage et de la consommation d'énergie totale, avec seulement quelques petites incohérences.

Les immeubles d'habitations multi-logements de faible et de forte hauteur ont démontré la même tendance quant à la consommation énergétique de chauffage, cependant, les scénarios où on analysait la consommation totale d'énergie ont révélé un plus grand nombre de cas ou des fenêtres avec un indice RE élevé résultait en une consommation énergétique totale supérieure. Ces bâtiments ont généralement un ratio de surface fenêtre/mur plus élevé, et, par conséquent, une consommation énergétique de climatisation supérieure, ce qui a un impact plus important sur la consommation d'énergie totale du bâtiment. Sur la base de ces constatations, le RE est approprié pour les immeubles d'habitations en rangée, mais pas pour les immeubles d'habitations de plus de trois étages. Les facteurs liés à l'ombragement, l'orientation et le ratio fenêtre/mur ont un impact plus important dans ces types de bâtiments. Par extension, les préoccupations de confort thermique seraient également plus grandes pour ces types de bâtiments.

Conclusions

Le RE est un indice de performance approprié pour comparer des fenêtres sur la base de leur consommation énergétique quand elles sont installées sur une résidence canadienne typique. Le RE offre une meilleure comparaison de la consommation énergétique des fenêtres que valeur U uniquement. Lorsque des anomalies ont été observées (c.-à-d. une fenêtre avec un RE supérieur, consommant plus d'énergie), les différences, autant entre les valeurs RE que pour la consommation énergétique, étaient faibles. Cependant, le RE n'est pas le seul indice de performance à considérer lorsqu'on choisit des fenêtres pour une maison et/ou une localisation et/ou orientation atypique. En particulier, utiliser seulement le RE pour évaluer des fenêtres n'est pas approprié:

- À l'extrême nord du pays, incluant les territoires canadiens
- Lorsque les fenêtres subissent beaucoup d'ombragement hivernal
- Pour une maison dont la majorité des fenêtres sont orientées principalement dans une même direction

Malgré ces exceptions, la formule mathématique actuelle du RE fonctionne pour la majorité des maisons, dans la plupart des localisations, et en conséquence est un indice de performance approprié pour comparer la performance énergétique des fenêtres. Cependant, pour les maisons atypiques, et les maisons conçues spécifiquement pour un site particulier ou pour obtenir efficacité énergétique supérieure, il serait plus approprié de choisir des fenêtres basées également sur leurs valeurs U et le CGCS, au lieu de seulement se fier au RE. Si le RE est spécifié dans des normes de construction, un texte expliquant quand il est approprié ou non de se fier uniquement à la valeur du RE devrait accompagner cette spécification. De même, si la valeur U uniquement est spécifiée pour choisir une fenêtre éco-énergétique, un texte expliquant le potentiel de réduction de la consommation énergétique par un CGCS moyen ou élevé, devrait également accompagner cette spécification. La méthode d'évaluation des performances énergétiques des fenêtres par la valeur RE devrait être maintenue mais elle devrait également être accompagnée d'une mention faisant référence à la méthode d'évaluation par la valeur U pour les cas de conditions dites atypiques.

224 WEST 8TH AVENUE
VANCOUVER BC V5Y 1N5
TEL 604 873 1181
FAX 604 873 0933
rdhbe.com

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[2] Appendices are not included with this report but may be obtained upon request from RDH Building Engineering.

1. Introduction

The Energy Rating (ER) is an energy efficiency metric that is utilized as part of the CSA A440.2-09 standard entitled Fenestration Energy Performance. The purpose of the ER is to facilitate the ranking of energy performance so that consumers can assess the relative energy efficiency of windows and doors. The formula is based on the balance between heat loss through conduction and air leakage, and solar heat gain through the window or door. The formula provides a simple one number value ranging from about zero (poor performance) to about 50 (excellent performance). ER values may theoretically be lower than zero and higher than 50, though this range is typical. The Canadian ER formula was designed mainly for ranking products in a heating dominated climate and for windows and doors installed in low-rise residential buildings. The ER also only applies to vertically installed fenestration; hence, a skylight cannot have an ER. The ER metric is part of the Canadian ENERGY STAR® technical specification for fenestration products and similar ER formulas (adjusted to match prevailing home archetypes and climate) have been adopted in Great Britain and Australia. International Organization for Standardization (ISO) has a similar guide for the development of ER formulas.

1.1. Background

The Canadian ER formula was developed in 1989 (Calculating the Window Energy Rating) by Enermodal Engineering Ltd. in collaboration with the Federal department of Energy Mines and Resources (now Natural Resources Canada or NRCan). The ER was developed because other more traditional methods of measuring fenestration energy performance (R-value, U-value) only indicated the heat loss through conduction and did not consider the heat loss through air leakage, nor the passive solar heat gain. The ER appeared in the first edition of CSA A440.2 standard (1991) and the first and only edition of the now retired CSA A453.0 standard (1995).

The Enermodal study divided the variables in the ER equation into two main categories: 1) window dependent factors, and 2) location dependent factors. Window dependent factors included heat loss through U-factor (a measurement of the rate of heat transfer from warm to cold), the measured air leakage adjusted to the sample size of the window or door, and the Shading Coefficient (the Solar Heat Gain Coefficient (SHGC) value is now used) which is a measure of potential passive solar heat gain. Location dependent factors included the off-angle incidence factor (measuring solar reflection), the average annual solar radiation (averaged over four orientations of the building envelope), and the assumed average building temperature during the heating and cooling seasons. Air leakage is also included in the location dependent factors because the calculation of it depends partly on an assumed wind speed and temperature differential.

A few years ago, two significant changes were made to the ER formula. A “solar reduction factor” of 20% was added in response to industry concerns that the ER approach assumed too much solar gain. This factor accounts for things such as trees, houses situated close to one another, large overhangs, even dirty glass. A constant value was also added to make all numbers positive in response to NRCan concerns about consumer confusion over negative values. Originally, the ER values were expressed in Watts per square metre and ranged from about -40 W/m^2 (poor performance) to about 10 W/m^2 (excellent performance) or higher. NRCan reported that consumers often confused a negative ER value with a temperature rating similar to the “good down to” temperature values used for sleeping bags.

Over the years, some potential issues have been brought forward by industry that could affect the validity of the ER as a tool for properly ranking windows and doors for their energy performance. Most, if not all, fall into the location dependent factors noted above, mainly solar gain assumptions and home archetype (reference house). In addition, low-e coating technology and other component parts as well as the overall design and materials of windows and doors have changed greatly since the late 1980s. Lastly, the ER formula does not contain any cooling component and there has been criticism that the ER does not give a complete picture because of this.

The original 1989 Enermodal report itself identified one area that needed further research and that is for locations with average heating degree day (HDD) values below 4000 (mainly south-western B.C. and the extreme southern areas of southern Ontario). These areas were identified as being "heating and cooling dominated' and the ER for these regions needed "further analysis" mainly due to the cooling aspect.

A report done for BC Hydro in 2002 (*Performance Evaluation of Low-E Residential Windows in B.C.)* by SAR Engineering Ltd. looked at whether it is better to use low-e coatings that give higher solar gains but higher U-factors, or coatings that give lower U-factors but lower solar gains in the southern mainland of British Columbia in terms of overall home energy consumption. The region studied has HDD values below 4000. The study concluded that homes that have glazing with low-e coatings that give lower U-factors and lower solar gains used less energy overall if they were air conditioned. Since ER values tend to be higher when low-e coatings that give higher solar gains are used, this points to a potential issue with the ER in these regions. It is felt by some that windows with higher ER values will cause people in the southern mainland of B.C. to purchase air conditioners for their homes due to a comfort issue leading to higher energy consumption.

In September, 2009, a group of experts from industry and government met at the Ecotay Education Centre near Ottawa, Ontario to discuss the ER. A summary report was issued on October 29, 2009 entitled *Task Group Recommendations Concerning the Energy Rating Procedure in CSA A440.2* authored by Mr. Tim Mayo, a retired employee from NRCan. The report noted that:

> "Concerns have been raised by some that the assumptions used to calculate ER are inaccurate or incomplete. Some believe that the solar gain may be overestimated in some cases leading to a false impression of energy savings or underestimated in other cases leading to overheating, discomfort and increased cooling loads."

There was general agreement that the parameters of the reference house in the A440.2 be reviewed, that cooling loads be considered in the ER, that the solar gain assumptions be reviewed and that perhaps the ER needs to adapted to the different climatic regions found within Canada. The report also laid out 16 different windows types (including their glazing options) to use and a list of 17 locations that reflect a range of geography, heating degree days and solar availability (including one location in the far north) for any modeling.

Lastly, a 2007 NRC study entitled *Selection of Optimum Low-E Coated Glass Type for Residential Glazing in Heating Dominated Climates* concluded that "the use of high SHGC, Low-E residential glazing will save more annual energy than low SHGC, Low-E, glass in areas where the heating load is greater than the cooling load: i.e. from a line approximately from Portland Oregon to New York City and anywhere northwards." This study involved two actual test houses on the CMHC campus in Ottawa, Ontario. The conclusion shows that a ranking system utilizing passive solar gain as part of its parameters is the preferred choice over a system that strictly looks at the insulation value (U-value or R-value) alone.

1.2. Objective

The objective of the current research is to determine if the ER in its current form can still be used to rank the overall energy performance of windows and doors appropriately for all areas of Canada for low-rise Part 9 buildings. If not, what changes need to be made to the ER so that it can do this, or does the ER need to be abandoned altogether.

1.3. Scope

The scope of this research includes a detailed investigation of windows used in single family dwellings and low-rise multi-unit residential buildings in Canada. The research also includes a preliminary investigation of doors, skylights, and high-rise multi-unit residential buildings.

In the user guide to the CSA A440.2 standard, there are two ER formulas. One called the ERS (Energy Rating Specific) and the other ERC (Energy Rating Cooling). This research covers a study of the ER formula found in the main body of the standard only, while the ERS and ERC are beyond the scope of this project.

1.4. Approach

The approach is divided into several tasks in order to manage the project work. The following is a summary of each task presented in the following sections.

Section 2: Literature Review

Several background documents are reviewed, including reports related to the calculation and development of the ER, and other research related to energy consumption of windows.

Section 3: Evaluate ER Calculation Methodology

The current ER calculation methodology is analysed and discussed. The assumptions from the original study are being reviewed, as well as issues relating to solar heat gain, air leakage and climate.

Section 4: Determination of Housing Archetypes

The two-storey archetype house from the original ER study is assessed, and other housing archetypes are identified to use in the analysis. Archetype house parameters are selected, including three sizes (single-storey, two-storey and large two-storey) and two sets of enclosure parameters (typical existing and new house).

Section 5: Geographic Locations

Several representative geographic locations across Canada are chosen in order to facilitate analysis that considers different climates. Locations are assessed based on the number of Heating Degree Days (HDD), Cooling Degree Days (CDD) and annual solar radiation for each city.

Section 6: Window and Glazing Options

A set of windows are identified to use in the energy simulations based on U-value and SHGC. The window parameters are selected based on an analysis of the current ENERGY STAR® database of windows.

Section 7: Energy Simulations

Energy simulations are performed using the archetype houses, climates, and window configurations discussed in Sections 4, 5 and 6. Plots are generated for a variety of different cases to study each of the parameters discussed in the previous sections. Energy consumption results are plotted by order of increasing ER to show how the ER rates or ranks energy consumption of different windows.

Section 8: Greenhouse Gas Emissions

An evaluation of Greenhouse Gas (GHG) emissions is performed using the energy simulation results from Section 7.

Section 9: Thermal Comfort

The impact of window U-value and SHGC on thermal comfort is further studied in this section using ASHRAE Standard 55 guidelines on thermal comfort. Hourly energy simulations are performed for a reduced number of glazing configurations to view the impact on room operative temperature and window surface temperature.

Section 10: Other Fenestration Systems

The analysis is extended to include doors and skylights. A review of existing products is completed to select several appropriate doors and skylights for simulation. Similar to Section 7, energy simulations are completed with the housing archetypes modified as necessary to include the door and skylight products. Three types of doors are included in the analysis: a sliding glass door, a door with a half lite, and a solid slab door. Two types of skylights are analyzed: flat glazed skylights and tubular daylighting devices.

Section 11: Multi-Unit Residential Buildings

Multi-unit residential buildings (MURBs) perform differently than houses. These buildings often have higher glazing ratios and less shading. A preliminary investigation of the extension of the ER to MURBs is performed in this section. The buildings analyzed include a row house, a four-storey wood-frame building and a 20-storey concrete building.

Section 12: Conclusions and Recommendations

The results and analysis from Sections 2 through 11 are compiled and summarized to develop recommendations for the continued use of the ER. A number of areas for future work are suggested.

1.5. Abbreviations

The following abbreviations and symbols are used throughout this report.

ACH	Air Changes per Hour
ACH_{50}	Air Changes per Hour at a pressure difference of 50 Pascals
CDD	Cooling Degree Days
ER	Energy Rating
ERS	Specific Energy Rating
ERC	Cooling Energy Rating
F_θ	Off-normal incidence angle factor for solar radiation, dimensionless
HDD	Heating Degree Days
HRV	Heat Recovery Ventilation
H_t	Average incident solar radiation on vertical fenestration systems facing the four cardinal directions during hours of the year when solar heat gains influence heating load, W/m^2
HVAC	Heating, Ventilating and Air Conditioning
$kgCO_2e$	Kilograms CO_2 equivalent
kWh_e	Equivalent kilowatt hours
L_{75}	Fenestration system air leakage rate at a pressure differential of 75 Pa, $L/s/m^2$
MURB	Multi-Unit Residential Building
NBCC	National Building Code of Canada
PF	Pressure Factor
SHGC	Solar Heat Gain Coefficient
T_{bi}	average indoor temperature during hours of the year when daily average outdoor temperature is below 12°C
T_{bo}	Average outdoor temperature during hours of the year when daily average outdoor temperature is below 12°C
TDD	Tubular Daylighting Device
WWR	Window to Wall Ratio

2. Literature Review

Various sources of technical information relevant to the project were identified and reviewed. This process has provided significant background information regarding the development and application of the Energy Rating (ER) as well as other studies related to window energy efficiency, and more indirectly related to the ER rating. However, it was also noted that little research has been undertaken on the ER rating since its initial development.

A list of references and a summary sheet for each reference that has been reviewed in detail can be found in Appendix A.

2.1. Standards

The calculation for the ER is presented in CSA A440.2-09/A440.3-09 Fenestration Energy Performance / User guide to CSA A440.2-09 Fenestration energy performance (Canadian Standards Association, 2009). This standard also provides a calculation procedure for a Specific Energy Rating (ERS) and a Cooling Energy Rating (ERC). The ERS is an ER value calculated for a specific house, location, orientation, and window size. The ERC can be used to compare fenestration systems to avoid overheating or to reduce cooling energy consumption, and was developed in a similar manner to the ER (by averaging weather dependent values for Canadian locations).

The International Organization for Standardization (ISO) has a standard for determining window energy performance ratings, “ISO18292 Energy performance of fenestration systems for residential buildings – Calculation procedure.” The standard suggests a similar rating procedure to the Canadian ER, where solar gain, air infiltration and transmission (conduction) losses are added to determine an overall rating. The rating can be calculated for both heating and cooling conditions.

More detailed calculations of the ISO rating are beyond the scope of this study. However, the primary difference between the ISO standard and the CSA ER appears to be in how the solar heat gain term is calculated. The ISO standard discusses two different approaches to the solar heat gain component: a gain utilization factor approach and a degree day approach. The degree day approach does not directly incorporate solar and internal heat gains, but factors this in by calculating heat losses at hours below a certain temperature. The utilization factor approach does determine energy needs for heating based on the difference between gains and losses.

The gain utilization factor is based on a ratio of total heat gains over transmission and infiltration losses (Fig.2.1). If the internal and solar heat gains are smaller than the losses, the gain utilization factor is 1 since all solar and internal heat gains are used to help offset the heating demand. However, if the internal and solar heat gains are greater than the losses, the gain utilization factor is less than 1.

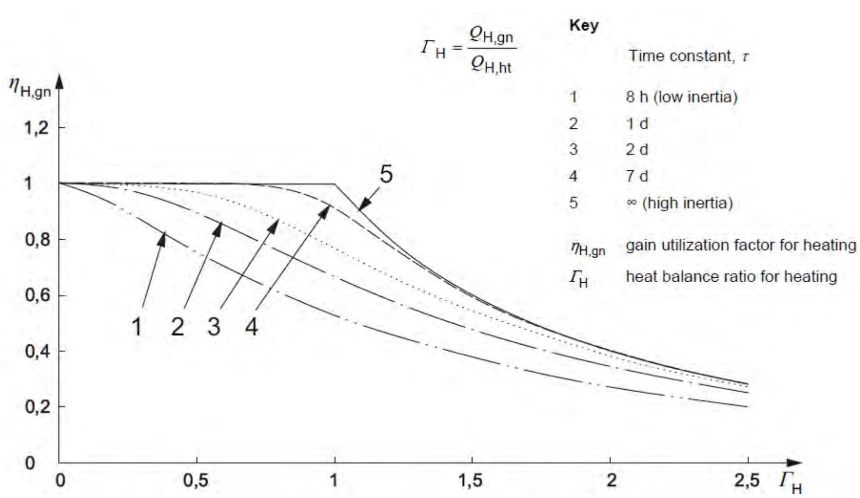

Fig.2.1 Illustration of gain utilization factors (ISO, 2011).

The ISO standard employs the gain utilization factor approach for its energy rating. The Canadian ER appears to use a combination of the degree-day method and the gain utilization factor; the degree day like method was initially used by only averaging hours where the outdoor temperature was less than 12°C (i.e. assuming that above this temperature heating would not be required due to internal and solar gains). However, the addition of the solar gain reduction factor (R = 0.8) appears to be similar to a simplified gain utilization approach. The ISO standard provides a method of calculating a gain utilization factor.

Further study of the European standards related to windows is beyond the scope of this report. However, a subsequent study is planned to compare the European and North American window standards.

2.2. ER Specific Research

Little research specific to the ER has been done since the initial ER development. The initial report by Enermodal Engineering Ltd. focuses on the determination of location-dependent variables in the ER equation (Enermodal Engineering Ltd., 1989). The report states that the ER equation was decided at "the Feb. 7 meeting of Working Group A of the Window Labelling Project," however, no additional documentation could be located regarding the initial development of this equation.

Several of the reports by Enermodal Engineering Ltd. incorporate energy simulations of window options based on ER ratings, with various methods of selecting window parameters based on an ER rating (Enermodal Engineering Ltd., 2003, 2005, 2008, 2011; see R7, R9, R10, R11 in Appendix A).

A study was performed on the air infiltration term in the ER (Bernier & Hallé, 2005; see R12 in Appendix A). This study suggests that the current ER calculation overestimates infiltration energy losses, and also that air infiltration losses are small compared to conduction losses and solar gains.

2.3. Determination of Modeling Parameters

Several studies that establish modeling inputs and parameters for energy simulation of various window and glazing configurations were reviewed. A number of reports by Enermodal Engineering Ltd. (Enermodal Engineering Ltd., 2003, 2005, 2008, 2011; see R7, R9, R10, R11 in Appendix A) go through the process of establishing archetype houses by reviewing code requirements, typical existing house construction and costs in various locations. These studies also present a rationale for selecting window and glazing options for modeling. The background work performed for these studies is a good reference for the current ER study.

2.4. Energy Modeling

Several of the studies incorporated energy modeling of houses and parametric analysis of glazing options. The original ER study (Enermodal Engineering Ltd., 1989) utilized hourly energy modeling to determine average weather parameters for the ER calculation. Some discussion is provided in the report on various modeling strategies, including hourly calculations versus the heating degree day method.

Several studies utilized the program HOT2000 for energy simulation of houses to study glazing options (SAR Engineering Ltd., 2002; Enermodal Engineering Ltd., 2005, 2011; see R2, R7, R10 in Appendix A). Another study (Enermodal Engineering Ltd., 2003; see R9 in Appendix A) used RESFEN to compare energy consumption of window options, while (Enermodal Engineering Ltd., 2008; see R11 in Appendix A) used RESFEN (to simulate energy costs of glazing options), RETScreen (to calculate annual energy costs for a whole house) and eQuest (to investigate electrochromic glazing and blinds, i.e. varying the SHGC of windows). Little discussion is provided within these reports on the merits of the modeling programs used.

An NRC study on low-e glass types (Barry & Elmahdy, 2007; see R3 in Appendix A) modeled houses using three different programs: RESFEN, HOT2000 and ESPr. The modeled results were compared to monitoring data from two test houses, and it was found that ESPr provided the closest results to the actual performance.

2.5. International Window Energy Ratings

Several countries have fenestration performance ratings. The United Kingdom has a rating that is similar to the Canadian ER, established by the British Fenestration Rating Council (BFRC). The equation is,

$$\text{BFRC Rating} = 218.6 \times \text{Window Solar Factor} - 68.5 \times (\text{Window U-value} + \text{Effective } L_{50})$$

The BFRC rating is translated to a letter rating, A to G, displayed on a reader-friendly label along with the rating number, window U-value, solar factor, and effective air leakage rate (Fig.2.2).

Certain European countries have window energy rating programs, including Denmark and Sweden where windows are rated based only on their U-value (Avasoo & Andersson, 2003). The German Fenestration Institute has adopted an energy rating system following the ISO standard.

Australia and New Zealand have fenestration energy rating systems called WERS and NZ-WERS, respectively (www.wers.net and Burgess & Skates, 2011). This rating system is different from the Canadian ER system. To determine the WERS rating, windows are simulated using a software program called CHENatH, with the specific window U-value, SHGC and air leakage rate. The energy consumption of a particular window is compared to that of a reference window with single glazing, clear glass and an aluminum frame. The reference single glazed window is denoted one star, with higher performing windows scaled accordingly between 1 and 10. Three different ratings are given, for heating, cooling and interior fading damage. Fig.2.3 shows example NZ-WERS ratings for a selection of generic windows.

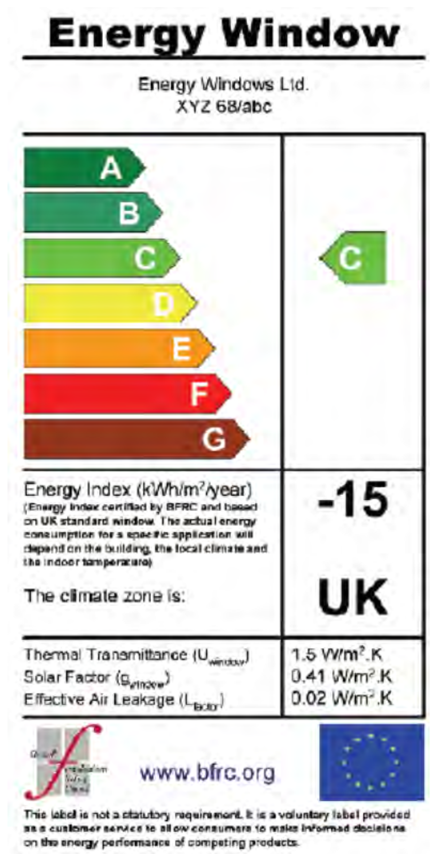

Fig.2.2 Sample BFRC window energy rating label (www.bfrc.org).

GENERIC WINDOWS ZONES 1 & 2		Winter Heating Stars	Summer Cooling Stars	Fading Stars
GANZ single grey standard tint	Aluminium frame	★	★★½	★★★½
Single advanced tint	Aluminium frame	★	★★★	★★★
Double grey reflective / clear	Aluminium frame	★½	★★★★★	★★★★★
Single clear	Aluminium frame	★★	★½	★
Double bronze tint / clear	Aluminium frame	★★½	★★★★½	★★★½
Double advanced tint / clear	Aluminium frame	★★½	★★★★½	★★★½
Double grey tint / clear	Aluminium frame	★★½	★★★★	★★★½
Double clear laminated /clear	Aluminium frame	★★½	★★★★	★★★★½
Double tint / low emissivity	Aluminium frame	★★★	★★★★½	★★★½
Double clear	Aluminium frame	★★★½	★★	★★
Double clear / low-e clear	Aluminium frame	★★★★	★★½	★★½
Double clear / low-e clear + Argon	Aluminium frame	★★★★½	★★½	★★½
Single advanced tint	Composite frame	★	★★★	★★★
Single clear	Composite frame	★★	★	★
Double advanced tint / clear	Composite frame	★★★	★★★★	★★★½
Double tint / low-e	Composite frame	★★★	★★★★½	★★★½
Double clear	Composite frame	★★★★	★★	★★
Double clear / low-e clear	Composite frame	★★★★½	★★	★★½
Double clear / low-e + Argon	Composite frame	★★★★★	★★	★★½
Single advanced tint	Thermally broken Aluminium frame	★	★★★	★★★
Single clear	Thermally broken Aluminium frame	★★½	★½	★
Double advanced tint / clear	Thermally broken Aluminium frame	★★★	★★★★½	★★★½
Double tint / low-e	Thermally broken Aluminium frame	★★★	★★★★★	★★★½
Double clear	Thermally broken Aluminium frame	★★★½	★★½	★★
Double clear / low-e clear	Thermally broken Aluminium frame	★★★★½	★★½	★★½
Double clear / low-e + Argon	Thermally broken Aluminium frame	★★★★★	★★½	★★½
Single advanced tint	PVC / Timber frame	★½	★★★½	★★★
Single clear	PVC / Timber frame	★★½	★★	★
Double advanced tint / clear	PVC / Timber frame	★★★	★★★★½	★★★½
Double tint / low-e	PVC / Timber frame	★★★½	★★★★★	★★★½
Double grey tint laminated / low-e	PVC / Timber frame	★★★½	★★★★½	★★★★½
Double clear	PVC / Timber frame	★★★★	★★½	★★
Double clear / low-e clear	PVC / Timber frame	★★★★½	★★★	★★½
Double clear / low-e + Argon	PVC / Timber frame	★★★★★	★★★	★★½

Fig.2.3 NZ-WERS ratings for select windows (www.wanz.co.nz).

In the United States, windows are rated for the ENERGY STAR® program based on their U-value and SHGC (Table 2.1). A study by Lawrence Berkeley National Laboratory (LBNL) looked at the impact of relaxing U-value requirements and balancing the increase in energy consumption with changes to the SHGC (Huang, Mitchell, Selkowitz, & Arasteh, 2004). The study found that in northern zones, increasing the U-value would result in values above code-minimum. However, the study determined that if in the future ENERGY STAR® U-value requirements are lowered (i.e. made more stringent), it could be feasible to permit higher U-values with higher SHGC.

Table 2.1 United States ENERGY STAR® qualification criteria.

	Windows & Doors		Skylights	
Zone	**U-factor**	**SHGC**	**U-factor**	**SHGC**
Northern	≤0.35	Any	≤0.60	Any
North/Central	≤0.40	≤0.55	≤0.60	≤0.40
South/Central	≤0.40	≤0.40	≤0.60	≤0.40
Southern	≤0.65	≤0.40	≤0.75	≤0.40

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3. Energy Rating Calculation Methodology

The purpose of this section is to gain a thorough understanding of the ER calculation and each of the terms used in the equation, and to perform a sensitivity analysis on the variables.

3.1. Energy Rating (ER) Equation

The Energy Rating (ER) calculation is given in CSA A440.2 standard,

$$ER = \frac{[SHGC_w \times F_\theta \times H_t \times R] - [(T_{bi} - T_{bo}) \times U_w] - [(T_{bi} - T_{bo}) \times (PF/20) \times L_{75} \times \rho C_p]}{DF} + SF$$

(Equation 1)

Where,

$SHGC_w$ = fenestration system solar heat gain coefficient for the reference size, dimensionless

F_θ = off-normal incidence angle factor for solar radiation, dimensionless

H_t = average incident solar radiation on vertical fenestration systems facing the four cardinal directions during hours of the year when solar heat gains influence heating load, W/m^2

R = solar gain reduction factor to account for shading, dimensionless, = 0.8

T_{bi} = average indoor temperature during hours of the year when daily average outdoor temperature is below 12°C (assumed to be 20°C)

T_{bo} = average outdoor temperature during hours of the year when daily average outdoor temperature is below 12°C (assumed to be -1.9°C)

U_w = fenestration system U-factor for the reference size, W/m^2-K

PF/20 = factor that reduces the air infiltration at 75 Pa to the air infiltration at the average pressure difference experienced in low-rise residential buildings, dimensionless

L_{75} = fenestration system air leakage rate at a pressure difference of 75 Pa, L/s-m^2

ρC_p = thermal capacitance of air, 1.2 kJ/m^3-K

DF = division factor used to make ER dimensionless, 1 W/m^2

SF = scaling factor, dimensionless, 40

The location factors used for the ER equation, determined in the original report, are:

$F_\theta \times H_t$ = 72.20 W/m^2

$(T_{bi} - T_{bo})$ = 21.90 K

PF = 1.5 $m^3/s/m^2$

Using these values the ER equation simplifies to,

$$ER = (57.76 \times SHGC_w) - (21.90 \times U_w) - (1.97 \times L_{75}) + 40$$

(Equation 2)

The original report groups the variables into two categories: window dependent and location dependent. The window dependent variables are $SHGC_w$, U_w and L_{75}. These values are determined by testing or modeling for each product. The location dependent variables are F_θ, H_t, T_{bo}, and PF. A standard set of values for these parameters are used in the ER calculation for all fenestration products in all Canadian locations. The standard inputs were calculated by averaging the variables calculated for a number of Canadian and US locations.

The remaining variables, R, DF and SF were added after the original development. R was added to reduce the weighting of solar heat gain in the equation. DF is simply a division factor to make the ER number dimensionless, and the SF value of 40 was added so that the values are positive to reduce confusion over negative ER numbers.

This analysis will examine the variables used in the ER calculation. A sensitivity analysis is performed for each of the window and location dependent variables to determine its relative effect on the overall ER number.

3.2. Specific Energy Rating (ERS) Equation

CSA A440.3 includes the calculation of a Specific Energy Rating (ERS) that can be used to calculate an energy rating for a particular fenestration size, orientation and climate. The ERS calculation is,

$$ERS = F_s \times SHGC_w \times R - [(T_i - T_o) \times U_w] - [K_{PF} \times (L_{75} \times 3.6)]$$

(Equation 3)

Where,

F_s = average rate of usable incident solar radiation on a fenestration system for a specific location and orientation during the heating season, W/m^2

$SHGC_w$ = fenestration system solar heat gain coefficient, dimensionless

R = solar gain reduction factor, 0.8, dimensionless

T_i = average indoor air temperature during the heating season for the specific location, °C

T_o = average outdoor air temperature during the heating season for the specific location, °C

U_w = fenestration system overall coefficient of heat transfer, W/m^2-K

K_{PF} = factor that includes a conversion factor and the local pressure factor, which is dependent on the wind and stack pressures causing air leakage, W-h/m^3

L_{75} = fenestration system air leakage rate at a pressure differential of 75 Pa, L/s/m^2

The ERS has two terms that are different from the ER, F_s and K_{PF}. Values for F_s and K_{PF} are given in the standard for various Canadian cities. It is important to note that the ERS is calculated differently from the ER, and therefore the two values should not be directly compared. The ERS also does not have the scaling factor, SF, which the ER includes (+40).

3.3. Window Dependent Variables

The window dependent variables are $SHGC_w$, U_w and L_{75}. The following discussion provides a general range of values for the window dependent variables to be used in the sensitivity analysis.

SHGC values can vary between 0 and 1, where 0 is completely opaque and 1 transmits all solar heat gain that reaches the window. A single sheet of clear glass has a SHGC of about 0.8 to 0.9 (depending on clearness). By comparison, a triple glazed window with two soft coat low-e coatings has a SHGC of about 0.2 to 0.3. (WINDOW 6.2, LBNL 2010)

Window U-values may be as high as U_{SI}-6.8 (U-1.2) for a single glazed window with a metal frame. However, many jurisdictions in Canada now typically require at least a double glazed window with a thermally broken metal frame, which have U-values in the general range of about U_{SI}-2.27 to U_{SI}-3.4 (U-0.4 to U-0.6). A triple glazed window with a low conductivity frame may have a U-value to about U_{SI}-0.79 (U-0.14). (ASHRAE, 2009). Lower U-values are possible with advanced glazing technologies such as quadruple or higher layers of glass, multiple heat mirror films, or vacuum insulated glazing. However, these products are less common in the current market.

Maximum air leakage rates for windows are given in CSA Standard A440. This standard gives airtightness ratings based on the air leakage rate tested at 75 Pa, with rating levels shown in Table 3.1. The air leakage rate can be reported in two ways, averaged over the crack length or averaged over the frame area. To meet ENERGY STAR®, windows must have an air leakage rating of at most 1.65 $m^3/h/m$ or 1.5 $L/s/m^2$.

Table 3.1 CSA A440-00 and NAFS-08 airtightness A ratings.

Window Rating	CSA A440-00		NAFS-08
	Maximum air leakage rate, $m^3/h/m$	Maximum air leakage rate, converted to $L/s/m^2$ (1200 mm x 1500 mm window)	Maximum air leakage rate for R Class, $L/s/m^2$
A1	2.79	1.86	n/a
A2	1.65	1.10	1.5
A3	0.55	0.37	0.5
Fixed	0.25	0.17	0.2

A sensitivity analysis was performed where each of the three window-dependent variables was changed independently to determine their relative impact on the ER. Base values of U_{SI}-2.0 (U-0.35), SHGC-0.4 and L_{75} 0.37 $L/s/m^2$ (A440-00 A3 rating for a standard 1200 mm x 1500 mm window) were used, which results in an ER of 19. Note that these base values were chosen as a common residential window, however, the focus of this analysis is on the relative change in ER due to each variable and therefore the base values are of little significance to the analysis. Using these inputs, the ER was plotted versus each variable individually. Fig.3.1, Fig.3.2 and Fig.3.3 show the plots.

Changing the SHGC between 0.1 and 0.8 varies the ER between 0 and 40 (Fig.3.1). Changing the U-value from U_{SI}-5.7 (U-1) to U_{SI}-0.6 (U-0.16) varies the ER between -60 and 50 (Fig.3.2). Changing the air leakage rate from 0 to 1.5 $L/s/m^2$ (no air leakage to an A2 rating for a standard 1200 mm x 1500 mm) varies the ER between 20 and 17 (Fig.3.3). The SHGC and U-value variables have a much greater impact on the ER than the air leakage variable.

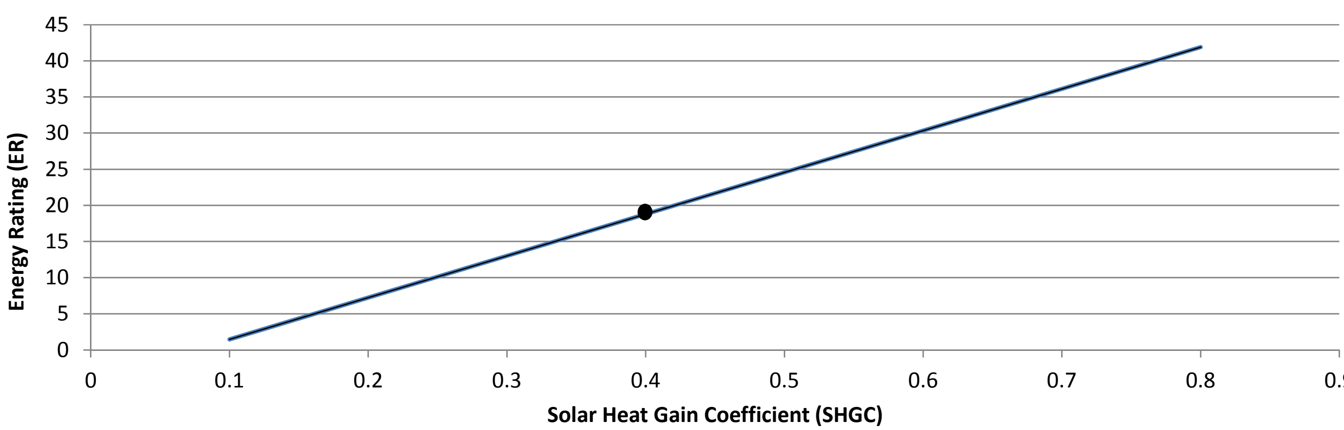


Fig.3.1 Energy rating versus Solar Heat Gain Coefficient.

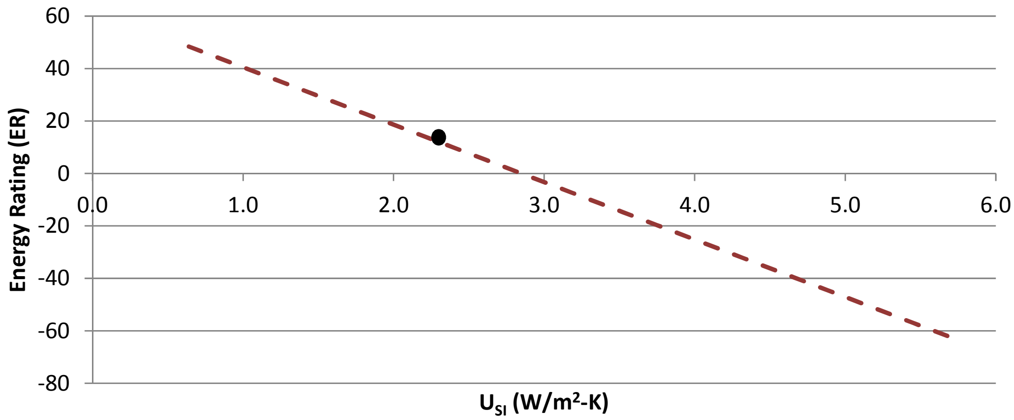


Fig.3.2 Energy rating versus U-value.

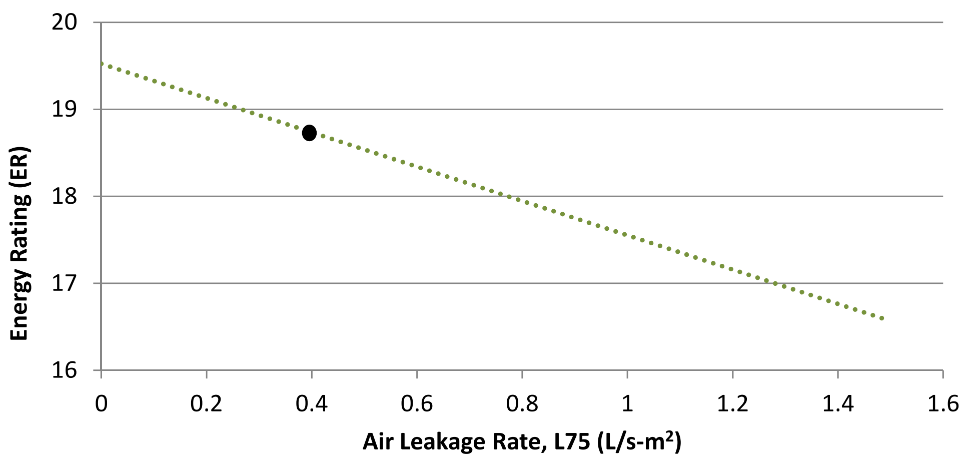


Fig.3.3 Energy rating versus Air Leakage Rate.

To illustrate further the impact of each window dependent variable, the ER rating was plotted versus the percent change in each variable (Fig.3.4). This plot shows that the U-value changes result in the greatest range of ER values, followed closely by the SHGC changes. Changes to the air leakage rate have a relatively minor effect on the ER value.

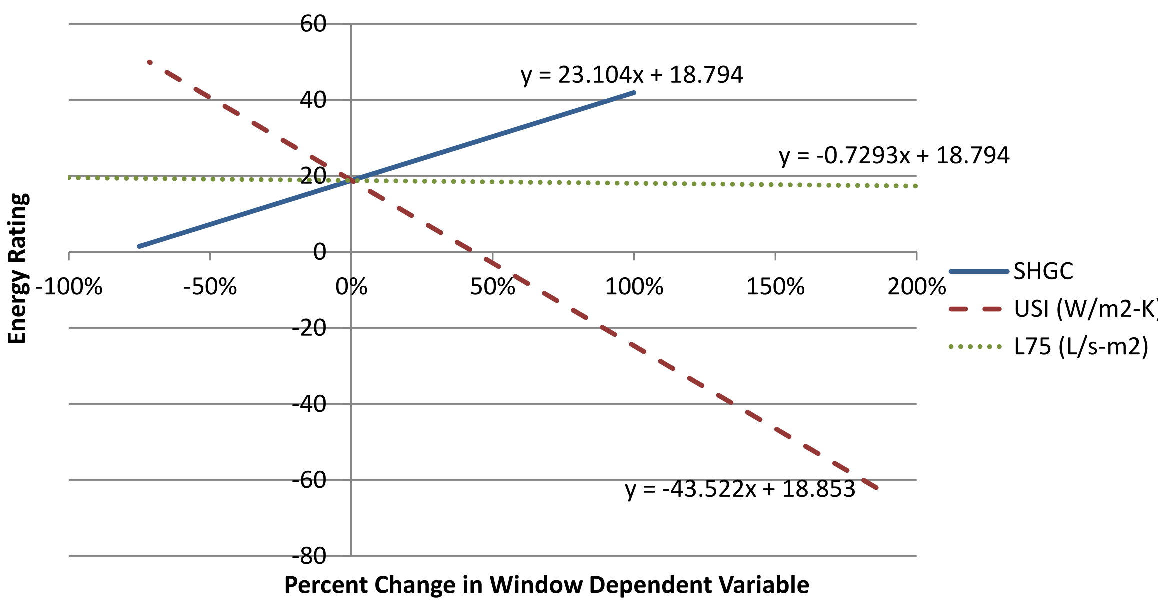


Fig.3.4 Energy rating versus change in Solar Heat Gain Coefficient, U-value and air leakage rate (using a base window with U_{SI}-2.0, SHGC-0.4, L_{75} = 0.37 L/s-m^2).

Fig.3.5 shows a three-dimensional plot of U-value and SHGC versus ER (since air leakage has a relatively small effect on ER it was held constant in this plot; an air leakage rate of 0.37 L/s-m^2 is used, A3 for a standard 1200 mm x 1500 mm window). The plot shows that a window with a low U-value and low SHGC can have a better ER than a window with a high U-value and high SHGC, and vice versa. For example, a window with U_{SI}-1.02 (U-0.18) and SHGC-0.1 has ER-23, while a window with U_{SI}-2.61 (U-0.46) and SHGC-0.70 also has ER-23.

Fig.3.6 shows a table of ER values for a variety of U-value and SHGC combinations. This table allows for quick comparison of U-value, SHGC and ER values. Fig.3.7 and Fig.3.8 shows windows that qualify for ENERGY STAR® on the U-value path and the ER path, respectively. This figure highlights the two paths, and demonstrates the significant impact of the SHGC on the ER path.

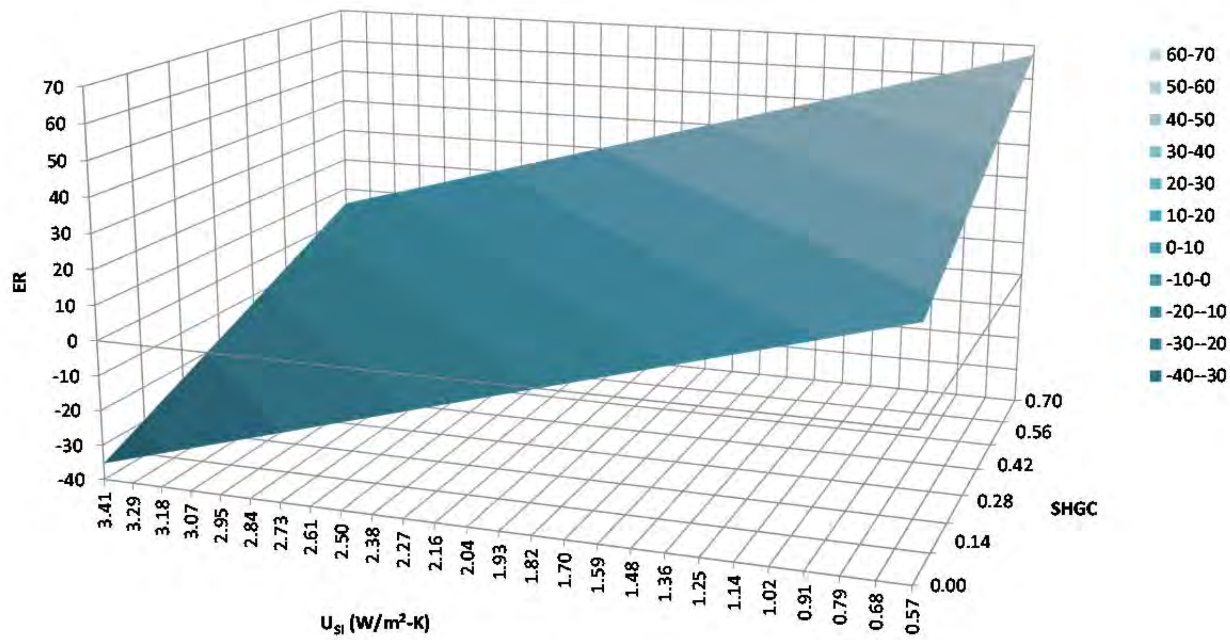


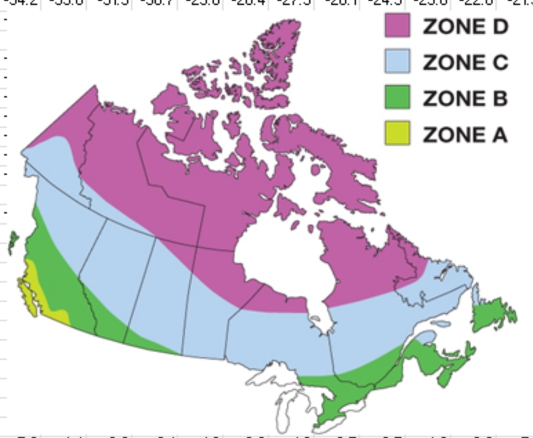
Fig.3.5 ER versus Solar Heat Gain Coefficient and U-value.

U-value		SHGC																																	
SI	IP	0.00	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.28	0.30	0.32	0.34	0.36	0.38	0.40	0.42	0.44	0.46	0.48	0.50	0.52	0.54	0.56	0.58	0.60	0.62	0.64	0.66	0.68	0.70
3.41	0.60	-35	-34	-33	-32	-31	-30	-28	-27	-26	-25	-24	-23	-21	-20	-19	-18	-17	-16	-15	-13	-12	-11	-10	-9	-8	-6	-5	-4	-3	-2	-1	0	2	3	4	5
3.35	0.59	-34	-33	-32	-31	-29	-28	-27	-26	-25	-24	-23	-21	-20	-19	-18	-17	-16	-14	-13	-12	-11	-10	-9	-8	-6	-5	-4	-3	-2	-1	1	2	3	4	5	6
3.29	0.58	-33	-32	-31	-29	-28	-27	-26	-25	-24	-22	-21	-20	-19	-18	-17	-16	-14	-13	-12	-11	-10	-9	-7	-6	-5	-4	-3	-2	-1	1	2	3	4	5	6	8
3.24	0.57	-32	-30	-29	-28	-27	-26	-25	-24	-22	-21	-20	-19	-18	-17	-15	-14	-13	-12	-11	-10	-9	-7	-6	-5	-4	-3	-2	0	1	2	3	4	5	7	8	9
3.18	0.56	-30	-29	-28	-27	-26	-25	-23	-22	-21	-20	-19	-18	-17	-15	-14	-13	-12	-11	-10	-8	-7	-6	-5	-4	-3	-1	0	1	2	3	4	5	7	8	9	10
3.12	0.55	-29	-28	-27	-26	-24	-23	-22	-21	-20	-19	-18	-16	-15	-14	-13	-12	-11	-9	-8	-7	-6	-5	-4	-3	-1	0	1	2	3	4	6	7	8	9	10	11
3.07	0.54	-28	-27	-26	-24	-23	-22	-21	-20	-19	-17	-16	-15	-14	-13	-12	-11	-9	-8	-7	-6	-5	-4	-2	-1	0	1	2	3	4	6	7	8	9	10	11	13
3.01	0.53	-27	-25	-24	-23	-22	-21	-20	-19	-17	-16	-15	-14	-13	-12	-10	-9	-8	-7	-6	-5	-4	-2	-1	0	1	2	3	5	6	7	8	9	10	11	13	14
2.95	0.52	-25	-24	-23	-22	-21	-20	-18	-17	-16	-15	-14	-13	-12	-10	-9	-8	-7	-6	-5	-3	-2	-1	0	1	2	3	5	6	7	8	9	10	12	13	14	15
2.90	0.51	-24	-23	-22	-21	-20	-18	-17	-16	-15	-14	-13	-11	-10	-9	-8	-7	-6	-5	-3	-2	-1	0	1	2	4	5	6	7	8	9	11	12	13	14	15	16
2.84	0.50	-23	-22	-21	-19	-18	-17	-16	-15	-14	-13	-11	-10	-9	-8	-7	-6	-4	-3	-2	-1	0	1	3	4	5	6	7	8	9	11	12	13	14	15	16	18
2.78	0.49	-22	-21	-19	-18	-17	-16	-15	-14	-12	-11	-10	-9	-8	-7	-5	-4	-3	-2	-1	0	1	3	4	5	6	7	8	10	11	12	13	14	15	16	18	19
2.73	0.48	-20	-19	-18	-17	-16	-15	-13	-12	-11	-10	-9	-8	-7	-5	-4	-3	-2	-1	0	2	3	4	5	6	7	8	10	11	12	13	14	15	17	18	19	20
2.67	0.47	-19	-18	-17	-16	-15	-13	-12	-11	-10	-9	-8	-6	-5	-4	-3	-2	-1	0	2	3	4	5	6	7	9	10	11	12	13	14	15	17	18	19	20	21
2.61	0.46	-18	-17	-16	-14	-13	-12	-11	-10	-9	-8	-6	-5	-4	-3	-2	-1	1	2	3	4	5	6	7	9	10	11	12	13	14	16	17	18	19	20	21	23
2.56	0.45	-17	-16	-14	-13	-12	-11	-10	-9	-7	-6	-5	-4	-3	-2	-1	1	2	3	4	5	6	8	9	10	11	12	13	15	16	17	18	19	20	21	23	24
2.50	0.44	-15	-14	-13	-12	-11	-10	-9	-7	-6	-5	-4	-3	-2	0	1	2	3	4	5	7	8	9	10	11	12	13	15	16	17	18	19	20	22	23	24	25
2.44	0.43	-14	-13	-12	-11	-10	-8	-7	-6	-5	-4	-3	-1	0	1	2	3	4	5	7	8	9	10	11	12	14	15	16	17	18	19	20	22	23	24	25	26
2.38	0.42	-13	-12	-11	-9	-8	-7	-6	-5	-4	-3	-1	0	1	2	3	4	6	7	8	9	10	11	12	14	15	16	17	18	19	21	22	23	24	25	26	27
2.33	0.41	-12	-11	-9	-8	-7	-6	-5	-4	-2	-1	0	1	2	3	4	6	7	8	9	10	11	13	14	15	16	17	18	19	21	22	23	24	25	26	28	29
2.27	0.40	-10	-9	-8	-7	-6	-5	-4	-2	-1	0	1	2	3	5	6	7	8	9	10	11	13	14	15	16	17	18	20	21	22	23	24	25	26	28	29	30
2.21	0.39	-9	-8	-7	-6	-5	-3	-2	-1	0	1	2	3	5	6	7	8	9	10	12	13	14	15	16	17	18	20	21	22	23	24	25	27	28	29	30	31
2.16	0.38	-8	-7	-6	-5	-3	-2	-1	0	1	2	4	5	6	7	8	9	11	12	13	14	15	16	17	19	20	21	22	23	24	26	27	28	29	30	31	32
2.10	0.37	-7	-6	-4	-3	-2	-1	0	1	3	4	5	6	7	8	9	11	12	13	14	15	16	18	19	20	21	22	23	24	26	27	28	29	30	31	33	34
2.04	0.36	-5	-4	-3	-2	-1	0	1	3	4	5	6	7	8	10	11	12	13	14	15	16	18	19	20	21	22	23	25	26	27	28	29	30	31	33	34	35
1.99	0.35	-4	-3	-2	-1	0	2	3	4	5	6	7	8	10	11	12	13	14	15	17	18	19	20	21	22	23	25	26	27	28	29	30	32	33	34	35	36
1.93	0.34	-3	-2	-1	0	2	3	4	5	6	7	9	10	11	12	13	14	15	17	18	19	20	21	22	24	25	26	27	28	29	30	32	33	34	35	36	37
1.87	0.33	-2	-1	1	2	3	4	5	6	7	9	10	11	12	13	14	16	17	18	19	20	21	22	24	25	26	27	28	29	31	32	33	34	35	36	38	39
1.82	0.32	-1	1	2	3	4	5	6	8	9	10	11	12	13	14	16	17	18	19	20	21	23	24	25	26	27	28	30	31	32	33	34	35	36	38	39	40
1.76	0.31	1	2	3	4	5	6	8	9	10	11	12	13	15	16	17	18	19	20	22	23	24	25	26	27	28	30	31	32	33	34	35	37	38	39	40	41
1.70	0.30	2	3	4	5	7	8	9	10	11	12	14	15	16	17	18	19	20	22	23	24	25	26	27	29	30	31	32	33	34	35	37	38	39	40	41	42
1.65	0.29	3	4	6	7	8	9	10	11	12	14	15	16	17	18	19	21	22	23	24	25	26	27	29	30	31	32	33	34	36	37	38	39	40	41	42	44
1.59	0.28	4	6	7	8	9	10	11	13	14	15	16	17	18	19	21	22	23	24	25	26	28	29	30	31	32	33	34	36	37	38	39	40	41	43	44	45
1.53	0.27	6	7	8	9	10	11	13	14	15	16	17	18	20	21	22	23	24	25	26	28	29	30	31	32	33	35	36	37	38	39	40	42	43	44	45	46
1.48	0.26	7	8	9	10	12	13	14	15	16	17	18	20	21	22	23	24	25	27	28	29	30	31	32	34	35	36	37	38	39	40	42	43	44	45	46	47
1.42	0.25	8	9	10	12	13	14	15	16	17	19	20	21	22	23	24	26	27	28	29	30	31	32	34	35	36	37	38	39	41	42	43	44	45	46	47	49
1.36	0.24	9	11	12	13	14	15	16	18	19	20	21	22	23	24	26	27	28	29	30	31	33	34	35	36	37	38	39	41	42	43	44	45	46	48	49	50
1.31	0.23	11	12	13	14	15	16	18	19	20	21	22	23	25	26	27	28	29	30	31	33	34	35	36	37	38	40	41	42	43	44	45	46	48	49	50	51
1.25	0.22	12	13	14	15	17	18	19	20	21	22	23	25	26	27	28	29	30	32	33	34	35	36	37	38	40	41	42	43	44	45	47	48	49	50	51	52
1.19	0.21	13	14	15	17	18	19	20	21	22	24	25	26	27	28	29	30	32	33	34	35	36	37	39	40	41	42	43	44	46	47	48	49	50	51	52	54
1.14	0.20	14	16	17	18	19	20	21	22	24	25	26	27	28	29	31	32	33	34	35	36	38	39	40	41	42	43	44	46	47	48	49	50	51	53	54	55
1.08	0.19	16	17	18	19	20	21	23	24	25	26	27	28	30	31	32	33	34	35	36	38	39	40	41	42	43	45	46	47	48	49	50	51	53	54	55	56
1.02	0.18	17	18	19	20	22	23	24	25	26	27	28	30	31	32	33	34	35	37	38	39	40	41	42	43	45	46	47	48	49	50	52	53	54	55	56	57
0.97	0.17	18	19	20	22	23	24	25	26	27	29	30	31	32	33	34	35	37	38	39	40	41	42	44	45	46	47	48	49	50	52	53	54	55	56	57	59
0.91	0.16	19	21	22	23	24	25	26	27	29	30	31	32	33	34	36	37	38	39	40	41	42	44	45	46	47	48	49	51	52	53	54	55	56	57	59	60
0.85	0.15	21	22	23	24	25	26	28	29	30	31	32	33	34	36	37	38	39	40	41	43	44	45	46	47	48	49	51	52	53	54	55	56	58	59	60	61
0.79	0.14	22	23	24	25	26	28	29	30	31	32	33	35	36	37	38	39	40	42	43	44	45	46	47	48	50	51	52	53	54	55	57	58	59	60	61	62
0.74	0.13	23	24	25	27	28	29	30	31	32	34	35	36	37	38	39	40	42	43	44	45	46	47	49	50	51	52	53	54	55	57	58	59	60	61	62	64
0.68	0.12	24	26	27	28	29	30	31	32	34	35	36	37	38	39	41	42	43	44	45	46	47	49	50	51	52	53	54	56	57	58	59	60	61	62	64	65
0.62	0.11	26	27	28	29	30	31	33	34	35	36	37	38	39	41	42	43	44	45	46	48	49	50	51	52	53	54	56	57	58	59	60	61	63	64	65	66
0.57	0.10	27	28	29	30	31	33	34	35	36	37	38	40	41	42	43	44	45	46	48	49	50	51	52	53	55	56	57	58	59	60	61	63	64	65	66	67

Fig.3.6 ER ratings for various U-value and Solar Heat Gain Coefficient combinations.

U-value		SHGC																																			
SI	IP	0.00	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.28	0.30	0.32	0.34	0.36	0.38	0.40	0.42	0.44	0.46	0.48	0.50	0.52	0.54	0.56	0.58	0.60	0.62	0.64	0.66	0.68	0.70
3.41	0.60	-35.3	-34.2	-33.0	-31.9	-30.7	-29.6	-28.4	-27.3	-26.1	-24.9	-23.8	-22.6	-21.5	-20.3	-19.2	-18.0	-16.9	-15.7	-14.5	-13.4	-12.2	-11.1	-9.9	-8.8	-7.6	-6.5	-5.3	-4.1	-3.0	-1.8	-0.7	0.5	1.6	2.8	3.9	5.1
3.35	0.59	-34.1												.2	-19.1	-17.9	-16.8	-15.6	-14.5	-13.3	-12.1	-11.0	-9.8	-8.7	-7.5	-6.4	-5.2	-4.1	-2.9	-1.7	-0.6	0.6	1.7	2.9	4.0	5.2	6.3
3.29	0.58	-32.9												.0	-17.8	-16.7	-15.5	-14.4	-13.2	-12.1	-10.9	-9.7	-8.6	-7.4	-6.3	-5.1	-4.0	-2.8	-1.7	-0.5	0.6	1.8	3.0	4.1	5.3	6.4	7.6
3.24	0.57	-31.6												.7	-16.6	-15.4	-14.3	-13.1	-12.0	-10.8	-9.7	-8.5	-7.3	-6.2	-5.0	-3.9	-2.7	-1.6	-0.4	0.7	1.9	3.0	4.2	5.4	6.5	7.7	8.8
3.18	0.56	-30.4												.5	-15.3	-14.2	-13.0	-11.9	-10.7	-9.6	-8.4	-7.3	-6.1	-4.9	-3.8	-2.6	-1.5	-0.3	0.8	2.0	3.1	4.3	5.4	6.6	7.8	8.9	10.1
3.12	0.55	-29.1												.3	-14.1	-12.9	-11.8	-10.6	-9.5	-8.3	-7.2	-6.0	-4.9	-3.7	-2.6	-1.4	-0.2	0.9	2.1	3.2	4.4	5.5	6.7	7.8	9.0	10.2	11.3
3.07	0.54	-27.9												.0	-12.9	-11.7	-10.5	-9.4	-8.2	-7.1	-5.9	-4.8	-3.6	-2.5	-1.3	-0.2	1.0	2.2	3.3	4.5	5.6	6.8	7.9	9.1	10.2	11.4	12.6
3.01	0.53	-26.6												.8	-11.6	-10.5	-9.3	-8.2	-7.0	-5.8	-4.7	-3.5	-2.4	-1.2	-0.1	1.1	2.2	3.4	4.6	5.7	6.9	8.0	9.2	10.3	11.5	12.6	13.8
2.95	0.52	-25.4												.5	-10.4	-9.2	-8.1	-6.9	-5.8	-4.6	-3.4	-2.3	-1.1	0.0	1.2	2.3	3.5	4.6	5.8	7.0	8.1	9.3	10.4	11.6	12.7	13.9	15.0
2.90	0.51	-24.1												.3	-9.1	-8.0	-6.8	-5.7	-4.5	-3.4	-2.2	-1.0	0.1	1.3	2.4	3.6	4.7	5.9	7.0	8.2	9.4	10.5	11.7	12.8	14.0	15.1	16.3
2.84	0.50	-22.9												.0	-7.9	-6.7	-5.6	-4.4	-3.3	-2.1	-1.0	0.2	1.4	2.5	3.7	4.8	6.0	7.1	8.3	9.4	10.6	11.8	12.9	14.1	15.2	16.4	17.5
2.78	0.49	-21.7												.8	-6.6	-5.5	-4.3	-3.2	-2.0	-0.9	0.3	1.4	2.6	3.8	4.9	6.1	7.2	8.4	9.5	10.7	11.8	13.0	14.2	15.3	16.5	17.6	18.8
2.73	0.48	-20.4												.6	-5.4	-4.2	-3.1	-1.9	-0.8	0.4	1.5	2.7	3.8	5.0	6.2	7.3	8.5	9.6	10.8	11.9	13.1	14.2	15.4	16.5	17.7	18.9	20.0
2.67	0.47	-19.2												.3	-4.2	-3.0	-1.8	-0.7	0.5	1.6	2.8	3.9	5.1	6.2	7.4	8.6	9.7	10.9	12.0	13.2	14.3	15.5	16.6	17.8	18.9	20.1	21.3
2.61	0.46	-17.9												.1	-2.9	-1.8	-0.6	0.6	1.7	2.9	4.0	5.2	6.3	7.5	8.6	9.8	11.0	12.1	13.3	14.4	15.6	16.7	17.9	19.0	20.2	21.3	22.5
2.56	0.45	-16.7												.8	-1.7	-0.5	0.6	1.8	3.0	4.1	5.3	6.4	7.6	8.7	9.9	11.0	12.2	13.3	14.5	15.7	16.8	18.0	19.1	20.3	21.4	22.6	23.7
2.50	0.44	-15.4												.6	-0.4	0.7	1.9	3.0	4.2	5.4	6.5	7.7	8.8	10.0	11.1	12.3	13.4	14.6	15.7	16.9	18.1	19.2	20.4	21.5	22.7	23.8	25.0
2.44	0.43	-14.2												.3	0.8	2.0	3.1	4.3	5.4	6.6	7.7	8.9	10.1	11.2	12.4	13.5	14.7	15.8	17.0	18.1	19.3	20.5	21.6	22.8	23.9	25.1	26.2
2.38	0.42	-13.0												.9	2.1	3.2	4.4	5.5	6.7	7.8	9.0	10.1	11.3	12.5	13.6	14.8	15.9	17.1	18.2	19.4	20.5	21.7	22.9	24.0	25.2	26.3	27.5
2.33	0.41	-11.7												.2	3.3	4.5	5.6	6.8	7.9	9.1	10.2	11.4	12.5	13.7	14.9	16.0	17.2	18.3	19.5	20.6	21.8	22.9	24.1	25.3	26.4	27.6	28.7
2.27	0.40	-10.5												.4	4.5	5.7	6.9	8.0	9.2	10.3	11.5	12.6	13.8	14.9	16.1	17.3	18.4	19.6	20.7	21.9	23.0	24.2	25.3	26.5	27.7	28.8	30.0
2.21	0.39	-9.2												.6	5.8	6.9	8.1	9.3	10.4	11.6	12.7	13.9	15.0	16.2	17.3	18.5	19.7	20.8	22.0	23.1	24.3	25.4	26.6	27.7	28.9	30.1	31.2
2.16	0.38	-8.0												.9	7.0	8.2	9.3	10.5	11.7	12.8	14.0	15.1	16.3	17.4	18.6	19.7	20.9	22.1	23.2	24.4	25.5	26.7	27.8	29.0	30.1	31.3	32.5
2.10	0.37	-6.7	-5.6	-4.4	-3.3	-2.1	-1.0	0.2	1.3	2.5	3.7	4.8	6.0	7.1	8.3	9.4	10.6	11.7	12.9	14.1	15.2	16.4	17.5	18.7	19.8	21.0	22.1	23.3	24.5	25.6	26.8	27.9	29.1	30.2	31.4	32.5	33.7
2.04	0.36	-5.5	-4.3	-3.2	-2.0	-0.9	0.3	1.4	2.6	3.7	4.9	6.1	7.2	8.4	9.5	10.7	11.8	13.0	14.1	15.3	16.5	17.6	18.8	19.9	21.1	22.2	23.4	24.5	25.7	26.9	28.0	29.2	30.3	31.5	32.6	33.8	34.9
1.99	0.35	-4.3	-3.1	-1.9	-0.8	0.4	1.5	2.7	3.8	5.0	6.1	7.3	8.5	9.6	10.8	11.9	13.1	14.2	15.4	16.5	17.7	18.9	20.0	21.2	22.3	23.5	24.6	25.8	26.9	28.1	29.2	30.4	31.6	32.7	33.9	35.0	36.2
1.93	0.34	-3.0	-1.9	-0.7	0.5	1.6	2.8	3.9	5.1	6.2	7.4	8.5	9.7	10.9	12.0	13.2	14.3	15.5	16.6	17.8	18.9	20.1	21.3	22.4	23.6	24.7	25.9	27.0	28.2	29.3	30.5	31.6	32.8	34.0	35.1	36.3	37.4
1.87	0.33	-1.8	-0.6	0.5	1.7	2.9	4.0	5.2	6.3	7.5	8.6	9.8	10.9	12.1	13.3	14.4	15.6	16.7	17.9	19.0	20.2	21.3	22.5	23.7	24.8	26.0	27.1	28.3	29.4	30.6	31.7	32.9	34.0	35.2	36.4	37.5	38.7
1.82	0.32	-0.5	0.6	1.8	2.9	4.1	5.3	6.4	7.6	8.7	9.9	11.0	12.2	13.3	14.5	15.7	16.8	18.0	19.1	20.3	21.4	22.6	23.7	24.9	26.0	27.2	28.4	29.5	30.7	31.8	33.0	34.1	35.3	36.4	37.6	38.8	39.9
1.76	0.31	0.7	1.9	3.0	4.2	5.3	6.5	7.7	8.8	10.0	11.1	12.3	13.4	14.6	15.7	16.9	18.1	19.2	20.4	21.5	22.7	23.8	25.0	26.1	27.3	28.4	29.6	30.8	31.9	33.1	34.2	35.4	36.5	37.7	38.8	40.0	41.2
1.70	0.30	2.0	3.1	4.3	5.4	6.6	7.7	8.9	10.1	11.2	12.4	13.5	14.7	15.8	17.0	18.1	19.3	20.4	21.6	22.8	23.9	25.1	26.2	27.4	28.5	29.7	30.8	32.0	33.2	34.3	35.5	36.6	37.8	38.9	40.1	41.2	42.4
1.65	0.29	3.2	4.4	5.5	6.7	7.8	9.0	10.1	11.3	12.5	13.6	14.8	15.9	17.1	18.2	19.4	20.5	21.7	22.8	24.0	25.2	26.3	27.5	28.6	29.8	30.9	32.1	33.2	34.4	35.6	36.7	37.9	39.0	40.2	41.3	42.5	43.6
1.59	0.28	4.5	5.6	6.8	7.9	9.1	10.2	11.4	12.5	13.7	14.9	16.0	17.2	18.3	19.5	20.6	21.8	22.9	24.1	25.2	26.4	27.6	28.7	29.9	31.0	32.2	33.3	34.5	35.6	36.8	38.0	39.1	40.3	41.4	42.6	43.7	44.9
1.53	0.27	5.7	6.9	8.0	9.2	10.3	11.5	12.6	13.8	14.9	16.1	17.2	18.4	19.6	20.7	21.9	23.0	24.2	25.3	26.5	27.6	28.8	30.0	31.1	32.3	33.4	34.6	35.7	36.9	38.0	39.2	40.4	41.5	42.7	43.8	45.0	46.1
1.48	0.26	6.9	8.1	9.3	10.4	11.6	12.7	13.9	15.0	16.2	17.3	18.5	19.6	20.8	22.0	23.1	24.3	25.4	26.6	27.7	28.9	30.0	31.2	32.4	33.5	34.7	35.8	37.0	38.1	39.3	40.4	41.6	42.8	43.9	45.1	46.2	47.4
1.42	0.25	8.2	9.3	10.5	11.6	12.8	14.0	15.1	16.3	17.4	18.6	19.7	20.9	22.0	23.2	24.4	25.5	26.7	27.8	29.0	30.1	31.3	32.4	33.6	34.8	35.9	37.1	38.2	39.4	40.5	41.7	42.8	44.0	45.2	46.3	47.5	48.6
1.36	0.24	9.4	10.6	11.7	12.9	14.0	15.2	16.4	17.5	18.7	19.8	21.0	22.1	23.3	24.4	25.6	26.8	27.9	29.1	30.2	31.4	32.5	33.7	34.8	36.0	37.2	38.3	39.5	40.6	41.8	42.9	44.1	45.2	46.4	47.5	48.7	49.9
1.31	0.23	10.7	11.8	13.0	14.1	15.3	16.4	17.6	18.8	19.9	21.1	22.2	23.4	24.5	25.7	26.8	28.0	29.2	30.3	31.5	32.6	33.8	34.9	36.1	37.2	38.4	39.6	40.7	41.9	43.0	44.2	45.3	46.5	47.6	48.8	49.9	51.1
1.25	0.22	11.9	13.1	14.2	15.4	16.5	17.7	18.8	20.0	21.2	22.3	23.5	24.6	25.8	26.9	28.1	29.2	30.4	31.6	32.7	33.9	35.0	36.2	37.3	38.5	39.6	40.8	41.9	43.1	44.3	45.4	46.6	47.7	48.9	50.0	51.2	52.3
1.19	0.21	13.2	14.3	15.5	16.6	17.8	18.9	20.1	21.2	22.4	23.6	24.7	25.9	27.0	28.2	29.3	30.5	31.6	32.8	34.0	35.1	36.3	37.4	38.6	39.7	40.9	42.0	43.2	44.3	45.5	46.7	47.8	49.0	50.1	51.3	52.4	53.6
1.14	0.20	14.4	15.6	16.7	17.9	19.0	20.2	21.3	22.5	23.6	24.8	26.0	27.1	28.3	29.4	30.6	31.7	32.9	34.0	35.2	36.3	37.5	38.7	39.8	41.0	42.1	43.3	44.4	45.6	46.7	47.9	49.1	50.2	51.4	52.5	53.7	54.8
1.08	0.19	15.6	16.8	18.0	19.1	20.3	21.4	22.6	23.7	24.9	26.0	27.2	28.4	29.5	30.7	31.8	33.0	34.1	35.3	36.4	37.6	38.7	39.9	41.1	42.2	43.4	44.5	45.7	46.8	48.0	49.1	50.3	51.5	52.6	53.8	54.9	56.1
1.02	0.18	16.9	18.0	19.2	20.4	21.5	22.7	23.8	25.0	26.1	27.3	28.4	29.6	30.8	31.9	33.1	34.2	35.4	36.5	37.7	38.8	40.0	41.1	42.3	43.5	44.6	45.8	46.9	48.1	49.2	50.4	51.5	52.7	53.9	55.0	56.2	57.3
0.97	0.17	18.1	19.3	20.4	21.6	22.8	23.9	25.1	26.2	27.4	28.5	29.7	30.8	32.0	33.1	34.3	35.5	36.6	37.8	38.9	40.1	41.2	42.4	43.5	44.7	45.9	47.0	48.2	49.3	50.5	51.6	52.8	53.9	55.1	56.3	57.4	58.6
0.91	0.16	19.4	20.5	21.7	22.8	24.0	25.2	26.3	27.5	28.6	29.8	30.9	32.1	33.2	34.4	35.5	36.7	37.9	39.0	40.2	41.3	42.5	43.6	44.8	45.9	47.1	48.3	49.4	50.6	51.7	52.9	54.0	55.2	56.3	57.5	58.7	59.8
0.85	0.15	20.6	21.8	22.9	24.1	25.2	26.4	27.5	28.7	29.9	31.0	32.2	33.3	34.5	35.6	36.8	37.9	39.1	40.3	41.4	42.6	43.7	44.9	46.0	47.2	48.3	49.5	50.7	51.8	53.0	54.1	55.3	56.4	57.6	58.7	59.9	61.1
0.79	0.14	21.9	23.0	24.2	25.3	26.5	27.6	28.8	29.9	31.1	32.3	33.4	34.6	35.7	36.9	38.0	39.2	40.3	41.5	42.7	43.8	45.0	46.1	47.3	48.4	49.6	50.7	51.9	53.1	54.2	55.4	56.5	57.7	58.8	60.0	61.1	62.3
0.74	0.13	23.1	24.3	25.4	26.6	27.7	28.9	30.0	31.2	32.3	33.5	34.7	35.8	37.0	38.1	39.3	40.4	41.6	42.7	43.9	45.1	46.2	47.4	48.5	49.7	50.8	52.0	53.1	54.3	55.5	56.6	57.8	58.9	60.1	61.2	62.4	63.5
0.68	0.12	24.3	25.5	26.7	27.8	29.0	30.1	31.3	32.4	33.6	34.7	35.9	37.1	38.2	39.4	40.5	41.7	42.8	44.0	45.1	46.3	47.5	48.6	49.8	50.9	52.1	53.2	54.4	55.5	56.7	57.8	59.0	60.2	61.3	62.5	63.6	64.8
0.62	0.11	25.6	26.7	27.9	29.1	30.2	31.4	32.5	33.7	34.8	36.0	37.1	38.3	39.5	40.6	41.8	42.9	44.1	45.2	46.4	47.5	48.7	49.9	51.0	52.2	53.3	54.5	55.6	56.8	57.9	59.1	60.2	61.4	62.6	63.7	64.9	66.0
0.57	0.10	26.8	28.0	29.1	30.3	31.5	32.6	33.8	34.9	36.1	37.2	38.4	39.5	40.7	41.9	43.0	44.2	45.3	46.5	47.6	48.8	49.9	51.1	52.3	53.4	54.6	55.7	56.9	58.0	59.2	60.3	61.5	62.6	63.8	65.0	66.1	67.3

Fig.3.7 ENERGY STAR® qualified windows based on the U-value path.



U-value		SHGC																																			
SI	IP	0.00	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.28	0.30	0.32	0.34	0.36	0.38	0.40	0.42	0.44	0.46	0.48	0.50	0.52	0.54	0.56	0.58	0.60	0.62	0.64	0.66	0.68	0.70
3.41	0.60	-35.3	-34.2	-33.0	-31.9	-30.7	-29.6	-28.4	-27.3	-26.1	-24.9	-23.8	-22.6	-21.5	-20.3	-19.2	-18.0	-16.9	-15.7	-14.5	-13.4	-12.2	-11.1	-9.9	-8.8	-7.6	-6.5	-5.3	-4.1	-3.0	-1.8	-0.7	0.5	1.6	2.8	3.9	5.1
3.35	0.59	-34.1													-19.1	-17.9	-16.8	-15.6	-14.5	-13.3	-12.1	-11.0	-9.8	-8.7	-7.5	-6.4	-5.2	-4.1	-2.9	-1.7	-0.6	0.6	1.7	2.9	4.0	5.2	6.3
3.29	0.58	-32.9													-17.8	-16.7	-15.5	-14.4	-13.2	-12.1	-10.9	-9.7	-8.6	-7.4	-6.3	-5.1	-4.0	-2.8	-1.7	-0.5	0.6	1.8	3.0	4.1	5.3	6.4	7.6
3.24	0.57	-31.6													-16.6	-15.4	-14.3	-13.1	-12.0	-10.8	-9.7	-8.5	-7.3	-6.2	-5.0	-3.9	-2.7	-1.6	-0.4	0.7	1.9	3.0	4.2	5.4	6.5	7.7	8.8
3.18	0.56	-30.4													-15.3	-14.2	-13.0	-11.9	-10.7	-9.6	-8.4	-7.3	-6.1	-4.9	-3.8	-2.6	-1.5	-0.3	0.8	2.0	3.1	4.3	5.4	6.6	7.8	8.9	10.1
3.12	0.55	-29.1													-14.1	-12.9	-11.8	-10.6	-9.5	-8.3	-7.2	-6.0	-4.9	-3.7	-2.6	-1.4	-0.2	0.9	2.1	3.2	4.4	5.5	6.7	7.8	9.0	10.2	11.3
3.07	0.54	-27.9													-12.9	-11.7	-10.5	-9.4	-8.2	-7.1	-5.9	-4.8	-3.6	-2.5	-1.3	-0.2	1.0	2.2	3.3	4.5	5.6	6.8	7.9	9.1	10.2	11.4	12.6
3.01	0.53	-26.6													-11.6	-10.5	-9.3	-8.2	-7.0	-5.8	-4.7	-3.5	-2.4	-1.2	-0.1	1.1	2.2	3.4	4.6	5.7	6.9	8.0	9.2	10.3	11.5	12.6	13.8
2.95	0.52	-25.4													-10.4	-9.2	-8.1	-6.9	-5.8	-4.6	-3.4	-2.3	-1.1	0.0	1.2	2.3	3.5	4.6	5.8	7.0	8.1	9.3	10.4	11.6	12.7	13.9	15.0
2.90	0.51	-24.1													-9.1	-8.0	-6.8	-5.7	-4.5	-3.4	-2.2	-1.0	0.1	1.3	2.4	3.6	4.7	5.9	7.0	8.2	9.4	10.5	11.7	12.8	14.0	15.1	16.3
2.84	0.50	-22.9													-7.9	-6.7	-5.6	-4.4	-3.3	-2.1	-1.0	0.2	1.4	2.5	3.7	4.8	6.0	7.1	8.3	9.4	10.6	11.8	12.9	14.1	15.2	16.4	17.5
2.78	0.49	-21.7													-6.6	-5.5	-4.3	-3.2	-2.0	-0.9	0.3	1.4	2.6	3.8	4.9	6.1	7.2	8.4	9.5	10.7	11.8	13.0	14.2	15.3	16.5	17.6	18.8
2.73	0.48	-20.4													-5.4	-4.2	-3.1	-1.9	-0.8	0.4	1.5	2.7	3.8	5.0	6.2	7.3	8.5	9.6	10.8	11.9	13.1	14.2	15.4	16.5	17.7	18.9	20.0
2.67	0.47	-19.2													-4.2	-3.0	-1.8	-0.7	0.5	1.6	2.8	3.9	5.1	6.2	7.4	8.6	9.7	10.9	12.0	13.2	14.3	15.5	16.6	17.8	18.9	20.1	21.3
2.61	0.46	-17.9													-2.9	-1.8	-0.6	0.6	1.7	2.9	4.0	5.2	6.3	7.5	8.6	9.8	11.0	12.1	13.3	14.4	15.6	16.7	17.9	19.0	20.2	21.3	22.5
2.56	0.45	-16.7													-1.7	-0.5	0.6	1.8	3.0	4.1	5.3	6.4	7.6	8.7	9.9	11.0	12.2	13.3	14.5	15.7	16.8	18.0	19.1	20.3	21.4	22.6	23.7
2.50	0.44	-15.4													-0.4	0.7	1.9	3.0	4.2	5.4	6.5	7.7	8.8	10.0	11.1	12.3	13.4	14.6	15.7	16.9	18.1	19.2	20.4	21.5	22.7	23.8	25.0
2.44	0.43	-14.2													0.8	2.0	3.1	4.3	5.4	6.6	7.7	8.9	10.1	11.2	12.4	13.5	14.7	15.8	17.0	18.1	19.3	20.5	21.6	22.8	23.9	25.1	26.2
2.38	0.42	-13.0													2.1	3.2	4.4	5.5	6.7	7.8	9.0	10.1	11.3	12.5	13.6	14.8	15.9	17.1	18.2	19.4	20.5	21.7	22.9	24.0	25.2	26.3	27.5
2.33	0.41	-11.7													3.3	4.5	5.6	6.8	7.9	9.1	10.2	11.4	12.5	13.7	14.9	16.0	17.2	18.3	19.5	20.6	21.8	22.9	24.1	25.3	26.4	27.6	28.7
2.27	0.40	-10.5													4.5	5.7	6.9	8.0	9.2	10.3	11.5	12.6	13.8	14.9	16.1	17.3	18.4	19.6	20.7	21.9	23.0	24.2	25.3	26.5	27.7	28.8	30.0
2.21	0.39	-9.2													5.8	6.9	8.1	9.3	10.4	11.6	12.7	13.9	15.0	16.2	17.3	18.5	19.7	20.8	22.0	23.1	24.3	25.4	26.6	27.7	28.9	30.1	31.2
2.16	0.38	-8.0													7.0	8.2	9.3	10.5	11.7	12.8	14.0	15.1	16.3	17.4	18.6	19.7	20.9	22.1	23.2	24.4	25.5	26.7	27.8	29.0	30.1	31.3	32.5
2.10	0.37	-6.7	-5.6	-4.4	-3.3	-2.1	-1.0	0.2	1.3	2.5	3.7	4.8	6.0	7.1	8.3	9.4	10.6	11.7	12.9	14.1	15.2	16.4	17.5	18.7	19.8	21.0	22.1	23.3	24.5	25.6	26.8	27.9	29.1	30.2	31.4	32.5	33.7
2.04	0.36	-5.5	-4.3	-3.2	-2.0	-0.9	0.3	1.4	2.6	3.7	4.9	6.1	7.2	8.4	9.5	10.7	11.8	13.0	14.1	15.3	16.5	17.6	18.8	19.9	21.1	22.2	23.4	24.5	25.7	26.9	28.0	29.2	30.3	31.5	32.6	33.8	34.9
1.99	0.35	-4.3	-3.1	-1.9	-0.8	0.4	1.5	2.7	3.8	5.0	6.1	7.3	8.5	9.6	10.8	11.9	13.1	14.2	15.4	16.5	17.7	18.9	20.0	21.2	22.3	23.5	24.6	25.8	26.9	28.1	29.2	30.4	31.6	32.7	33.9	35.0	36.2
1.93	0.34	-3.0	-1.9	-0.7	0.5	1.6	2.8	3.9	5.1	6.2	7.4	8.5	9.7	10.9	12.0	13.2	14.3	15.5	16.6	17.8	18.9	20.1	21.3	22.4	23.6	24.7	25.9	27.0	28.2	29.3	30.5	31.6	32.8	34.0	35.1	36.3	37.4
1.87	0.33	-1.8	-0.6	0.5	1.7	2.9	4.0	5.2	6.3	7.5	8.6	9.8	10.9	12.1	13.3	14.4	15.6	16.7	17.9	19.0	20.2	21.3	22.5	23.7	24.8	26.0	27.1	28.3	29.4	30.6	31.7	32.9	34.0	35.2	36.4	37.5	38.7
1.82	0.32	-0.5	0.6	1.8	2.9	4.1	5.3	6.4	7.6	8.7	9.9	11.0	12.2	13.3	14.5	15.7	16.8	18.0	19.1	20.3	21.4	22.6	23.7	24.9	26.0	27.2	28.4	29.5	30.7	31.8	33.0	34.1	35.3	36.4	37.6	38.8	39.9
1.76	0.31	0.7	1.9	3.0	4.2	5.3	6.5	7.7	8.8	10.0	11.1	12.3	13.4	14.6	15.7	16.9	18.1	19.2	20.4	21.5	22.7	23.8	25.0	26.1	27.3	28.4	29.6	30.8	31.9	33.1	34.2	35.4	36.5	37.7	38.8	40.0	41.2
1.70	0.30	2.0	3.1	4.3	5.4	6.6	7.7	8.9	10.1	11.2	12.4	13.5	14.7	15.8	17.0	18.1	19.3	20.4	21.6	22.8	23.9	25.1	26.2	27.4	28.5	29.7	30.8	32.0	33.2	34.3	35.5	36.6	37.8	38.9	40.1	41.2	42.4
1.65	0.29	3.2	4.4	5.5	6.7	7.8	9.0	10.1	11.3	12.5	13.6	14.8	15.9	17.1	18.2	19.4	20.5	21.7	22.8	24.0	25.2	26.3	27.5	28.6	29.8	30.9	32.1	33.2	34.4	35.6	36.7	37.9	39.0	40.2	41.3	42.5	43.6
1.59	0.28	4.5	5.6	6.8	7.9	9.1	10.2	11.4	12.5	13.7	14.9	16.0	17.2	18.3	19.5	20.6	21.8	22.9	24.1	25.2	26.4	27.6	28.7	29.9	31.0	32.2	33.3	34.5	35.6	36.8	38.0	39.1	40.3	41.4	42.6	43.7	44.9
1.53	0.27	5.7	6.9	8.0	9.2	10.3	11.5	12.6	13.8	14.9	16.1	17.2	18.4	19.6	20.7	21.9	23.0	24.2	25.3	26.5	27.6	28.8	30.0	31.1	32.3	33.4	34.6	35.7	36.9	38.0	39.2	40.4	41.5	42.7	43.8	45.0	46.1
1.48	0.26	6.9	8.1	9.3	10.4	11.6	12.7	13.9	15.0	16.2	17.3	18.5	19.6	20.8	22.0	23.1	24.3	25.4	26.6	27.7	28.9	30.0	31.2	32.4	33.5	34.7	35.8	37.0	38.1	39.3	40.4	41.6	42.8	43.9	45.1	46.2	47.4
1.42	0.25	8.2	9.3	10.5	11.6	12.8	14.0	15.1	16.3	17.4	18.6	19.7	20.9	22.0	23.2	24.4	25.5	26.7	27.8	29.0	30.1	31.3	32.4	33.6	34.8	35.9	37.1	38.2	39.4	40.5	41.7	42.8	44.0	45.2	46.3	47.5	48.6
1.36	0.24	9.4	10.6	11.7	12.9	14.0	15.2	16.4	17.5	18.7	19.8	21.0	22.1	23.3	24.4	25.6	26.8	27.9	29.1	30.2	31.4	32.5	33.7	34.8	36.0	37.2	38.3	39.5	40.6	41.8	42.9	44.1	45.2	46.4	47.5	48.7	49.9
1.31	0.23	10.7	11.8	13.0	14.1	15.3	16.4	17.6	18.8	19.9	21.1	22.2	23.4	24.5	25.7	26.8	28.0	29.2	30.3	31.5	32.6	33.8	34.9	36.1	37.2	38.4	39.6	40.7	41.9	43.0	44.2	45.3	46.5	47.6	48.8	49.9	51.1
1.25	0.22	11.9	13.1	14.2	15.4	16.5	17.7	18.8	20.0	21.2	22.3	23.5	24.6	25.8	26.9	28.1	29.2	30.4	31.6	32.7	33.9	35.0	36.2	37.3	38.5	39.6	40.8	41.9	43.1	44.3	45.4	46.6	47.7	48.9	50.0	51.2	52.3
1.19	0.21	13.2	14.3	15.5	16.6	17.8	18.9	20.1	21.2	22.4	23.6	24.7	25.9	27.0	28.2	29.3	30.5	31.6	32.8	34.0	35.1	36.3	37.4	38.6	39.7	40.9	42.0	43.2	44.3	45.5	46.7	47.8	49.0	50.1	51.3	52.4	53.6
1.14	0.20	14.4	15.6	16.7	17.9	19.0	20.2	21.3	22.5	23.6	24.8	26.0	27.1	28.3	29.4	30.6	31.7	32.9	34.0	35.2	36.3	37.5	38.7	39.8	41.0	42.1	43.3	44.4	45.6	46.7	47.9	49.1	50.2	51.4	52.5	53.7	54.8
1.08	0.19	15.6	16.8	18.0	19.1	20.3	21.4	22.6	23.7	24.9	26.0	27.2	28.4	29.5	30.7	31.8	33.0	34.1	35.3	36.4	37.6	38.7	39.9	41.1	42.2	43.4	44.5	45.7	46.8	48.0	49.1	50.3	51.5	52.6	53.8	54.9	56.1
1.02	0.18	16.9	18.0	19.2	20.4	21.5	22.7	23.8	25.0	26.1	27.3	28.4	29.6	30.8	31.9	33.1	34.2	35.4	36.5	37.7	38.8	40.0	41.1	42.3	43.5	44.6	45.8	46.9	48.1	49.2	50.4	51.5	52.7	53.9	55.0	56.2	57.3
0.97	0.17	18.1	19.3	20.4	21.6	22.8	23.9	25.1	26.2	27.4	28.5	29.7	30.8	32.0	33.1	34.3	35.5	36.6	37.8	38.9	40.1	41.2	42.4	43.5	44.7	45.9	47.0	48.2	49.3	50.5	51.6	52.8	53.9	55.1	56.3	57.4	58.6
0.91	0.16	19.4	20.5	21.7	22.8	24.0	25.2	26.3	27.5	28.6	29.8	30.9	32.1	33.2	34.4	35.5	36.7	37.9	39.0	40.2	41.3	42.5	43.6	44.8	45.9	47.1	48.3	49.4	50.6	51.7	52.9	54.0	55.2	56.3	57.5	58.7	59.8
0.85	0.15	20.6	21.8	22.9	24.1	25.2	26.4	27.5	28.7	29.9	31.0	32.2	33.3	34.5	35.6	36.8	37.9	39.1	40.3	41.4	42.6	43.7	44.9	46.0	47.2	48.3	49.5	50.7	51.8	53.0	54.1	55.3	56.4	57.6	58.7	59.9	61.1
0.79	0.14	21.9	23.0	24.2	25.3	26.5	27.6	28.8	29.9	31.1	32.3	33.4	34.6	35.7	36.9	38.0	39.2	40.3	41.5	42.7	43.8	45.0	46.1	47.3	48.4	49.6	50.7	51.9	53.1	54.2	55.4	56.5	57.7	58.8	60.0	61.1	62.3
0.74	0.13	23.1	24.3	25.4	26.6	27.7	28.9	30.0	31.2	32.3	33.5	34.7	35.8	37.0	38.1	39.3	40.4	41.6	42.7	43.9	45.1	46.2	47.4	48.5	49.7	50.8	52.0	53.1	54.3	55.5	56.6	57.8	58.9	60.1	61.2	62.4	63.5
0.68	0.12	24.3	25.5	26.7	27.8	29.0	30.1	31.3	32.4	33.6	34.7	35.9	37.1	38.2	39.4	40.5	41.7	42.8	44.0	45.1	46.3	47.5	48.6	49.8	50.9	52.1	53.2	54.4	55.5	56.7	57.8	59.0	60.2	61.3	62.5	63.6	64.8
0.62	0.11	25.6	26.7	27.9	29.1	30.2	31.4	32.5	33.7	34.8	36.0	37.1	38.3	39.5	40.6	41.8	42.9	44.1	45.2	46.4	47.5	48.7	49.9	51.0	52.2	53.3	54.5	55.6	56.8	57.9	59.1	60.2	61.4	62.6	63.7	64.9	66.0
0.57	0.10	26.8	28.0	29.1	30.3	31.5	32.6	33.8	34.9	36.1	37.2	38.4	39.5	40.7	41.9	43.0	44.2	45.3	46.5	47.6	48.8	49.9	51.1	52.3	53.4	54.6	55.7	56.9	58.0	59.2	60.3	61.5	62.6	63.8	65.0	66.1	67.3

Fig.3.8 ENERGY STAR® qualified windows based on the ER path.

3.4. Location Dependent Variables

The location dependent variables are F_θ, H_t, T_{bo}, and PF. The variables F_θ and H_t define solar heat gain in the ER equation, T_{bo} is the outdoor temperature used to calculate heat loss due to conduction and air leakage, and PF is the pressure factor used for the air leakage calculation.

3.4.1 Solar Heat Gain Variables

There are two location-dependent components that determine how much heat from the sun enters a space: the amount of solar radiation that falls on the window (H_t) and the angle at which it hits the window (F_θ).

F_θ is the off-normal angle incidence factor, which reduces the solar heat gain to the space since more solar radiation is reflected off of a window as the angle of incidence increases. CSA A440.3 defines this factor as the value of the SHGC for any off-normal angle of incidence ($SHGC_a$) divided by the SHGC for the normal incidence angle ($SHGC_n$),

$$F_\theta = \frac{SHGC_a}{SHGC_n}$$

(Equation 4)

The original ER study reports that, since most windows use similar glass, F_θ is more a function of latitude and orientation than window type. Fig.3.9 shows a plot of solar heat gain versus solar angle of incidence using optical properties from WINDOW6 for a variety of glazing configurations. The glazing unit configurations used a hard coat for the high solar heat gain configuration and a soft coat for the double and triple low solar heat gain configurations. The incident angle has a significant impact on solar heat gain, and therefore this factor may be important to consider in an ER formula.

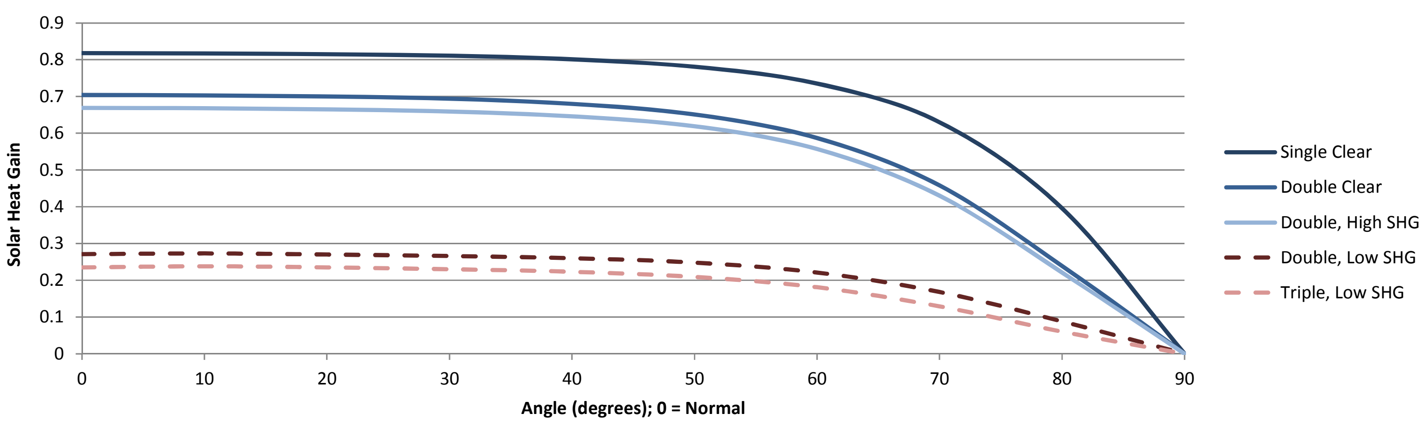


Fig.3.9 Solar heat gain versus angle of incidence for various glazing configurations.

At an incidence angle of 50°, the single glazing has 5% less solar heat gain than at normal incidence, the double glazing configurations have 7% to 8% less heat gain, and the triple glazing has 11% less heat gain. At an incidence angle of 80°, the single glazing has 52% less heat gain compared to normal incidence, the double glazing configurations have 66% to 68% less heat gain, and the triple glazing has 74% less heat gain. The different glazing configurations perform similarly, though more glass layers tend to have greater percent solar heat gain reductions at higher incidence angles.

The off angle incidence factor (F_θ) is also affected by latitude; that is, the angle at which solar radiation hits a window throughout the year. Northern latitudes see lower incident angles at the south vertical elevation (see Table 3.2). This means that northern latitudes will have more solar heat gain enter a space per unit of solar radiation that falls on the window.

Table 3.2 Solar angle of incidence at south elevation, noon (0 = Normal).

	June 21	December 21
Toronto	69.8°	23.1°
Vancouver	64.3°	17.7°
Edmonton	60.9°	15.2°
Yellowknife	52.1°	9.3°

H_t is the average solar radiation incident on a vertical surface during the heating season averaged over the four cardinal directions. The heating season is defined as when the daily average outdoor temperature is less than 12°C. In the ER development study, F_θ and H_t are combined into one variable, $F_\theta \times H_t$, and the average calculated value used in the ER equation is 72.2 W/m^2. The calculated $F_\theta \times H_t$ values for Canadian cities that are shown in the report range from a low of 48.37 in Vancouver to a high of 84.76 in Saskatoon. These calculations were based on simulations using a window with a U-value of 2.77 W/m2-K (U-0.49), a shading coefficient of 0.66 (SHGC-0.57), and an air leakage rate of 6.6 m^3/h-m (an A440 A2 Rating in 1989).

In CSA A440.3 the equation for the Specific Energy Rating (ERS) uses the term F_s instead of $F_\theta \times H_t$. F_s is the average rate of usable incident solar radiation on a fenestration system for a specific location and orientation during the heating season, in W/m^2. Values for F_s are calculated using the Solar Gain Index (SGI), where SGI is the SHGC times the ratio of fenestration area (A_w) to above grade floor area (A_{fl}). However, more specific details on the F_s calculation are not given in the standard.

$$SGI = SHGC_w \times \frac{A_w}{A_{fl}}$$

(Equation 5)

Though not a location dependent variable, it is important to address the solar gain reduction factor, R, as part of this discussion. This factor, set at 0.8, was introduced into the equation to reduce the weight of solar heat gain in the ER equation. A factor of 0.8 was chosen since it is the ASHRAE winter shading factor and is used in the program RESFEN.

RESFEN has different options for solar gain reduction, including none, overhangs, obstructions, blinds, shading, etc. The program also gives an option for "typical" solar gain reduction, which is 0.8 in the winter and 0.7 in the summer. The user manual includes the following explanation for the "typical" reduction factor of 0.8:

"To represent a statistically average solar gain reduction for a generic house, this option includes: interior shades (seasonal SHGC multiplier, summer value = 0.8, winter value = 0.9), 1' overhang, a 67% transmitting same-height obstruction 20' away intended to represent adjacent buildings. To account for other sources of solar heat gain reduction (insect screens, trees, dirt, building and window self-shading), the SHGC multiplier was further reduced by 0.1. This results in a final winter SHGC multiplier of 0.8 and a final summer SHGC multiplier of 0.7."

To summarize, the solar heat gain portion of the ER is dependent on the off-normal incidence factor (F_θ), and incident solar radiation (H_t) during the heating season. In the ERS the calculation is slightly different, using the value F_s, the average rate of usable incident solar radiation during the heating season. Both the ER and ERS also introduce a solar gain reduction factor, R.

3.4.2 Conduction and Air Leakage Heat Loss Variables

T_{bo} is the average outdoor temperature during heating conditions. In the development of the ER variables, heating conditions were assumed to occur when the outdoor temperature is below 12°C. An indoor temperature of 20°C was used for heating conditions. In the ER calculation a value of -1.9°C is used for T_{bo}. In the 1989 report, the calculated values ranged from a high of 5.6 in Vancouver to a low of -6 in Whitehorse. However, considering that only locations with between 4000 to 6200 HDD were used in the average, the range used for the average calculation was between 1.9 for St. John's to -5.8 for Winnipeg.

The air leakage calculation in the ER equation is based on the Sherman and Grimsrud model described in the 2009 ASHRAE Handbook – Fundamentals (page 16.23). The pressure factor (PF) term contained in the ER equation is based on this model:

$$PF = 10[A(T_{bi} - T_{bo}) + BV^2]^{0.5}$$

(Equation 6)

A and B are correlation coefficients related to stack effect and wind, respectively. The variable V is the wind speed in m/s. The units of the PF are $m^3/s/m^2$ (one $m^3/s/m^2$ equals 196.8 cfm/ft^2). To determine coefficients for the PF term, a two-storey house was used with moderate shielding. This resulted in values of 0.00029 for A and 0.000231 for B (the 2009 ASHRAE Handbook – Fundamentals gives values for these coefficients on page 16.23).

Fig.3.10 shows how the PF changes with different outdoor temperature and wind speeds. Average annual wind speeds range from about 3 m/s in less windy areas to 10 m/s in very windy locations (Fig.3.11); wind data is available from Environment Canada's *Canadian Wind Energy Atlas* (www.windatlas.ca).

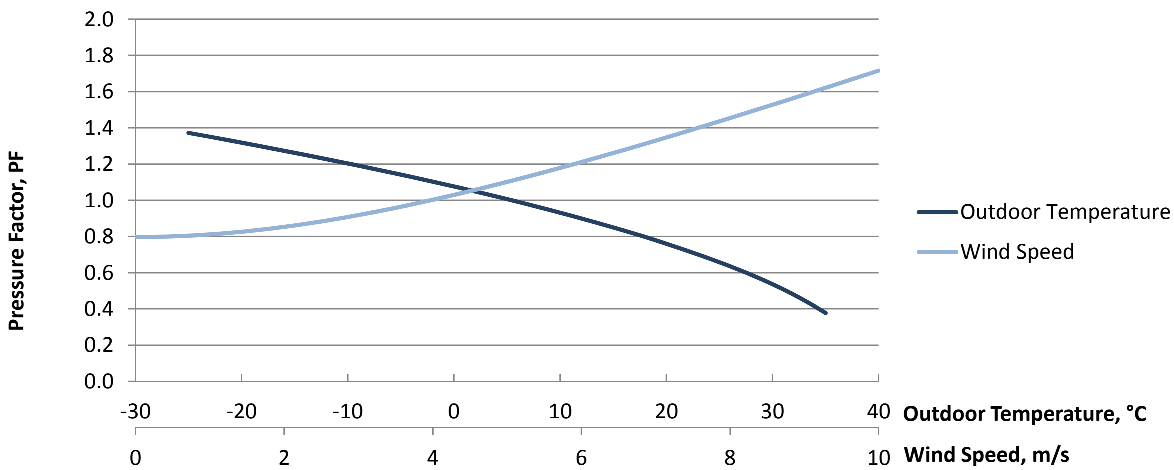
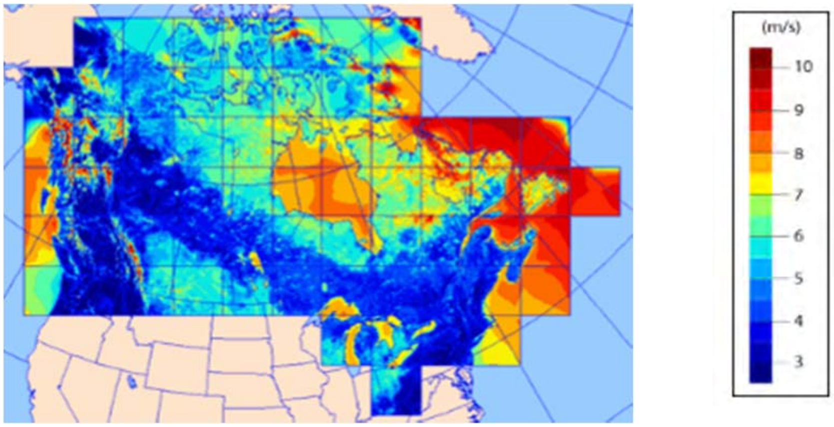
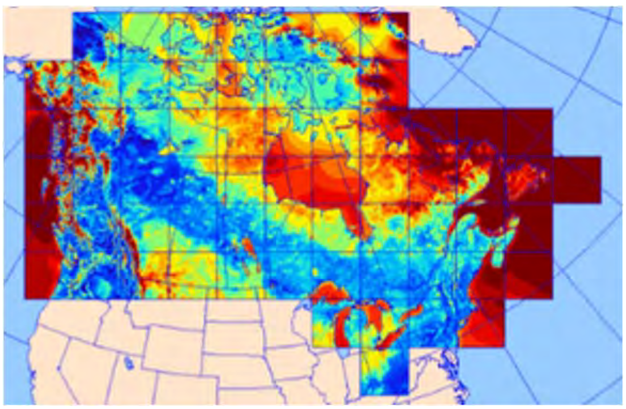


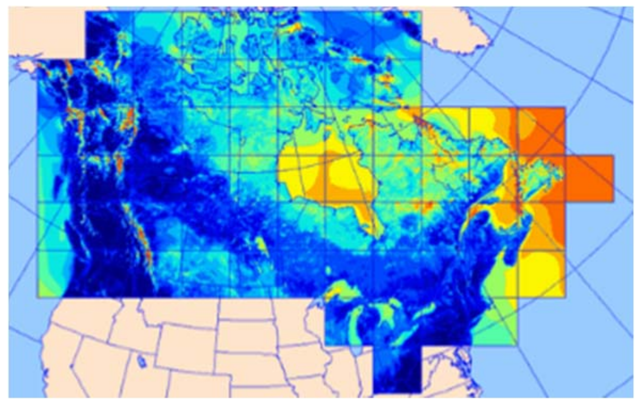
Fig.3.10 Change in PF with outdoor temperature and wind speed.



Average Annual Wind Speeds



Average Winter Wind Speeds



Average Summer Wind Speeds

Fig.3.11 Average Canadian wind speeds (Environment Canada 2003).

The PF decreases as the outdoor temperature decreases since a smaller pressure difference between indoors and outdoors results in less infiltration due to stack effect. The PF increases as wind speed increases since windier conditions create larger pressure differences across an enclosure and therefore drive more infiltration.

In the ER development report, the PF values range from a low of 1.14 in Vancouver to a high of 1.66 in Timmins. The average PF used in the ER calculation is 1.5.

The ERS uses a different factor to calculate air leakage losses, K_{PF}, in W-h/m^3. A440.3 provides a table of K_{PF} values calculated for various Canadian cities. No further information is given in the standard regarding the calculation of K_{PF}.

3.4.3 Sensitivity Analysis of Location Dependent Variables

Similar to the window-dependent variables, a sensitivity analysis was performed for each of the location dependent variables to determine their relative effect on the ER. The location dependent variables are F_θ, H_t, T_{bo}, PF. Table 3.3 shows typical ranges in Canada for these variables to use in the sensitivity analysis (ranges are from the original 1989 report).

Table 3.3 Location dependent variables for sensitivity analysis.

Variable	Range
F_θ x H_t	40 to 90
T_{bo}	-6 to 5.6
PF	0.5 to 2

Each of the variables were changed one at a time while keeping the other variables equal to the average location values used in the ER calculation. For this analysis, the window properties used were U_{SI}-2.0 (U-0.35), SHGC-0.4 and L_{75} = 0.37 (A3 rating for a standard 1200 mm x 1500 mm window). These properties result in an ER of 19. Note that the focus of this analysis is on the relative change due to the location dependent variables, and the base window inputs are of little significance. The ER was plotted versus each variable individually, and plots are shown in Fig.3.12, Fig.3.13 and Fig.3.14.

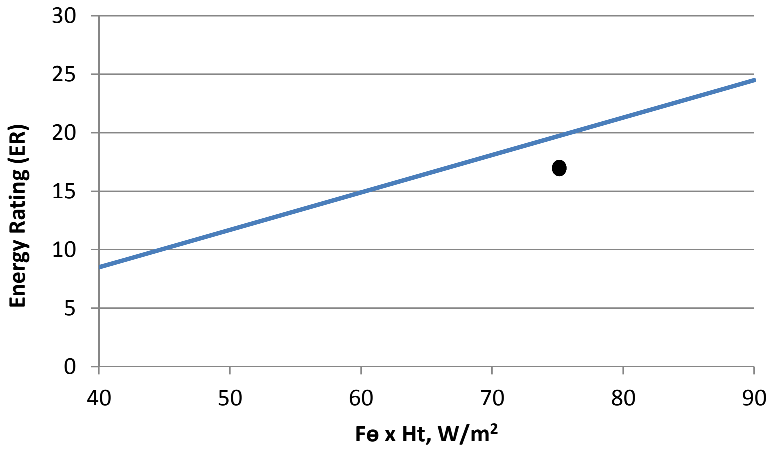


Fig.3.12 Energy Rating versus F_θ x H_t.

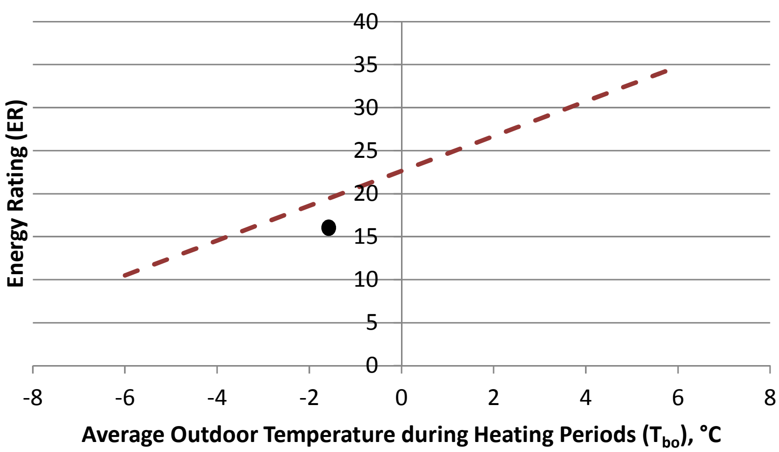


Fig.3.13 Energy Rating versus average outdoor temperature during heating conditions (T_{bo}).

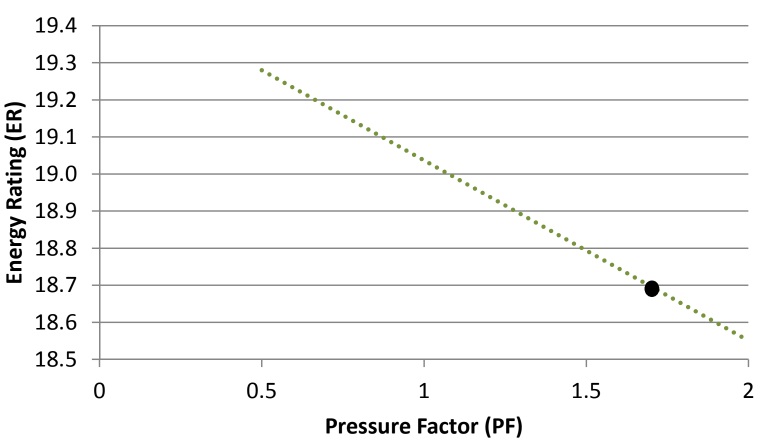


Fig.3.14 Energy Rating versus Pressure Factor (PF).

Changing F_θ x H_t between 40 and 90 varies the ER between 9 and 25 (Fig.3.12). Changing T_{bo} between -6°C and 6°C varies the ER between 11 and 35. Changing the pressure factor between 0.5 and 2 varies the ER between 18.6 and 19.3. The terms F_θ x H_t and T_{bo} have a much greater impact on the ER than the PF. This is similar to the window dependent variables, where it was seen that the SHGC and U-value had a much greater effect on the ER than the air leakage rate. This analysis shows that climates that are warmer, sunnier and less windy would have higher energy ratings if the actual climate values were used.

To compare the impact of changing the three variables on one plot, the ER rating was plotted versus the percent change in each variable (Fig.3.15). The F_θ x H_t and (T_{bi} – T_{bo}) both change the ER at a high rate, though the temperature difference (T_{bi} - T_{bo}) results in the widest range of ER values. The PF has the smallest effect on the ER.

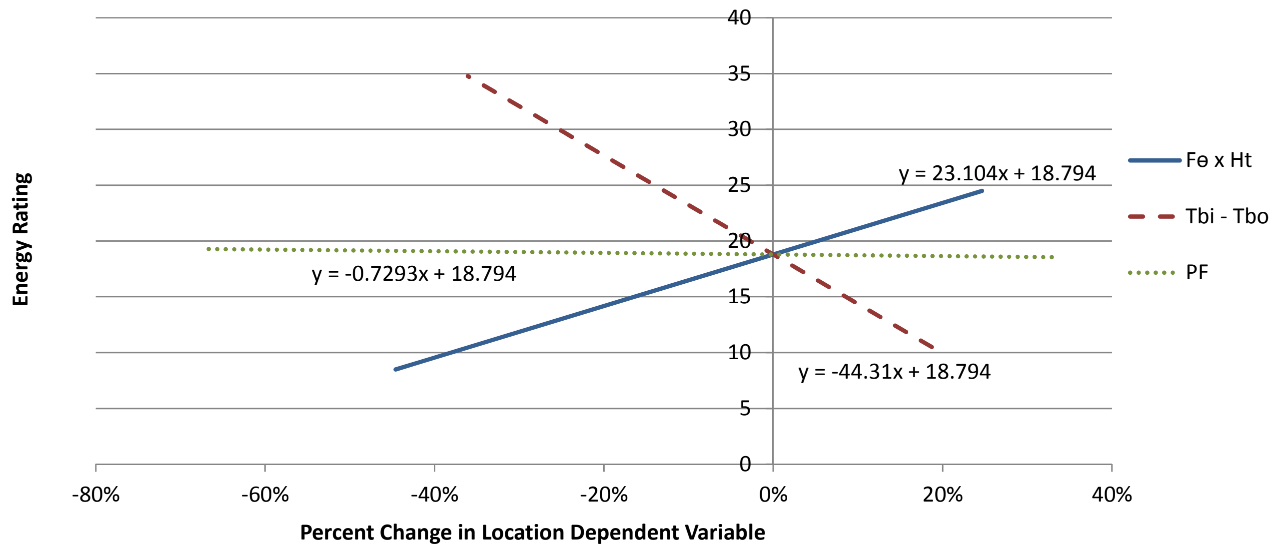


Fig.3.15 Energy rating versus change in location dependent variables.

3.5. Specific Energy Ratings

In general, ERS values should not be directly compared to the ER since the two ratings are calculated slightly differently. However, the ERS equation is more easily used to assess the difference between climates and orientations, since detailed calculations of certain ER variables for each climate (F_θ x H_t) are beyond the scope of this report.

Fig.3.16, Fig.3.17 and Fig.3.18 shows the ERS calculated for different Canadian cities and orientations, using a window with U_{SI}-2.0 (U-0.35) and L_{75}-0.37 L/s-m^2 (A3 for a standard 1200 mm x 1500 mm window). The plots show three different SHGCs: a low value of SHGC-0.25 (Fig.3.16), medium SHGC-0.4 (Fig.3.17), and high SHGC-0.5 (Fig.3.18).

Changing the orientation results in very different ERS values. South-facing windows have the highest ERS values (since they receive the most sun over a year), while north-facing windows receive the least sun and have the lowest ERS values. Climate also makes a difference to the ERS; cold climates and locations that receive less sun tend to have lower ERS values.

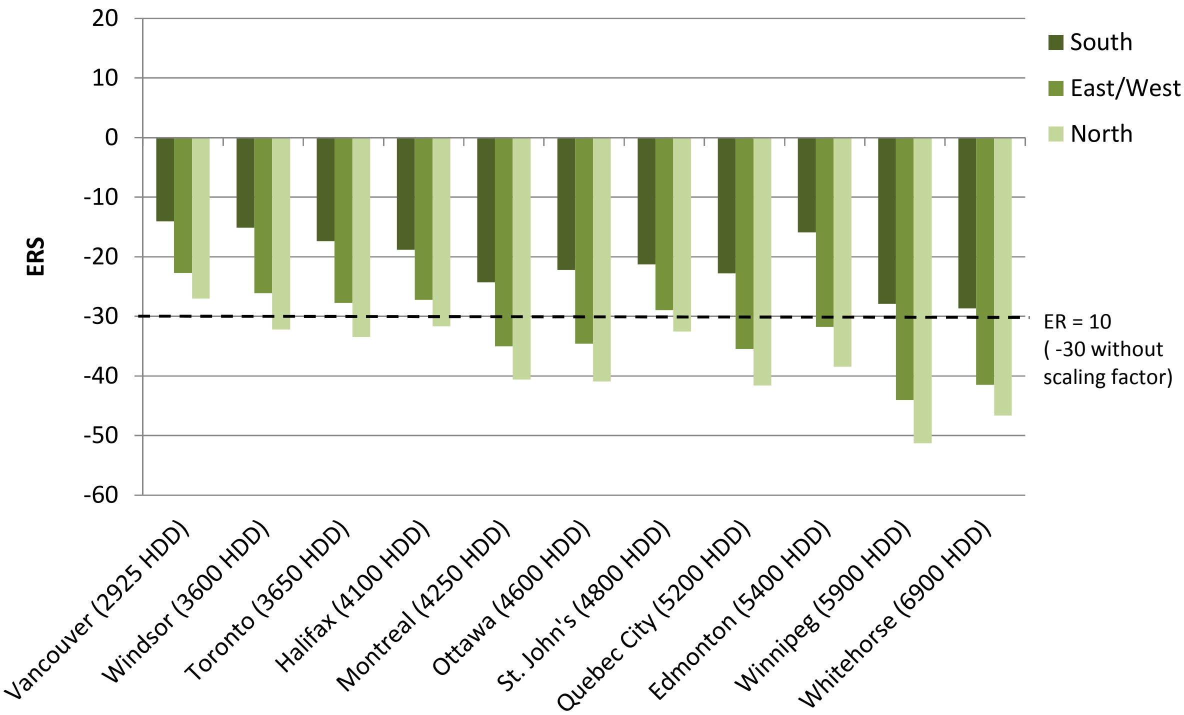


Fig.3.16 Specific Energy Rating (ERS) for Canadian cities at different orientations, SHGC-0.25.

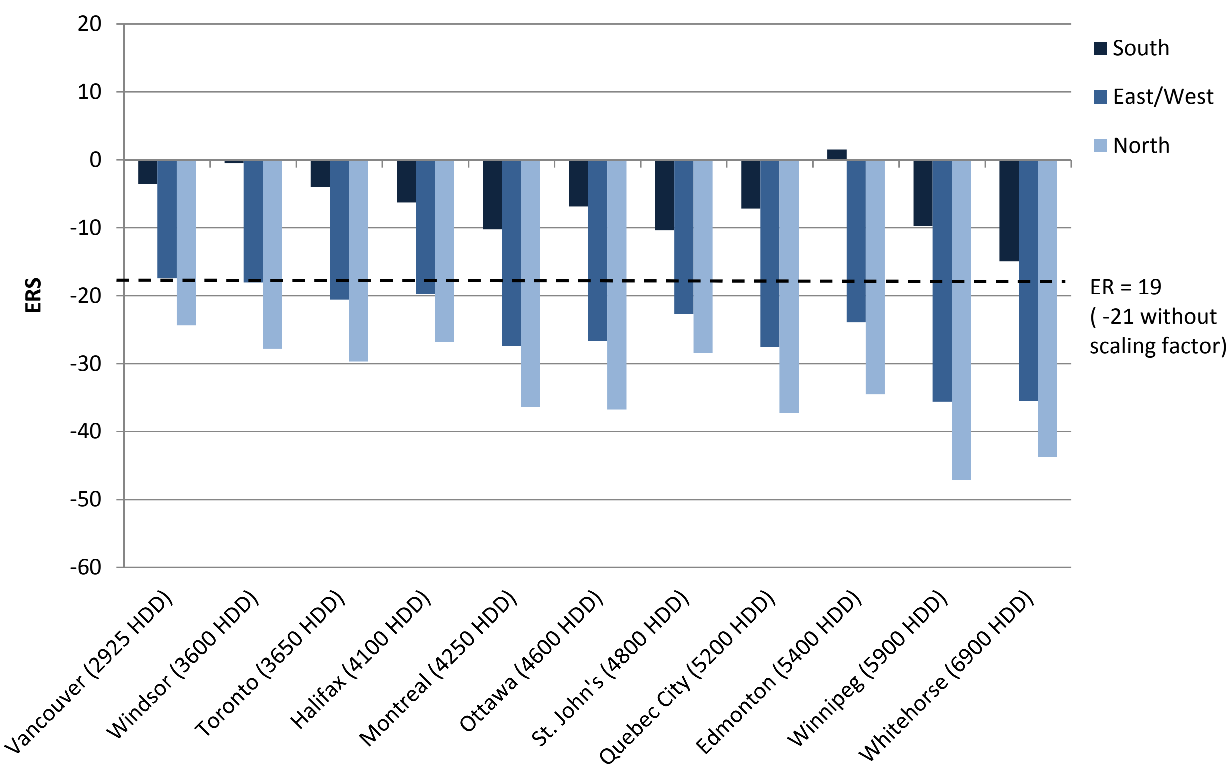


Fig.3.17 Specific Energy Rating (ERS) for Canadian cities at different orientations, SHGC-0.4.

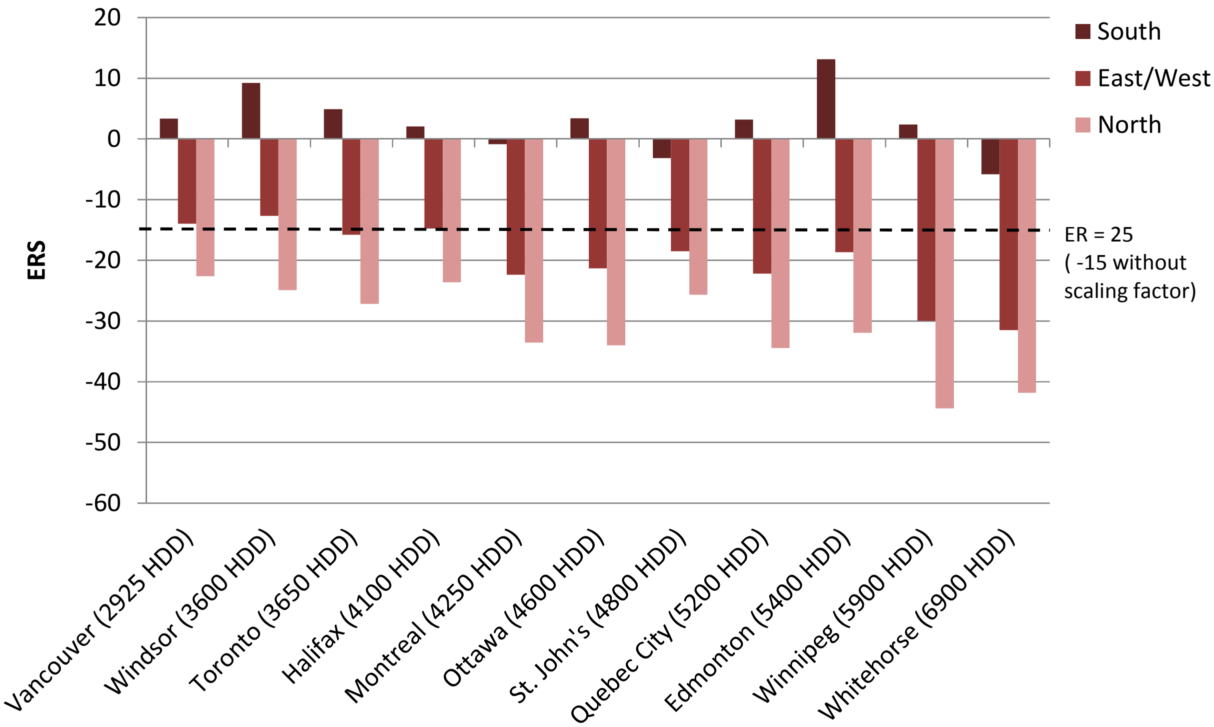


Fig.3.18 Specific Energy Rating (ERS) for Canadian cities at different orientations, SHGC-0.5.

3.6. Summary

The goal of the analysis in this section is to understand the terms and the assumptions in the ER calculation. Each term in the equation was analyzed, and sensitivity analysis was completed for the window dependent and the location dependent variables. Several important observations can be made based on this analysis.

The sensitivity analysis showed that for both the window and location dependent variables, the air leakage term has a relatively small effect on the ER. The calculation of the location dependent variables in the ER development report used several parameters that are now uncommon in the fenestration industry. The location dependent variables were calculated using a window with a U-value of 2.77 W/m^2, a SHGC of 0.58, and an air leakage rate of 6.6 m^3/h-m at 75 Pa. ENERGY STAR® and many building codes require windows with a better performance (for example, the ENERGY STAR® U-value path requires U_{SI}-1.80 for zone A). Also with the development of low-e coating technology many window products have lower SHGCs. It may be worthwhile to investigate the impact of re-calculating the ER location dependent variables as a future project, following the same methodology used in the 1989 study, but using parameters more representative of current construction and technology.

Finally, it is important to note that the ER is calculated differently from the ERS, and the two should not be directly compared or used interchangeably. The ERS uses a different calculation for the solar heat gain and air leakage components. The ERS also does not have the +40 scaling factor that the ER calculation includes. The ERS also varies for different locations and orientations.

3.7. References

ASHRAE. (2009). *2009 ASHRAE Handbook - Fundamentals.* Atlanta.

Canadian Standards Association. (2009). *CSA A440.2-09/A440.3-09 Fenestration energy performance / User guide to CSA A440.2-09 Fenestration energy performance.* Mississauga.

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4. Determination of Housing Archetypes

The original ER development (Enermodal Engineering Ltd., 1989) utilized an archetype house with the parameters shown in Table 4.1.

Table 4.1 Archetype house used in original ER development.

Floor area	200 m^2
Window to floor area, equally distributed in the four cardinal directions	10%
Heating set point	20° C
Cooling set point	26° C
Internal heat gains	14 kWh/day

A number of reports by Enermodal Engineering Ltd. on the ENERGY STAR® technical requirements established archetype houses for evaluating energy consumption of window and glazing options. The most recent report (Enermodal Engineering Ltd., 2011) utilized two housing archetypes, a typical house built in 1975 and a newly constructed house.

For the current research project, three house sizes and two enclosure types will be assessed:

- Single-storey, two-storey, and large two-storey
- Typical existing enclosure parameters and new (current building code) enclosure parameters

Additional parameters will be assessed within these archetypes, including the window to wall ratio and orientation.

4.1. Geometry of House Archetypes

The 2007 Survey of Household Energy Use (Natural Resources Canada, 2010) provides data on the size of houses in Canada (Table 4.2). However, it is important to note that this includes apartment and townhouse dwellings and, therefore, it cannot be used directly to select appropriate sizes of single family dwellings.

Table 4.2 Size of dwellings in Canada (Natural Resources Canada, 2010).

Heated Area of Dwelling	Percentage of Dwellings in Canada
56 m^2 or less (600 sf or less)	7.8%
56 to 93 m^2 (601 to 1,000 sf)	26.8%
93 to 139 m^2 (1,001 to 1,500 sf)	34.0%
139 to 186 m^2 (1,501 to 2,000 sf)	17.2%
186 to 232 m^2 (2,001 to 2,500 sf)	7.6%
232 m^2 or more (2,501 sf or more)	6.5%

Data is also provided by dwelling construction data. The data shows a clear trend in increasing sizes with newer dwellings. The number of dwellings in the group from 56 m^2 to 93 m^2 decreases for more recent years of construction, while the number of dwellings in the categories above 139 m^2 generally increases with year of construction.

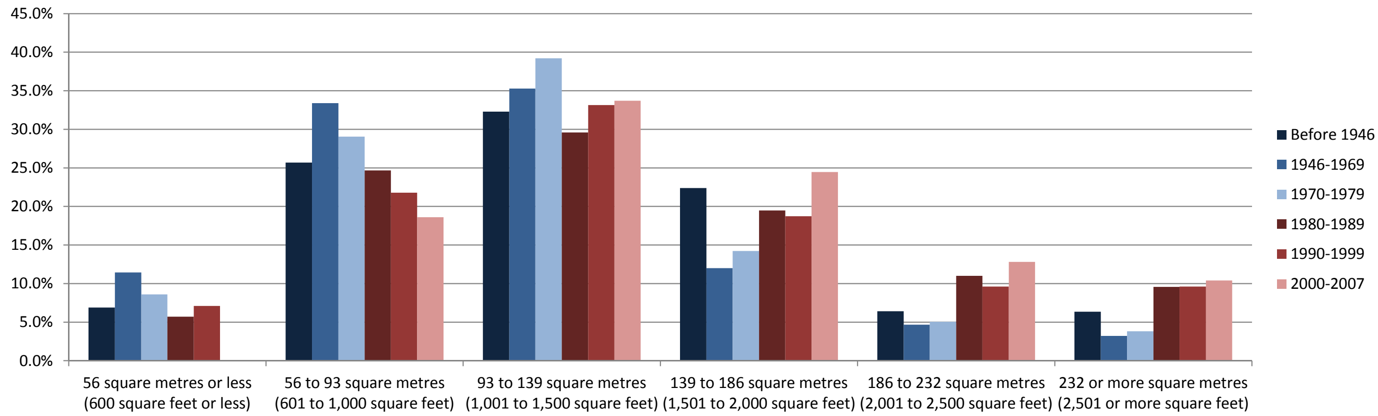

Fig.4.2 Heated area by dwelling construction date.

In order to investigate a variety of house sizes, three house types will be simulated: one single-storey house plus a smaller and larger two-storey house. The larger two-storey archetype was chosen to reflect the trend towards larger houses, particularly in certain geographic regions such as south-western British Columbia. Basic geometries of the three archetypes are shown in Table 4.3. The archetype houses used for the NBC energy code proposal, developed based on an analysis of the EnerGuide database of houses, included 11 houses ranging in size from 50 m^2 to 340 m^2 (not including the basement). Simulations will be completed to determine whether the archetype house has an impact on energy consumption related to windows. The archetype houses will also have basements, though the impact of basements on window energy consumption will be assessed in the modeling.

Table 4.3 Basic geometry of archetype houses.

	Single-Storey House	Two-Storey House	Large Two-Storey House
Above grade floor area	100 m^2 (1,100 sf)	180 m^2 (1,940 sf)	280 m^2 (3,000 sf)
Geometry	Square	Square	Square
Overall window to wall ratio	15% in base model Vary 5% to 30%	15% in base model Vary 5% to 30%	15% in base model Vary 5% to 30%
Window to wall ratio by elevation	Equal distribution in base model Vary with greater distribution in each cardinal direction	Equal distribution in base model Vary with greater distribution in each cardinal direction	Equal distribution in base model Vary with greater distribution in each cardinal direction
Number of doors	2	2	3
Number of skylights	None	None	None

Another important parameter in the definition of the archetype houses is the amount of window area. This can generally be reported in two ways: window to wall area or window to floor area. The 2011 National Energy Code of Canada for Buildings uses window to wall area, called FDWR (fenestration and door area to gross wall area ratio). Therefore, fenestration to gross wall area will be used as the primary ratio of identifying the amount of fenestration on a particular archetype. However, the results can also be assessed as a function of window to floor area during the modeling work. The terms “fenestration to wall area” and “window to wall area” are used interchangeably, and include all glazed fenestration (windows and sliding glass doors). Opaque doors will be considered separately in subsequent sections.

The proposed NBCC Part 9 changes for energy efficiency state that the minimum U-values were selected based on common fenestration area to gross wall area ratios ranging between 8% and 25%. The archetype houses used for the NBC energy proposal had an average window to wall ratio of 16%, with a high of 24% and a low of 7%, including door area. Therefore, a value of 15% will be used as the baseline value, and analyze ratios from 5% up to 30% (a higher top end is chosen to reflect certain geographic locations that typically have higher window to wall ratios such as south-western British Columbia).

4.2. Enclosure Parameters for 'Existing' Archetype

A typical existing house would have different levels of insulation in various geographic areas. For example, in Vancouver, many existing houses still have little attic insulation and single glazed windows due to the mild climate. However, in colder climates most existing houses have 2x4 walls filled with fibreglass batt insulation, basement insulation, double glazed windows and better airtightness.

The enclosure parameters for existing houses are shown in Table 4.4.

Table 4.4 Building enclosure parameters for a typical existing house.

Climate	Below Grade Walls	Above Grade Walls	Attic	Windows	Doors	Airtightness (ACH @ 50 Pa)
Mild (<4000 HDD)	2x4 with batt insulation	2x4 with batt insulation	R_{SI}-2.1 (R12) insulation	Single glazed, wood-frame	Solid wood	7
Cold (4000 to 6500 HDD)	2x4 with batt insulation	2x4 with batt insulation	R_{SI}-3.5 (R20) insulation	Double glazed, vinyl frame	Solid wood	4
Northern (>6500 HDD)	n/a	2x6 with batt insulation	R_{SI}-7.0 (R40) insulation	Double glazed, vinyl frame	Solid wood	3

4.3. Enclosure Parameters for 'New' Archetype

Building enclosure thermal performance requirements differ across the country for various code jurisdictions. Some provinces have a provincial building code, including Quebec, Ontario, Alberta, and British Columbia. In addition, the City of Vancouver has its own building by-law. Other provinces reference the NBCC, but have specific provincial amendments, including Nova Scotia and Manitoba. The remaining provinces and territories adopt the National Building Code of Canada (NBCC). The current version of the NBCC does not include enclosure R-value or U-value requirements, however, the proposed 2012 changes do include such requirements. Insulation code requirements are shown in Table 4.5.

Table 4.5 Canadian building code enclosures requirements for new Part 9 houses.

Location	Below Grade Wall Insulation m^2-K/W (hr-ft^2-F/Btu)	Above Grade Wall Insulation, m^2-K/W (hr-ft^2-F/Btu)	Attic Insulation, m^2-K/W (hr-ft^2-F/Btu)	Window U-Value, W/m^2-K (Btu/hr-ft^2-F)	Door U-Value, m^2-K/W (hr-ft^2-F/Btu)	Skylight U-Value, W/m^2-K (Btu/hr-ft^2-F)
NBCC 2012 Proposed Changes[3]						
Zone 4, <3000 HDD	2.05 (11.6)	2.93 (16.6)	6.90 (39.2)	1.80 (0.32)	1.80 (0.32)	2.90 (0.51)
Zone 5, 3000-3999 HDD	3.17 (18.0)	3.16 (17.9)	6.90 (39.2)	1.80 (0.32)	1.80 (0.32)	2.90 (0.51)
Zone 6, 4000-4999 HDD	3.17 (18.0)	3.16 (17.9)	8.6 (48.8)	1.60 (0.28)	1.60 (0.28)	2.70 (0.48)
Zone 7a, 5000-5999 HDD	3.17 (18.0)	3.16 (17.9)	8.66 (49.2)	1.60 (0.28)	1.60 (0.28)	2.70 (0.48)
Zone 7b, 6000-6999 HDD	3.17 (18.0)	3.27 (18.6)	10.43 (59.2)	1.40 (0.25)	1.40 (0.25)	2.40 (0.42)
Zone 8, >7000 HDD	3.57 (20.3)	3.27 (18.6)	10.43 (59.2)	1.40 (0.25)	1.40 (0.25)	2.40 (0.42)
Current Provincial Code Requirements						
Nova Scotia[4]	3.52 (20.0)	4.23 (24.0)	7.0 (39.7)	1.8 (0.32) or ER >25 op. / >35 fixed	R_{SI}-0.7 (R-4.0)	2.6 (0.46)
Quebec, <=6200 HDD[5]	2.99 (17.0)	4.31 (24.5)	7.22 (41.0)	2.0 (0.35) and ER > 21 or 1.8 (0.32) and ER > 13	0.9 (0.16)	2.85 (0.50)
Quebec, >6200 HDD[5]	2.99 (17.0)	5.11 (29.0)	9.00 (51.1)	2.0 (0.35) and ER > 25 or 1.6 (0.28) and ER >17	0.8 (0.14)	2.7 (0.48)
Ontario Zone 1[4,6] (<5000 HDD)	3.52 (20.0)	4.23 (24.0) gas 5.11 (29.0) electric	8.81 (50.0)	1.6 (0.28) or ER > 25	R_{SI}-0.7 (R-4.0)	2.8 (0.49)
Ontario Zone 2[4,6] (>5000 HDD)	3.52 (20.0)	5.11 (29.0)	8.81 (50.0)	1.6 (0.28) or ER > 25	R_{SI}-0.7 (R-4.0)	2.8 (0.49)
Manitoba[4]	3.50 (19.9)	3.5 (19.9)	8.8 (50.0)	prescriptive[7]	n/a	n/a
Alberta	1.40 (7.9)	2.10	6.00	Double glazed		
British Columbia[4]	2.10 (11.9)	3.5 (19.9)	7.7 (43.7)	2.0 (0.35)	R_{SI}-0.88 (R-5.0)	3.1 (0.55)
Vancouver (VBBL)[4]	2.10 (11.9)	3.5 (19.9)	7.0 (39.7)	2.0 (0.35)	R_{SI}-0.88 (R-5.0)	3.1 (0.55)

[3] Requirements shown are for houses that have an HRV. Alternate compliance values are given for houses without an HRV.
[4] R-values are for insulation only (nominal).
[5] Quebec fenestration performance requirements are proposed, currently under public review.
[6] Multiple compliance paths are available.
[7] Minimum prescriptive window requirements in Manitoba are sealed double glazed, 10mm gap, insulated spacer, one low-e coating.

4.4. Heating, Cooling and Ventilation Systems

The 2007 Survey of Household Energy Use (Natural Resources Canada, 2010) provides a breakdown of primary energy source used for heating in houses across Canada, shown in Table 4.6. Based on these breakdowns, electricity and natural gas heating systems will be investigated for all geographic areas with the exception of Atlantic Canada. For Atlantic provinces, electric and heating oil systems will be investigated. The impact of changing the heating system fuel type will be investigated through initial energy simulations to determine whether it is necessary to simulate multiple heating systems for every case. Electrically heated houses will be simulated with electric baseboards, and gas or oil heating systems will be simulated with a forced air furnace since these are likely the most common electric, gas and oil heating systems in Canadian houses.

Table 4.6 Main energy source used for heating (Natural Resources Canada, 2010).

	Canada	Atlantic	Quebec	Ontario	Manitoba / Saskatchewan	Alberta	British Columbia
Electricity	36%	43%	77%	19%	30%	12%	35%
Natural Gas	42%	-	4%	62%	66%	82%	54%
Heating Oil	7%	35%	9%	6%	-	-	4%
Other	15%	22%	10%	13%	4%	6%	7%

Table 4.7 shows the percentage of dwellings with air conditioning in Canada (Natural Resources Canada, 2010). Air conditioners are most common in Ontario where 80% of dwellings have either central or room air conditioning. Air conditioning is also common in Quebec where 47% of dwellings have air conditioning. In the remaining provinces about 20% of dwellings have air conditioning. Initial simulations will be completed with and without central air conditioning for all locations.

Table 4.7 Percentage of dwellings with air conditioning (Natural Resources Canada, 2010).

	Canada	Atlantic	Quebec	Ontario	Manitoba / Saskatchewan	Alberta	British Columbia
Central air conditioner	32%	4%	19%	58%	46%	16%	11%
Window or room air conditioner	20%	13%	28%	22%	24%	5%	9%
No air conditioner	48%	83%	53%	20%	30%	79%	80%

It is important to consider the zoning and control of the mechanical systems in the simulation work. The majority of central furnace and air conditioning systems are controlled by a single thermostat in the house. Electric baseboard heating systems commonly have multiple thermostats for different zones or spaces within the house.

Table 4.8 shows current code requirements for HVAC equipment. Existing houses likely have a range of furnace efficiencies. An efficiency of 80% will be used for existing houses, assuming that older inefficient furnaces will need to be replaced soon if they haven't already been replaced.

Ventilation in existing houses is typically provided by operable windows and intermittent exhaust fans (bathroom fans and kitchen range hoods), and/or by direct ventilation to the furnace. New houses may rely on operable windows and exhaust fans, or they may have a Heat Recovery Ventilator (HRV) or an Energy Recovery Ventilator (ERV). Some jurisdictions require an HRV with a minimum heat recovery efficiency (see Table 4.8).

Table 4.8 Minimum code HVAC efficiency requirements for new houses.

Location	Oil Furnace Efficiency [AFUE]	Gas Furnace Efficiency [AFUE]	Air Conditioner Efficiency	Ventilation Heat Recovery
NBCC 2012 Proposed Changes	85	92	Various types; e.g. Single package <19 kW: SEER = 14, EER = 11.5	60% efficient HRV[8]
Quebec	-	-	-	-
Ontario	n/a	90[9]	n/a	HRVs required for some compliance paths
Manitoba	n/a	94	n/a	55% efficient HRV, airflow >28 L/s
British Columbia	n/a	90	n/a	n/a
Vancouver	n/a	90	n/a	n/a

4.5. Exterior Shading

The impact of exterior shading should be investigated in the energy simulations. A house could have a variety of shading conditions:

- No shading
- Shading on either side from neighbouring houses
- Shading from trees (may or may not lose their leaves in the winter)
- Fixed exterior shading (with various dimensions)
- Operable exterior shading (with various control schemes)

4.6. Thermal Mass

The majority of Canadian houses have a similar level of thermal mass since most houses are constructed with wood framing and insulated with fibreglass batt insulation. The impact of thermal mass on window energy performance and the Energy Rating could be investigated for houses that are built with greater amounts of thermal mass. For example, houses constructed from Insulating Concrete Forms (ICF) would have a greater thermal mass than typical wood-frame construction. Or, houses could incorporate phase change material (PCM) in the floor or other enclosure assemblies to increase their thermal mass. The impact of these two options will be investigated.

4.7. Other Inputs

Additional inputs that will be required for the energy simulation of the archetype houses include temperature set points, and domestic hot water. EnerGuide standard conditions will be used as the basis for these inputs, with the exception of base electrical loads. EnerGuide standard conditions are shown in Table 4.9.

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[8] HRV efficiency requirement is 60% at 0°C for climates with a January 2.5% design temperature >-10°C, and 60% at 0°C, 55% at -25°C for climates with a January 2.5% design temperature <-10°C

[9] Efficiencies of 0.78 to 0.9 are permitted with higher thermal performance requirements for enclosure components.

Table 4.9 EnerGuide and R2000 standard conditions.

Main floor set point temperature	21°C
Hot water consumption	225 L/day
Hot water temperature set point	55 C
Occupancy	2 adults and 2 children, all 50% of the time
Base electrical loads	Lights 3 kWh/day Appliances 14 kWh/day Other 3 kWh/day External use 4 kWh/day (Total internal heat gains: 20 kWh/day)

Further discussion on the lighting and plug load inputs is required. The EnerGuide base electrical loads include 3kWh/d for lighting, 14 kWh/d for appliances, and 3 kWh/d for other electrical loads, for a total of 20 kWh/d internal electrical loads (this is the same as the R2000 program base electrical loads). The original ER study used a value of 14 kWh/d for internal gains, much lower than the EnerGuide standard conditions. The report states that 14 kWh/d was chosen since it is the value used for the R2000 program, however, it is not known whether this value increased since the 1989 study was completed, or whether the additional 6 kWh/d for "lights and other" in the current R2000 guidelines were not used for some reason.

The internal gains must be analyzed separately in terms of people, lighting and appliance/plug loads (this is because of how the hourly energy simulation program models these three internal gain sources). Starting with people loads, ASHRAE provides standard internal gain factors for people at a variety of activity levels that are typically used with hourly energy simulations. It is not known whether internal gains for people were accounted for in the original study as part of the 14 kWh/d gain value.

Regarding lighting and appliance/plug loads, several data sources were reviewed: the EnerGuide and R2000 standard conditions, data provided by Hydro Québec, and data referenced in the 2009 ASHRAE Handbook – Fundamentals. ASHRAE references a report by Building America to calculate typical residential lighting, appliance and plug loads, *Building America Research Benchmark Definition* (Hendron, 2005).

For lighting, the standard EnerGuide and R2000 lighting gains value is 3 kWh/d. Data provided by Hydro Québec also indicates an average lighting energy consumption of 3.0 kWh/d. The Building America report gives a calculation that incorporates the house floor area. For comparison, using the Building America benchmark gives 3.6 kWh/d for a smaller house (100 m^2) and 5.9 kWh/d for a larger house (200 m^2). Based on these three data sources, low and high values of 3 kWh/d and 6 kWh/d will be investigated for household lighting consumption for all archetypes. In reality, larger houses may use more lighting energy than smaller houses, however, the relationship is likely not linear and a statistical study of lighting energy consumption in houses is beyond the scope of this project. (An alternate approach would be to use the Building America calculation to determine a different lighting load for each size of archetype house; however, this would result in higher lighting gains than the EnerGuide standard conditions and the Hydro Québec data.)

For appliance and plug loads, the standard EnerGuide and R2000 gains value is 17 kWh/d (14 kW/d for appliances plus 3 kWh/d for other). Hydro Québec data indicates an average appliance/plug load of 12.8 kWh/d. The Building America report gives a calculation that incorporates the size of the house, resulting in 11.0 kWh/d for a smaller house (100 m^2) and 17.0 kWh/d for a larger house (200 m^2). As with lighting, appliance/plug load consumption may increase with house size though likely not linearly. Using a single value such as the EnerGuide conditions or Hydro Québec data for all archetypes may not appropriately represent different sizes of archetype houses. Low and high values of 11 kWh/d and 17 kWh/d will be investigated for all archetype sizes. (An alternate approach would be to use the Building America calculation to determine a different lighting load for each size of archetype house.)

An additional factor to consider in the discussion of lighting and plug loads is that the hourly energy simulation program requires the internal gain inputs in the form of a power density (W/m^2) plus a time of use schedule. This method of input is well suited to commercial buildings that typically run on a fairly regular operating schedule, where lights and equipment are either on or off during standard hours. For houses, occupancy schedules will vary greatly depending on the homeowners, and even when the house is occupied it is likely that not all lights, appliances and electronics will be on at the same time. This makes the use of standard W/m^2 lighting and plug load terms inappropriate (e.g. ASHRAE standard lighting power densities). To work around this issue, the lighting and appliance/plug load gains will be based on the kWh per day data discussed previously since reliable data for houses exists in this form. A typical time of use schedule will be chosen, and the average W/m^2 lighting and appliance/plug loads will be back-calculated so that the total daily lighting and appliance/plug consumption adds up to the values discussed above when simulated with the particular schedule.

4.8. References

Enermodal Engineering Ltd. (1989). *Calculating the Window Energy Rating.* Waterloo.

Hendron, R. (2005). *Building America Research Benchmark Definition, Version 3.1.* Golden, Colorado: National Renewable Energy Laboratory.

Natural Resources Canada. (2010). *Survey of Household Energy Use 2007.* Ottawa.

5. Geographic Locations

The original ER development report (Enermodal Engineering Ltd., 1989) looked at weather data for five cities to determine a methodology for selecting location dependant variables: Ottawa, Vancouver, Albuquerque, Miami and Winnipeg. Once a methodology had been selected, subsequent calculations were performed for a larger group of 24 cities, 14 in Canada and 10 in the United States. The report states that locations with heating degree day values between 4000 and 6200 were averaged to determine the weather conditions for use in the ER calculation. Of the Canadian cities, this means that 11 were averaged, with Vancouver, Windsor and Whitehorse omitted from the average (two US cities were also included in the average).

Energy flow through windows depends primarily on three factors: conduction, solar heat gain and air leakage (also the three components of the ER equation). With respect to climate, these are primarily affected by the outdoor temperature and the amount of solar radiation that reaches the window. Therefore, geographic locations will be grouped based on their heating degree days (HDD), cooling degree days (CDD) and solar radiation. These three factors may be used to reduce the number of cities to be simulated in order to decrease the number of simulations. Average monthly global solar radiation data (Fig.5.1) was obtained from the HOT2000 v10.51 weather file, which comes from the Atmospheric Environmental Services (AES) of Environment Canada. Note this data is only used for the purpose of grouping cities with similar climates, it is not being relied upon for energy simulations or analysis. Table 5.1 shows heating degree day (HDD) and cooling degree day (CDD) values for Canadian cities, with HDDs from the 2005 NBCC and CDDs from the 2009 ASHRAE handbook of fundamentals.

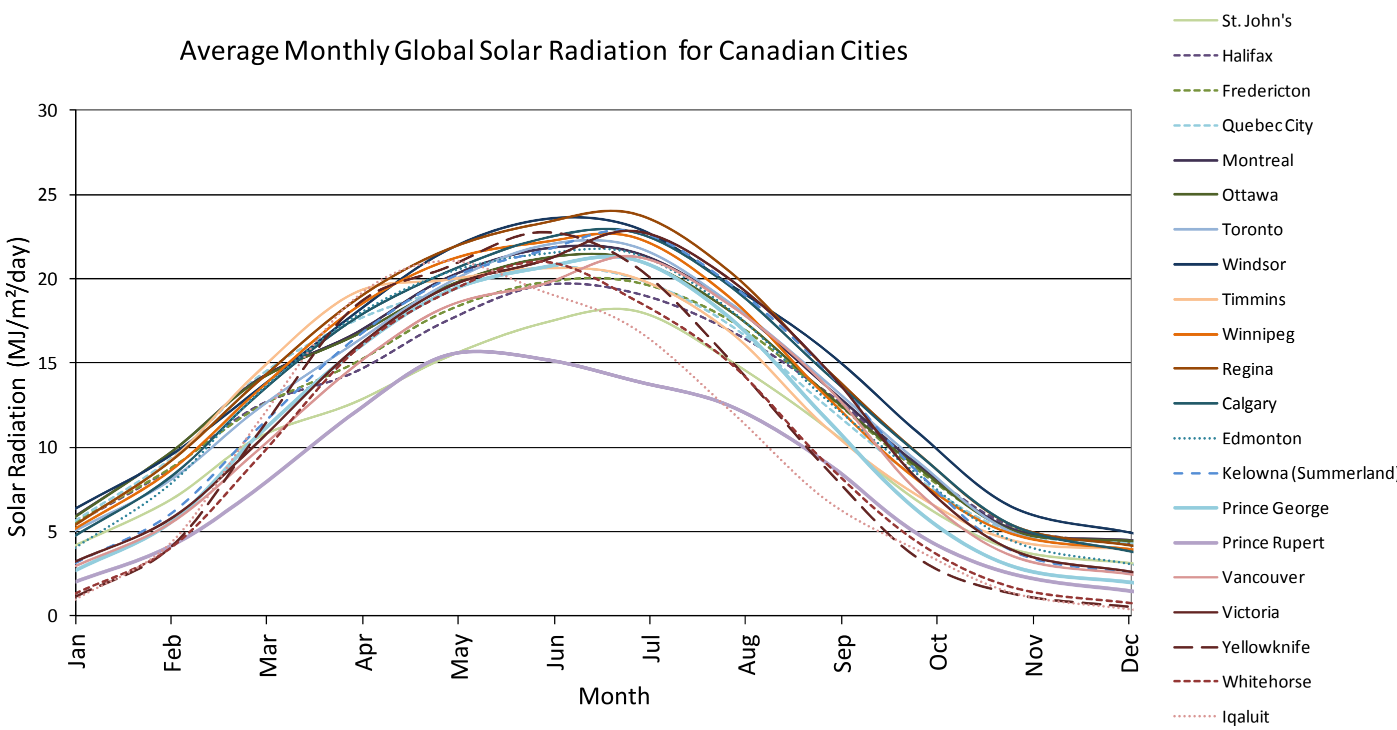


Fig.5.1 Average monthly global solar radiation for various Canadian cities (HOT2000 weather file).

Table 5.1 Heating and cooling degree day data for Canadian cities.

	HDD18[10]	CDD18[11]
St. John’s	4800	28
Halifax	4100	98
Fredericton	4650	132
Quebec City	5200	132
Montreal	4250	217
Ottawa	4600	236
Toronto	3650	237
Windsor	3600	418
Timmins	6200	84
Winnipeg	5900	168
Regina	5750	126
Calgary	5200	37
Edmonton	5400	63
Kelowna	3600	124
Prince George	5250	19
Prince Rupert	4050	No Data
Vancouver	2925	69
Victoria	2950	22
Yellowknife	8500	33
Whitehorse	6900	6
Iqaluit	10050	0

In order to compare the climate of different Canadian cities, the locations were grouped by heating degree days and average monthly global solar radiation was plotted for each group. These plots are shown in Fig.5.2 through Fig.5.8.

The plots and associated HDD groupings may be used to identify locations that do not need to be simulated twice (i.e. if two locations have similar HDD, CDD and solar radiation then only one may be simulated as they will perform similarly). Using the plots below, the locations for simulation were narrowed to 13 cities, shown in Table 5.2. An initial simulation will be completed for each location in the larger list of cities to confirm that the groups perform similarly.

[10] HDD values are from the 2005 National Building Code of Canada, Division B, Appendix C.
[11] CDD values are from the 2009 ASHRAE handbook of fundamentals.

Table 5.2 Canadian cities for energy simulations.

HDD Group	Cities for Simulation
<3500	Vancouver
3500 to 4000	Toronto, Kelowna
4000 to 4500	Montreal, Halifax, Prince Rupert
4500 to 5000	Ottawa, St. John’s
5000 to 5500	Quebec City, Edmonton
5500 to 6500	Timmins, Winnipeg
>6500	Yellowknife

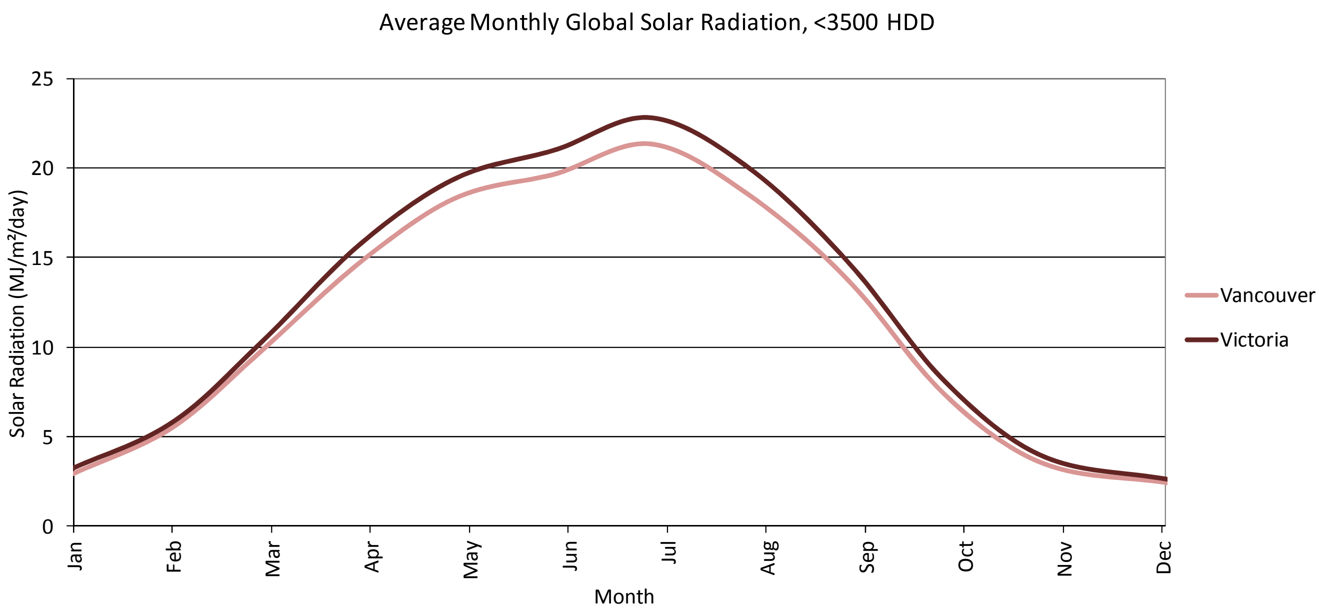


Fig.5.2 Average monthly global solar radiation for cities with <3500 HDD.

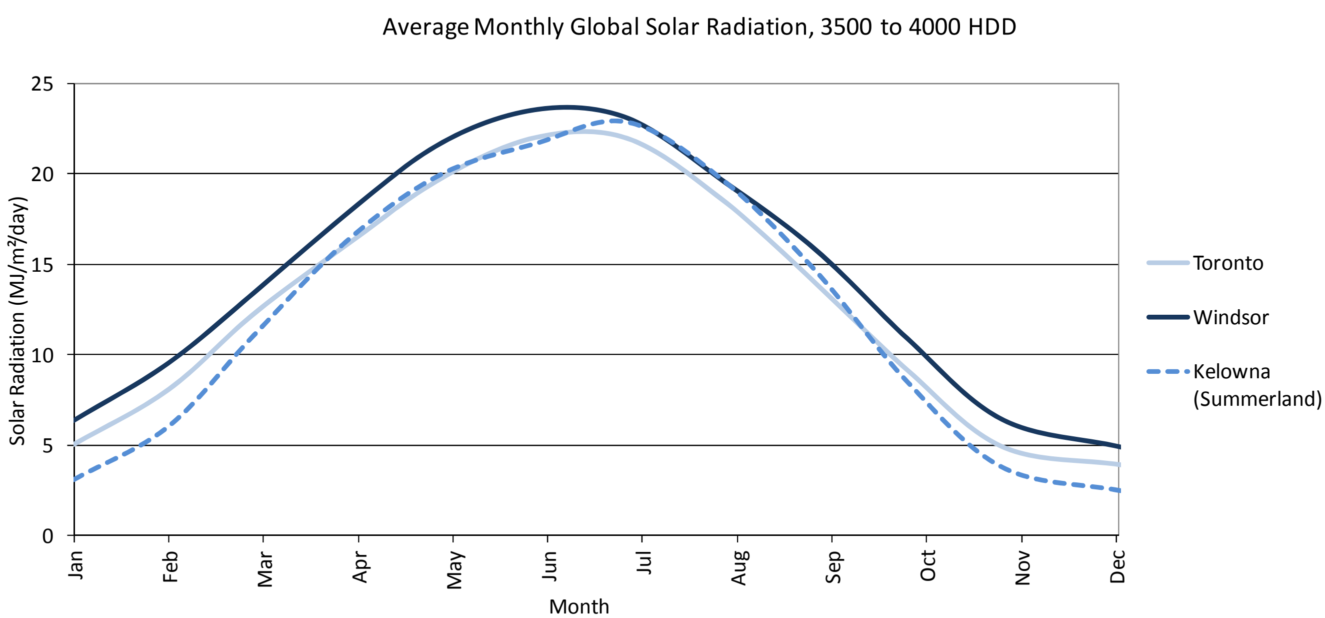


Fig.5.3 Average monthly global solar radiation for cities with 3500 to 4000 HDD.

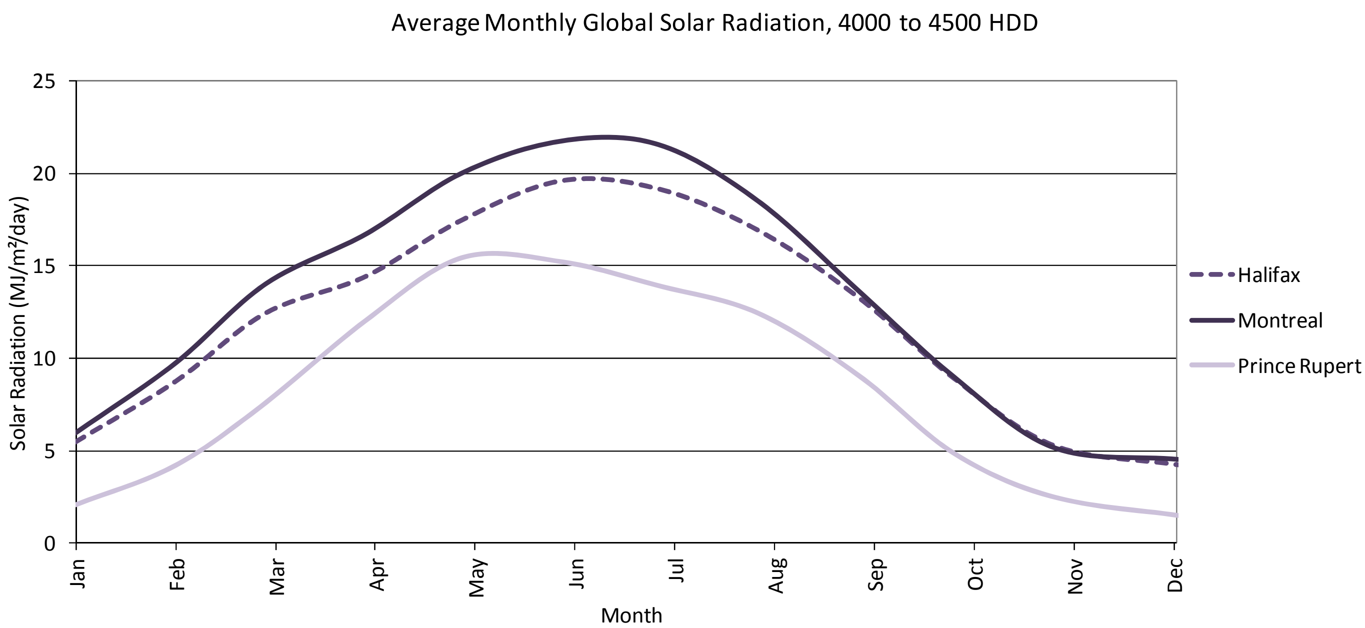


Fig.5.4 Average monthly global solar radiation for cities with 4000 to 4500 HDD.

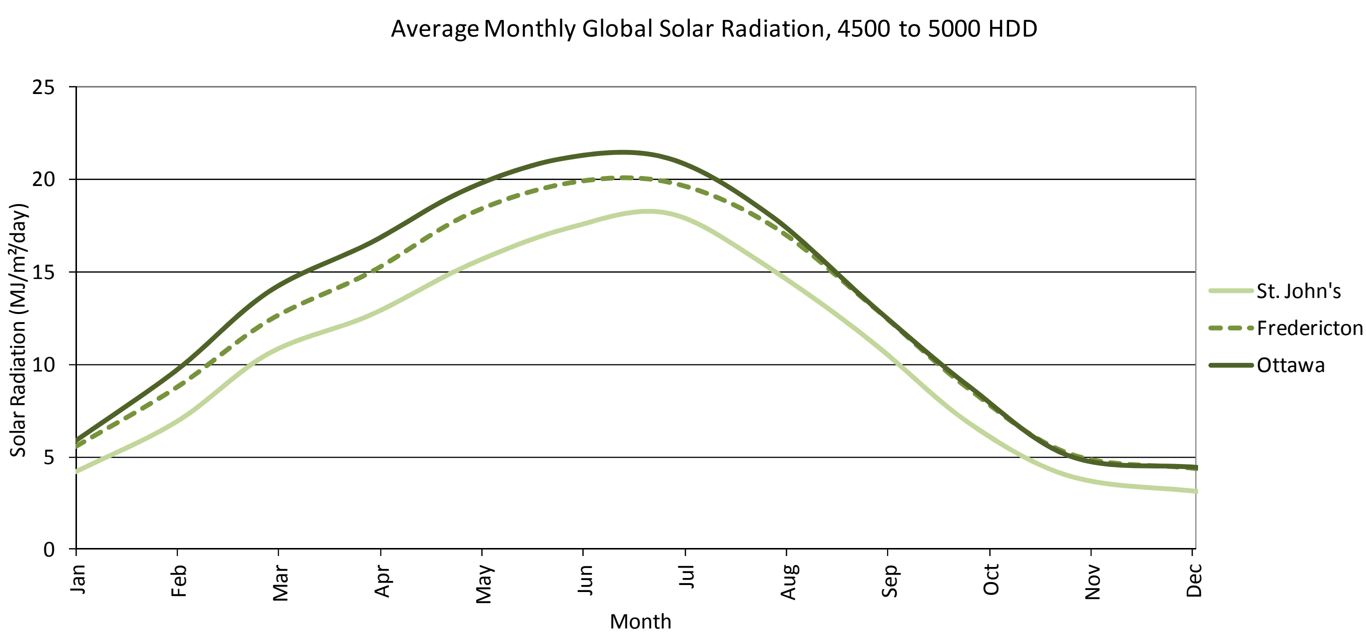


Fig.5.5 Average monthly global solar radiation for cities with 4500 to 5000 HDD.

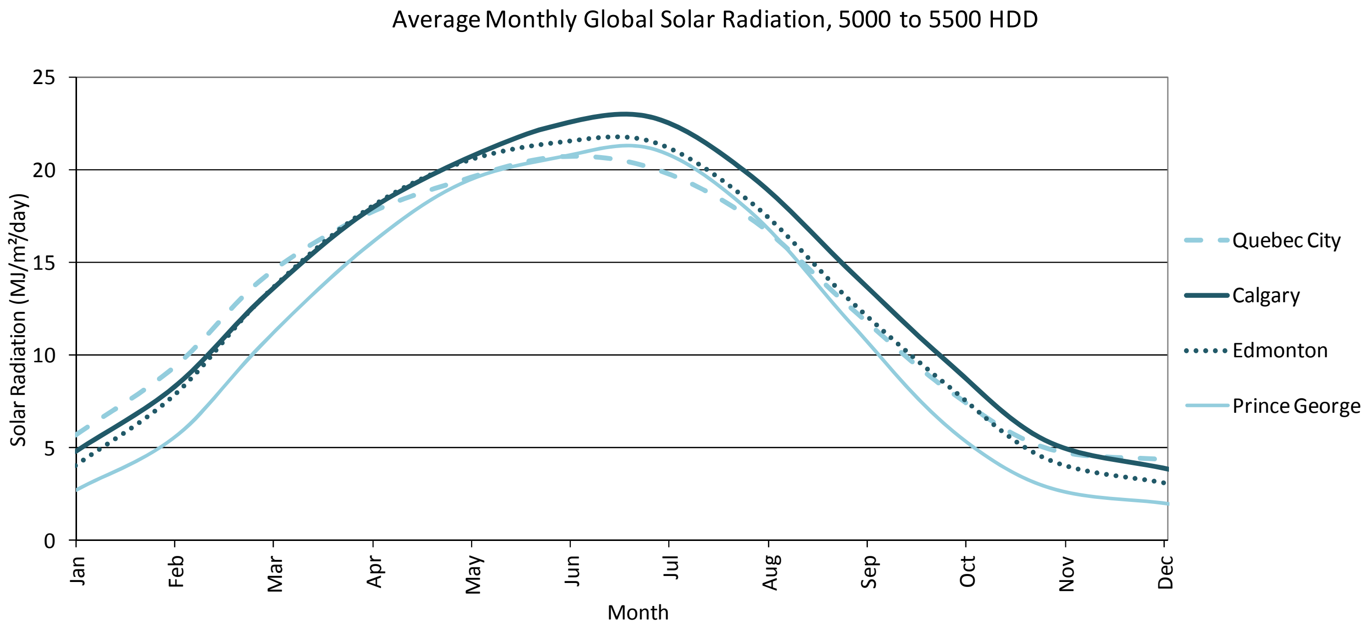


Fig.5.6 Average monthly global solar radiation for cities with 5000 to 5500 HDD.

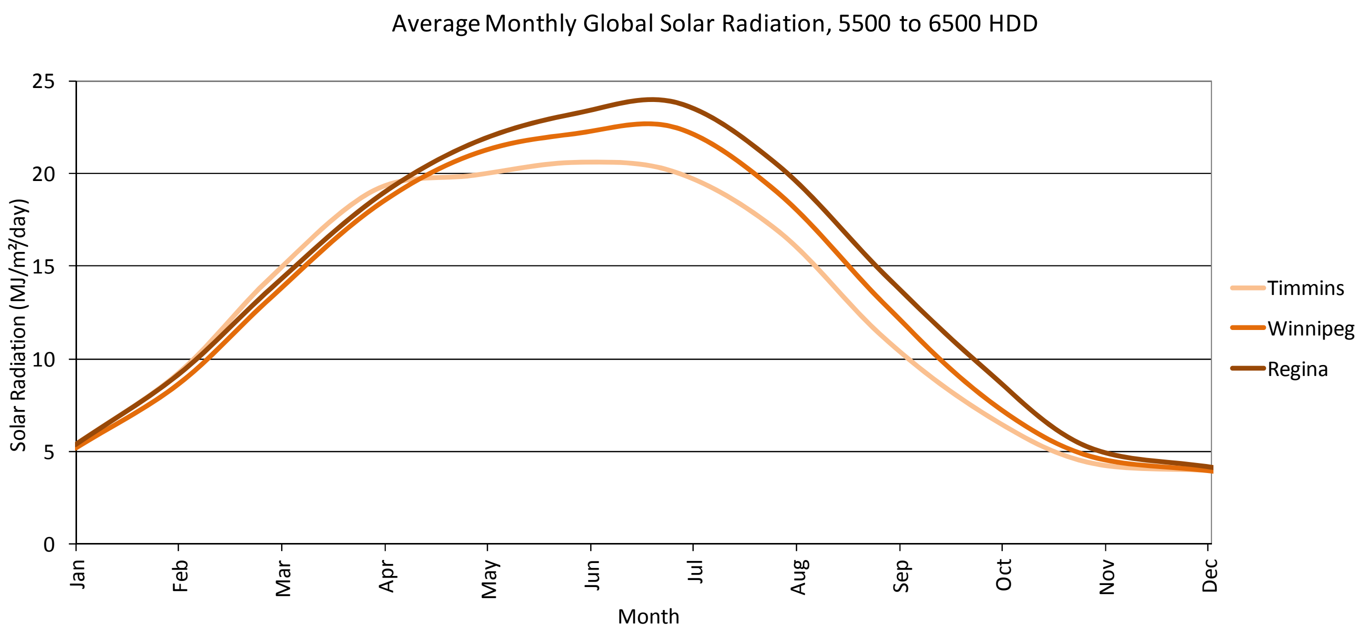


Fig.5.7 Average monthly global solar radiation for cities with 5500 to 6500 HDD.

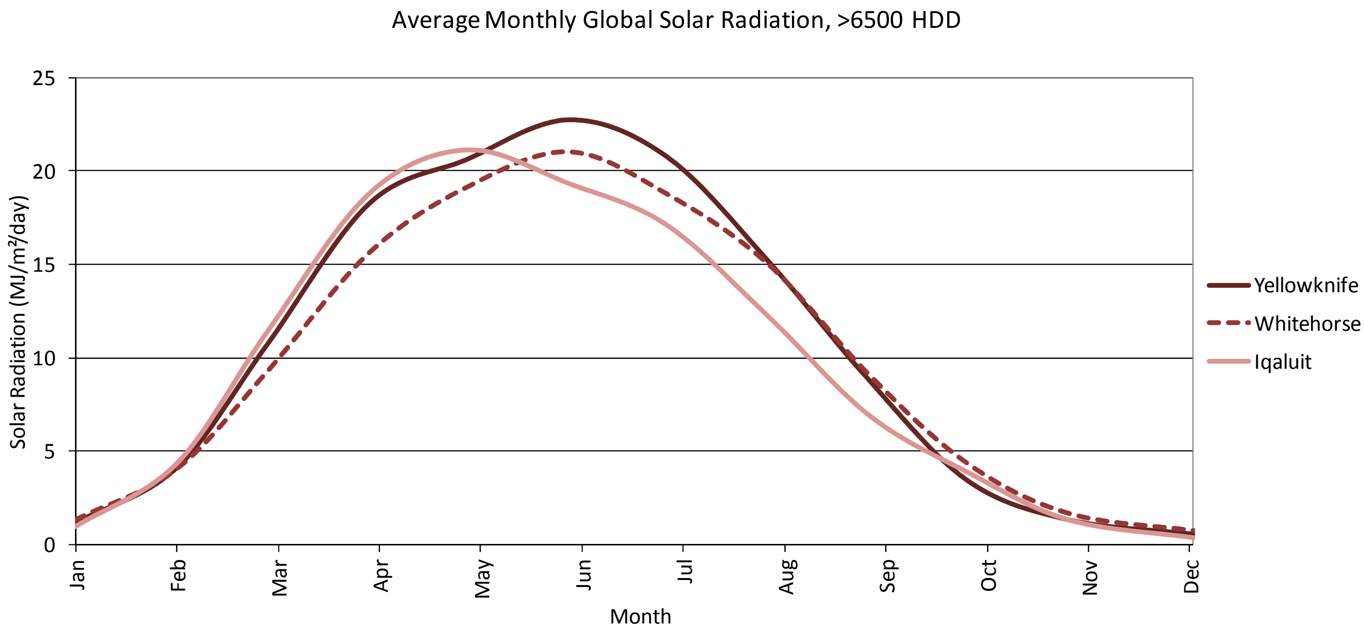


Fig.5.8 Average monthly global solar radiation for cities with >6500 HDD.

5.2. Climate Zones

Two groups of climate zones need to be considered in this study, ENERGY STAR® climate zones and NBCC climate zones. The current ENERGY STAR® requirements include four climate zones in Canada,

- Zone A (<3500 HDD)
- Zone B (3500 to 5500 HDD)
- Zone C (5500 to 8000 HDD)
- Zone D (>8000 HDD)

It has been proposed to change the ENERGY STAR® climate zones to three zones in Canada,

- Zone 1 (<4000 HDD but limited to south-western BC even though parts of southern Ontario could be included)
- Zone 2 (4000 to 6500 HDD)
- Zone 3 (>6500 HDD)

The proposed 2010 NBCC changes, which will replace the 1997 National Energy Code for Houses (NECH), include six zones,

- Zone 4 (<3000 HDD)
- Zone 5 (3000 to 3999 HDD)
- Zone 6 (4000 to 4999 HDD)
- Zone 7a (5000 to 5999 HDD)
- Zone 7b (6000 to 6999 HDD)
- Zone 8 (>=7000 HDD)

Some provincial building codes also include separate climate divisions. For example, the Ontario Building Code includes different enclosure requirements for locations above and below 5000 HDD, while new Quebec requirements will have different window performance targets for locations above and below 6200 HDD. Table 5.3 shows the climate zones for the cities selected for modeling. The cities chosen provide at least one location in each of the different climate zones.

Table 5.3 Heating and cooling degree day data for Canadian cities.

	HDD18[12]	Current ENERGY STAR® Zone	Proposed ENERGY STAR® Zone	NBCC Zone
St. John's	4800	B	2	6
Halifax	4100	B	2	6
Quebec City	5200	B	2	7a
Montreal	4250	B	2	6
Ottawa	4600	B	2	6
Toronto	3650	B	2	5
Timmins	6200	C	2	7b
Winnipeg	5900	C	2	7a
Edmonton	5400	B	2	7a
Kelowna	3600	B	1	5
Prince Rupert	4050	B	2	6
Vancouver	2925	A	1	4
Yellowknife	8500	D	3	8

[12] HDD values are from the 2005 National Building Code of Canada, Division B, Appendix C.

6. Window and Glazing Options

Several window and glazing configurations are selected for energy modeling. This section presents background research as well as the window frame and glazing parameters that will be used in the energy simulation phase.

6.1. Thermal Properties of Windows

Window energy performance is rated in the ER calculation through the product's U-value, Solar Heat Gain Coefficient (SHGC) and air leakage rate. The U-value and SHGC are largely dependent on the type of frame, the spacer type, and properties of the IGU. Table 6.1 shows U-values for several types of windows as listed in the 2009 ASHRAE Handbook of Fundamentals. These values show general U-values for generic window products. However, these values were calculated using standard metal spacers, and therefore slightly lower (better) U-values are possible with insulated edge spacers. Many window manufacturers have products with better properties than shown in these tables, as will be seen in the following sections. Also these U-values were determined using NFRC 100-91 and have not been updated to the current version.

Table 6.1 U-values for various fenestration products, from the 2009 ASHRAE Handbook – Fundamentals, W/m^2-K (Btu/hr-ft^2-F).

Window Type	Thermally Broken Aluminum		Wood or Vinyl		Insulated Vinyl or Fibreglass	
	Operable	Fixed	Operable	Fixed	Operable	Fixed
Single glazing, 3.2 mm glass	6.08 (1.07)	6.06 (1.07)	5.20 (0.91)	5.58 (0.98)	4.83 (0.85)	5.40 (1.04)
Double glazing, 12.7 mm air space	3.31 (0.58)	3.18 (0.56)	2.86 (0.50)	2.83 (0.50)	2.58 (0.45)	2.72 (0.48)
Double glazing, 12.7 mm argon space, e = 0.6 on surface 2 or 3	3.01 (0.53)	2.84 (0.50)	2.58 (0.45)	2.50 (0.44)	2.31 (0.41)	2.39 (0.41)
Double glazing, 12.7 mm argon space, e = 0.1 on surface 2 or 3	2.40 (0.42)	2.16 (0.38)	2.02 (0.36)	1.84 (0.32)	1.76 (0.31)	1.74 (0.27)
Triple glazing, 12.7 mm argon space, e = 0.1 on surfaces 2 or 3 and 4 or 5	1.73 (0.30)	1.51 (0.27)	1.45 (0.26)	1.22 (0.21)	1.24 (0.22)	1.12 (0.14)
Quadruple glazing, 12.7 mm argon space, e = 0.1 on surfaces 2 or 3 and 4 or 5	1.64 (0.29)	1.41 (0.25)	1.37 (0.24)	1.12 (0.20)	1.16 (0.20)	1.03 (0.18)

Table 6.2 shows SHGCs for several types of windows listed in the 2009 ASHRAE Handbook of Fundamentals. These values show general SHGC values for generic glazing systems. Operable windows generally have lower SHGC values than fixed windows since operable products typically have larger frame dimensions and, therefore, less solar heat gain through glazing. SHGC values are slightly higher for aluminum frames than non-metal frames since aluminum is more conductive and therefore transfers more incident solar radiation to the interior. Also, aluminum frames tend to have lower frame profiles and, therefore, higher glazed area and more solar heat gain.

Table 6.2 Total window SHGC at normal incidence for various glazing systems, from the 2009 ASHRAE Handbook – Fundamentals (all with 3 mm glass).

Glazing System	Aluminum		Other Frames	
	Operable	Fixed	Operable	Fixed
Single glazing, clear, uncoated	0.78	0.79	0.70	0.76
Double glazing, clear, uncoated	0.69	0.70	0.62	0.67
Double glazing, clear, e = 0.2 on surface 2	0.59	0.60	0.53	0.58
Double glazing, clear, e = 0.2 on surface 3	0.64	0.64	0.57	0.62
Double glazing, clear, e = 0.1 on surface 2	0.59	0.60	0.53	0.58
Double glazing, clear, e = 0.1 on surface 3	0.55	0.55	0.49	0.53
Double glazing, clear, e = 0.05 on surface 2	0.38	0.38	0.34	0.36
Triple glazing, clear, e = 0.1 on surface 2 and 5	0.38	0.38	0.34	0.36
Triple glazing, clear, e = 0.05 on surface 2 and 4	0.26	0.25	0.22	0.25

6.2. Thermal Properties of ENERGY STAR® Windows

A database of all ENERGY STAR® window products was obtained from Natural Resources Canada (NRCan) in order to analyze the properties of ENERGY STAR® windows that are currently available in Canada as of February 8, 2012. This database contains information on 583,120 different window products, including their U-value, SHGC, air leakage rate and ER. Databases with door and skylight products are also available and will be assessed later in this report. The following section presents statistics on U-value, SHGC, air leakage and ER were collected from the product database in order to characterize the current ENERGY STAR® window stock. It is important to note that the products in this database represent the ENERGY STAR® products that are available, but not necessarily the relative market share of different products.

The current ENERGY STAR® climate zones are shown in Fig.6.1, and current ENERGY STAR® window requirements are shown in Table 6.3. In addition to these requirements, windows must have a minimum air leakage performance of A2 (1.65 m^3/h/m).

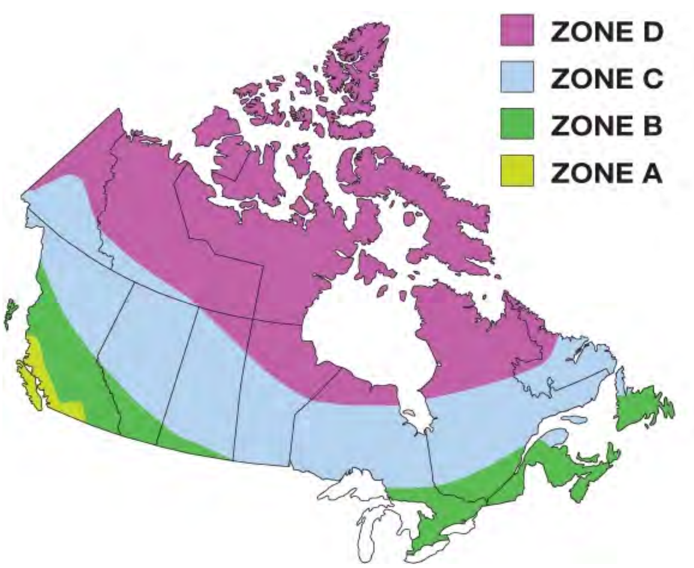


Fig.6.1 ENERGY STAR® climate zones.

Table 6.3 ENERGY STAR® requirements for windows, effective October 1, 2010.

Zone	Heating Degree Day Range	Compliance Paths			
		Minimum ER		U-Value	
		Maximum U-Value 2.00 W/m^2-K (0.35 Btu/h-ft^2-F)	or	Maximum U-Value, W/m^2-K (Btu/h-ft^2-F)	Minimum ER
A	<= 3500	21	or	1.80 (0.32)	13
B	> 3500 to <= 5500	25	or	1.60 (0.28)	17
C	> 5500 to <= 8000	29	or	1.40 (0.25)	21
D	> 8000	34	or	1.20 (0.21)	25

The ENERGY STAR® database contains a wide range of information that can be useful to characterize the energy efficient window market in Canada. Fig.6.2 shows the percentage of windows certified in each climate zone. More than half of the ENERGY STAR® windows are certified only in Zone A. Only 5% of the windows are certified in Zone D.

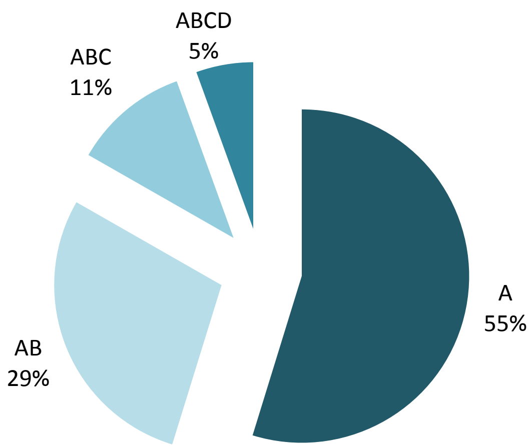


Fig.6.2 Percentage of windows certified in each climate zone.

As discussed in the previous section, proposed changes to ENERGY STAR® fenestration requirements are pending. It is proposed to reduce the number of zones from 4 to 3, as shown in Fig.6.3, and to change the requirements accordingly (Table 6.4). This report uses the current ENERGY STAR® climate zones for analysis since this is how windows are currently certified, and how the ENERGY STAR® window database is organized.

Fig.6.3 Proposed ENERGY STAR® changes to climate zones.

Table 6.4 Proposed changes to ENERGY STAR® requirements for windows.

Zone	Compliance Paths			
	Minimum ER		U-Value	
	Maximum U-Value 2.00 W/m^2-K (0.35 Btu/h-ft^2-F)	or	Maximum U-Value, W/m^2-K (Btu/h-ft^2-F)	Minimum ER
1	22	or	1.70 (0.30)	15
2	29	or	1.40 (0.25)	21
3	34	or	1.20 (0.21)	25

6.2.2 U-value

Table 6.5 shows the average, median, minimum and maximum window U-values for window products that qualify in each of the four climate zones. Fig.6.4 shows the percent distribution of U-values that qualify in each zone. Windows that qualify for colder zones tend to have lower U-values, although the maximum U-value in each zone is 2.0 W/m^2-K (0.35 Btu/h-ft^2-F).

Table 6.5 ENERGY STAR® window U-value statistics, W/m^2-K (Btu/hr-ft^2-F).

	U-Value, W/m^2-K (Btu/hr-ft^2-F)			
	A	AB	ABC	ABCD
Average	1.70 (0.30)	1.56 (0.27)	1.44 (0.25)	1.20 (0.21)
Median	1.70 (0.30)	1.53 (0.27)	1.42 (0.25)	1.14 (0.20)
Minimum	1.31 (0.23)	1.02 (0.18)	0.97 (0.17)	0.57 (0.10)
Maximum	2.00 (0.35)	2.00 (0.35)	2.00 (0.35)	1.99 (0.35)

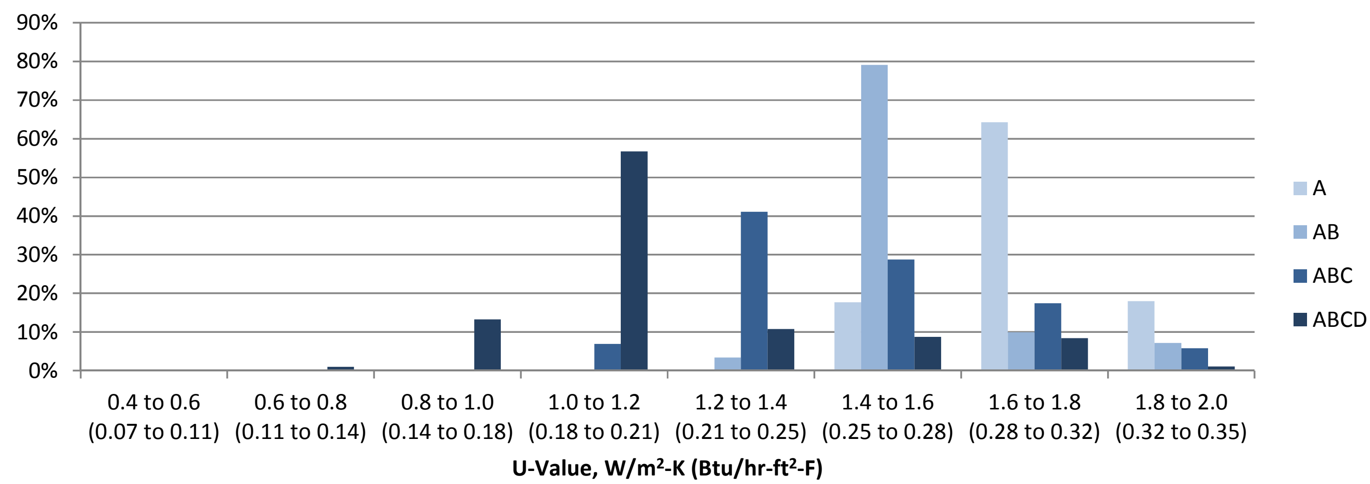


Fig.6.4 Distribution of window U-values by ENERGY STAR® zone.

6.2.3 Solar Heat Gain Coefficient

Table 6.6 shows the average, median, minimum and maximum window SHGCs for window products that qualify in each of the four climate zones. Fig.6.5 shows the percent distribution of SHGCs that qualify in each zone. The majority of the SHGC values in each zone are in the 0.2 to 0.3 range. However, windows that qualify in zones C and D tend to have a greater portion of products with higher SHGCs.

Table 6.6 ENERGY STAR® window SHGCs.

	SHGC			
	A	AB	ABC	ABCD
Average	0.25	0.28	0.32	0.33
Median	0.24	0.25	0.27	0.28
Minimum	0.08	0.06	0.06	0.11
Maximum	0.53	0.59	0.64	0.67

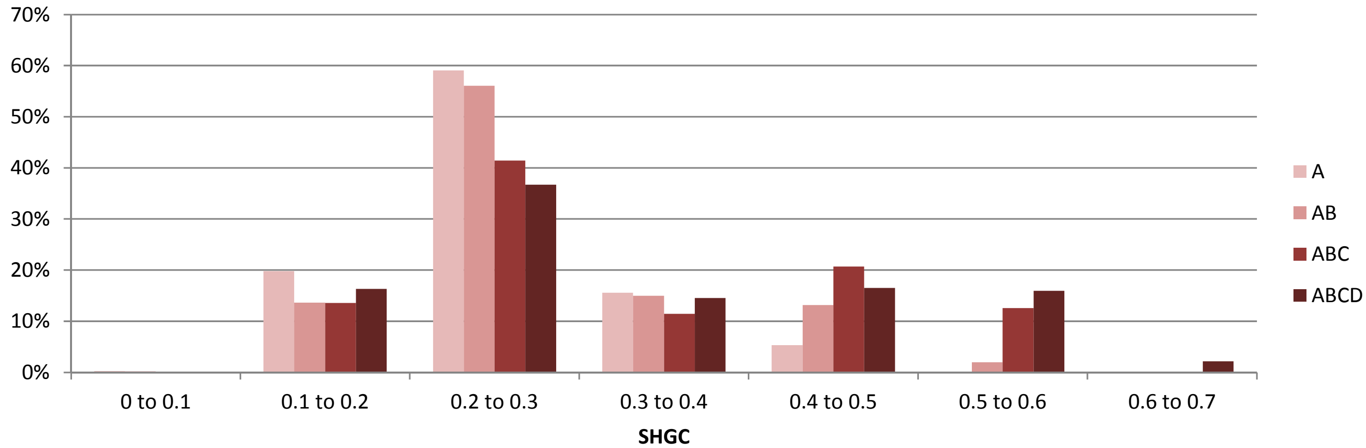


Fig.6.5 Distribution of window SHGCs by ENERGY STAR® zone.

High and low solar heat gain glazing is sometimes thought of in terms of the type of low-e coating(s). There are two basic types of low-e coatings, soft coats and hard coats. Soft coats, also referred to as sputtered coatings, typically have lower emittances, ranging from 0.10 to 0.02. Hard coats, also called pyrolytic coatings, typically have emittances of 0.20 to 0.10. For comparison, clear uncoated glass has an emissivity of about e = 0.84. (NFRC Simulation Manual, LBNL 2011) Soft coatings can result in less radiative heat transfer and therefore lower U-values, however, soft coatings sometimes also result in less solar heat gain. Modern soft coat products are now available with high solar gain.

6.2.4 Air Leakage

Table 6.7 shows the average, median, minimum and maximum window air leakage rate, in m^3/h-m @ 75 Pa, for window products that qualify in each of the four climate zones. Fig.6.6 shows the percent distribution of air leakage rates for windows that qualify in each zone. Window air leakage rates can be reported based on the crack length (m^3/h/m) or the frame area (L/s/m^2), and the ENERGY STAR® database contains one of these ratings for each product. However, it is not possible to convert between the two ratings using the information in the database since the crack length is not provided for windows that use the area method, and vice versa. Therefore, the statistics shown in the table and figure below include only the products for which an air leakage rate per crack length was reported. These products still show the typical range of air leakage rates for ENERGY STAR® windows. For reference, the A440 ratings are 1.65 m^3/h/m for A2, 0.55 m^3/h/m for A3, and 0.25 m^3/h/m for a fixed window.

The majority of ENERGY STAR® windows have very low air leakage rates. In all of the climate zones, more than 80% of windows achieve at least an A3 rating.

Table 6.7 ENERGY STAR® window air leakage rates, m^3/h/m.

	Air Leakage Rate, m^3/h/m			
	A	AB	ABC	ABCD
Average	0.33	0.22	0.23	0.15
Median	0.15	0.12	0.15	0.10
Minimum	0.00	0.00	0.00	0.00
Maximum	1.65	1.65	1.65	1.63

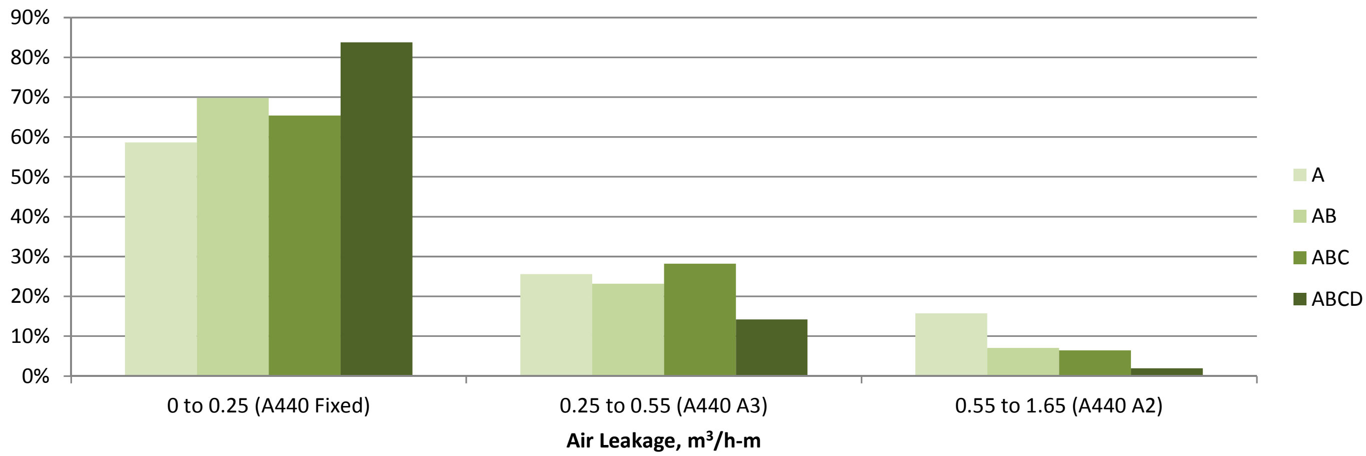


Fig.6.6 Distribution of window air leakage rates by ENERGY STAR® zone.

6.2.5 Energy Rating (ER)

Table 6.8 shows the average, median, minimum and maximum window ER for window products that qualify in each of the four climate zones. Fig.6.7 shows the percent distribution of ERs for windows that qualify in each zone.

Table 6.8 ENERGY STAR® window ERs.

	ER			
	A	AB	ABC	ABCD
Average	16.4	21.3	26.5	32.5
Median	16	20	26	33
Minimum	13	17	21	25
Maximum	24	29	33	52

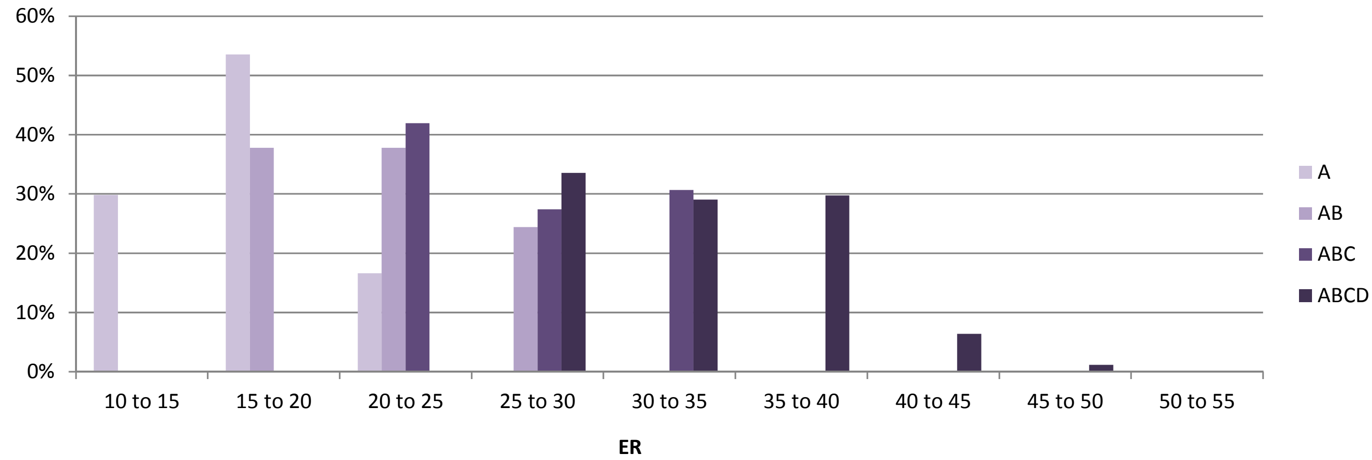
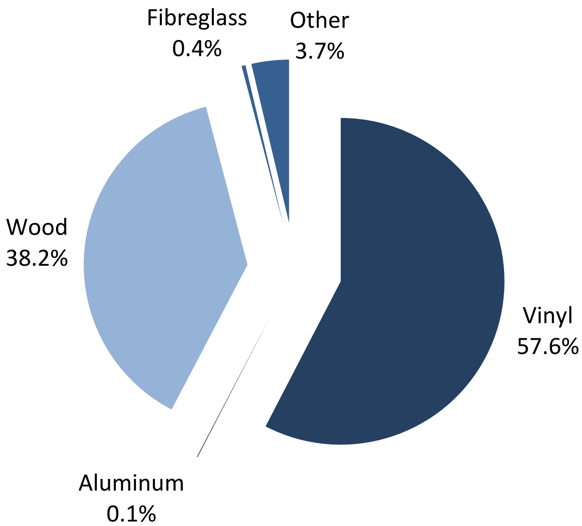


Fig.6.7 Distribution of window ER values by ENERGY STAR® zone.

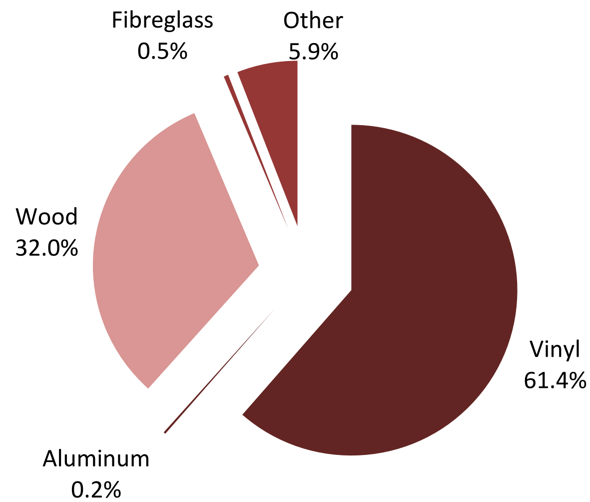
6.2.6 Frame Material

Fig.6.8 shows the percentage of windows by primary frame material certified in each zone. “Other” frame materials include composite, steel, and windows where the frame material was not stated. In the plots below, clad frames are included in the category of the primary frame material (e.g. aluminum clad vinyl was counted as a vinyl frame). It is important to note that the number of products in each category represents the products that are available, but not necessarily the market share of each type of product.

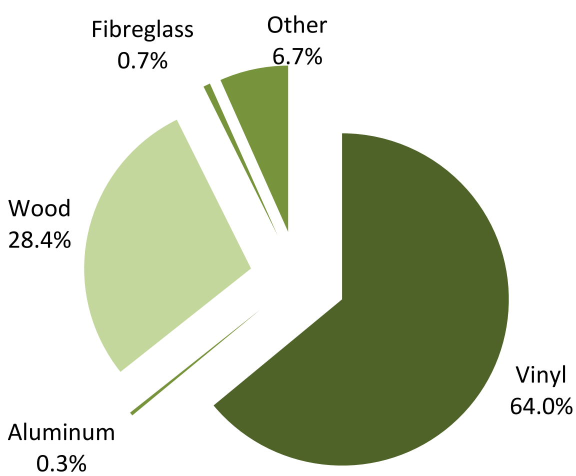
This data shows that the majority of ENERGY STAR® windows in all zones are vinyl frame windows. Wood windows make up the second greatest portion of windows certified in each zone. Aluminum and fibreglass frame windows make up a very small portion of ENERGY STAR® windows in Canada although likely for different reasons. Aluminum frame windows have greater difficulty in meeting modern performance requirements, particularly ENERGY STAR®. Fibreglass frames are less common because of the very limited number of manufacturers and higher price point. Thermally, fibreglass frames are very similar to vinyl frames.



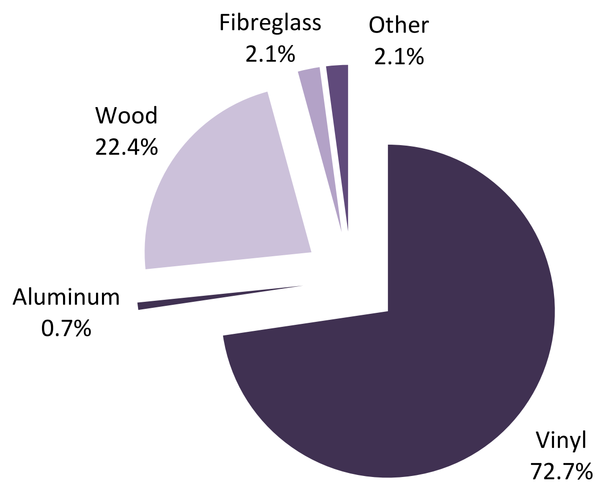
Climate Zone A



Climate Zone A, B



Climate Zone A, B, C



Climate Zone A, B, C, D

Fig.6.8 Percentage of windows by frame material certified in each climate zone.

6.2.7 U-Value and Solar Heat Gain Coefficient

The sensitivity analysis performed in Section 3 showed that air leakage rate has a relatively small effect on the ER. The ENERGY STAR® database shows that the large majority of E windows have an air leakage rating better than A3, with many below the fixed window rate. However, the U-value and SHGC both have a great effect on the ER, and a wide variety of U-value and SHGC combinations exist in the ENERGY STAR® window database. Additional analysis has been performed in order to further characterize window U-value and SHGC combinations.

It has been suggested that SHGCs may be grouped into the following general categories: high > 0.45, medium or moderate 0.30 to 0.45, and low < 0.30. The distribution of SHGC values in the ENERGY STAR® database are shown in Fig.6.5 (by zone) and Fig.6.9 (overall distribution). The data indicates that 55% of ENERGY STAR® windows have a SHGC between 0.2 and 0.3. By zone, 37% to 60% of windows have a SHGC between 0.2 and 0.3, with colder climate zones tending towards higher SHGCs. The average residential window may have a different distribution of SHGCs than ENERGY STAR® windows, however, further data on this is likely not available.

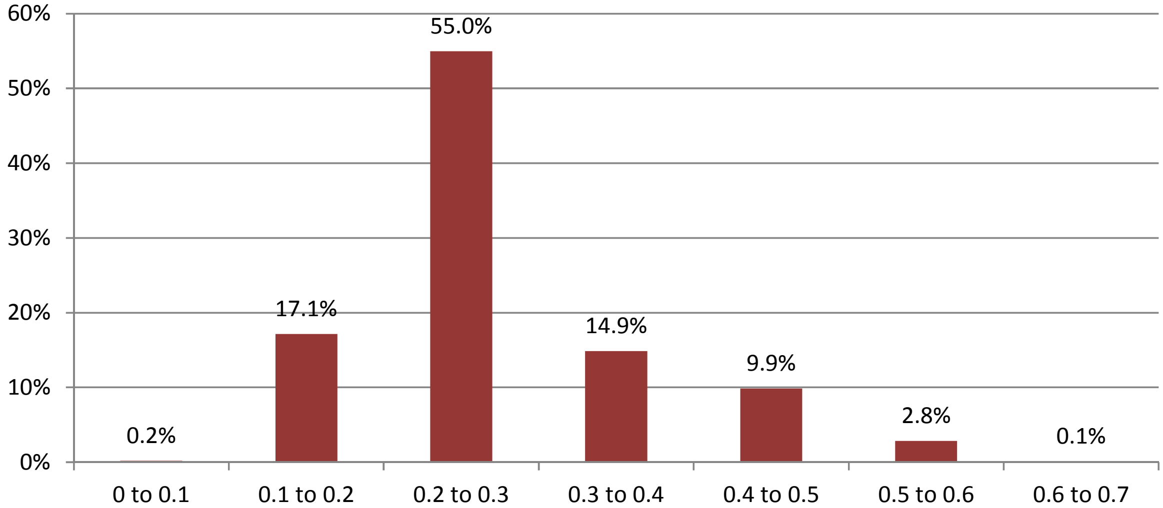


Fig.6.9 Overall distribution of SHGC for ENERGY STAR® windows in Canada.

To further study the range of U-value and SHGCs that exist for ENERGY STAR® windows, three SHGC ranges are defined: low < 0.2, medium 0.2 to 0.4, and high >0.4. High was chosen as greater than 0.4 since these SHGC values are more common in windows certified in zones C and D (see Fig.6.5).

Fig.6.10 shows the distribution of U-values in each of these three SHGC groups. The data shows that windows with lower SHGCs tend to have lower U-values. Windows with low SHGC have the greatest range of U-values, between U_{SI}-1.4 (U-0.25) and U_{SI}-1.6 (U-0.28). Windows with medium SHGC have the greatest range of U-values from U_{SI}-1.6 (U-0.28) to U_{SI}-1.8 (0.32), and windows with high SHGC have the greatest range of U-values between U_{SI}-1.8 (0.32) and U_{SI}-2.0 (U-0.35). However, all combinations of SHGCs exist in all of the major U-value groups except that there are no low SHGC products in the highest U-value group of U_{SI}-1.8 (U-0.32) to U_{SI}-2.0 (U-0.35).

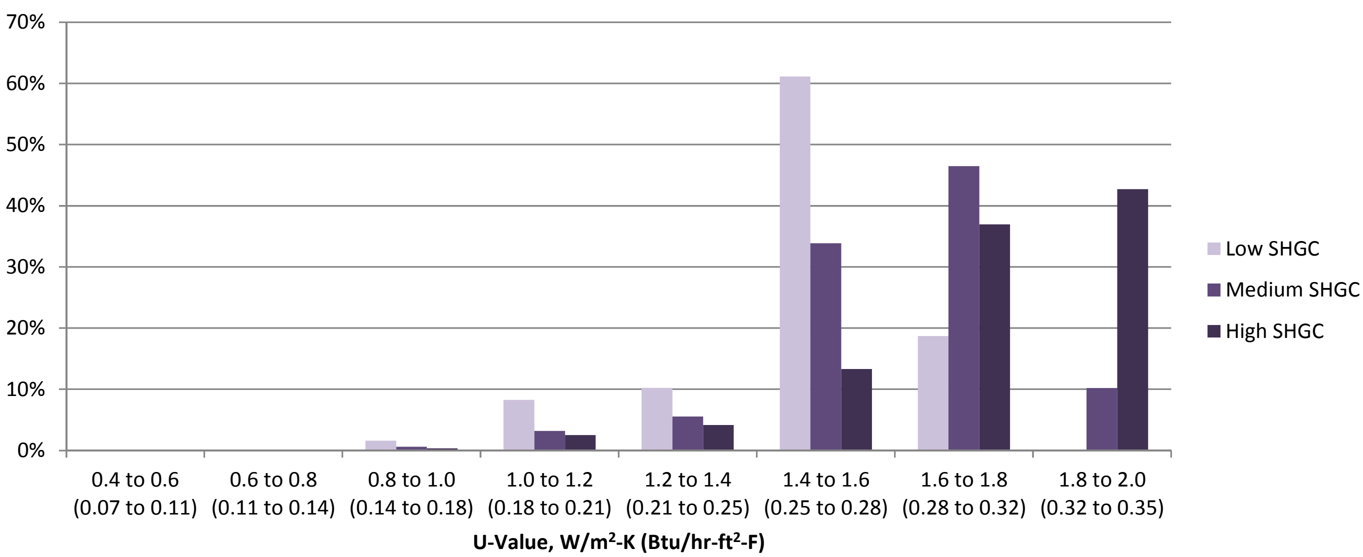


Fig.6.10 U-value distribution of ENERGY STAR® windows for low, medium and high SHGC.

6.2.8 Double versus Triple Glazing

The ENERGY STAR® database contains primarily double and triple glazed windows, plus a smaller number of quadruple glazed windows. Both double and triple glazed windows should be analyzed in the energy simulations, therefore it is important to look at the difference in U-value and SHGC of these products. Of the ENERGY STAR® windows, 86% are double glazed, 13% are triple glazed, and less than 1% are quadruple glazed. Again, this distribution represents the number of products available rather than market share.

Table 6.9 shows the average, median, maximum and minimum U-value, SHGC and ER for double and triple glazed windows. Fig.6.11 and Fig.6.12 show the distribution of U-value and SHGC, respectively, for double and triple glazed windows. Double glazed windows tend to have higher U-values than triple glazed windows. There is still a large portion of triple glazed windows with U-values greater than U_{SI}-1.4 (U-0.25). This appears to be due to a number of reasons. For example, some of these are aluminum frame windows, while many are vinyl or wood-frame windows with air fill, grills or dividers, and vinyl frames with metal reinforcing.

Triple glazed windows have a greater proportion of low SHGCs between 0.1 and 0.2. This is because to achieve low U-values typically requires very low emissivity coatings, which reduces the SHGC. The majority of double glazed windows have a SHGC between 0.2 and 0.3. There are still a significant number of triple glazed windows with high SHGC; 14% of products have SHGC values greater than 0.40, and 2% or 1,664 products have a SHGC greater than 50%.

Table 6.9 U-Value, SHGC and ER for double and triple glazed ENERGY STAR® windows.

	U-Value, W/m²-K (Btu/hr-ft²-F)		**SHGC**		**ER**	
	Double	**Triple**	**Double**	**Triple**	**Double**	**Triple**
Average	1.65 (0.29)	1.32 (0.23)	0.27	0.27	18.88	25.91
Median	1.65 (0.29)	1.31 (0.23)	0.25	0.24	18	25
Minimum	1.01 (0.18)	0.57 (0.10)	0.08	0.06	13	13
Maximum	2.00 (0.35)	2.00 (0.35)	0.67	0.64	43	52

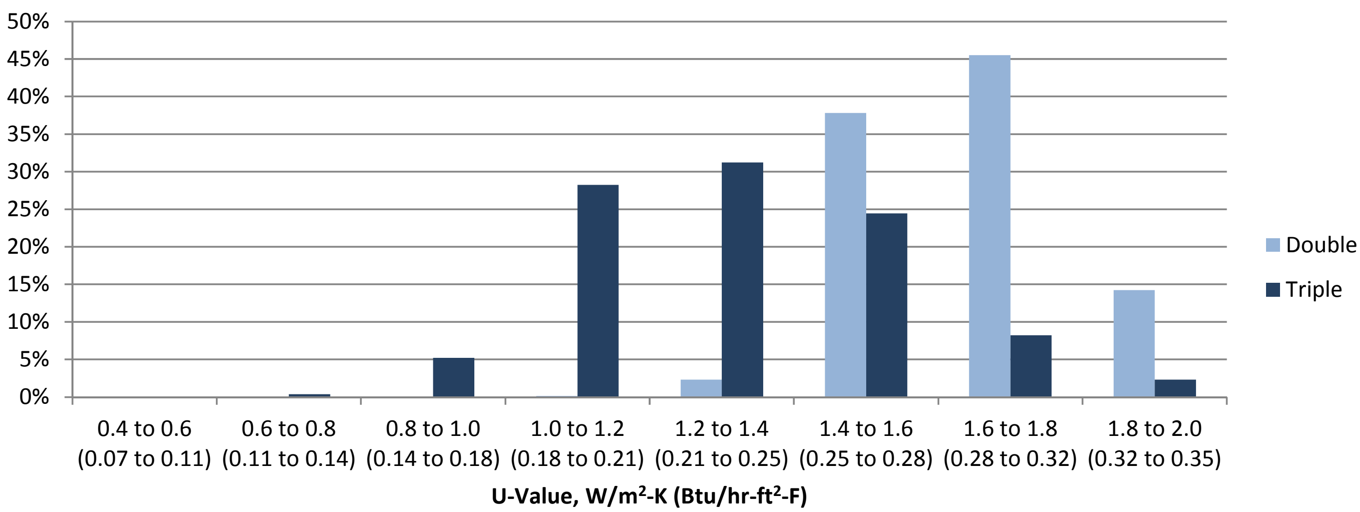


Fig.6.11 Distribution of U-values for double and triple glazed windows.

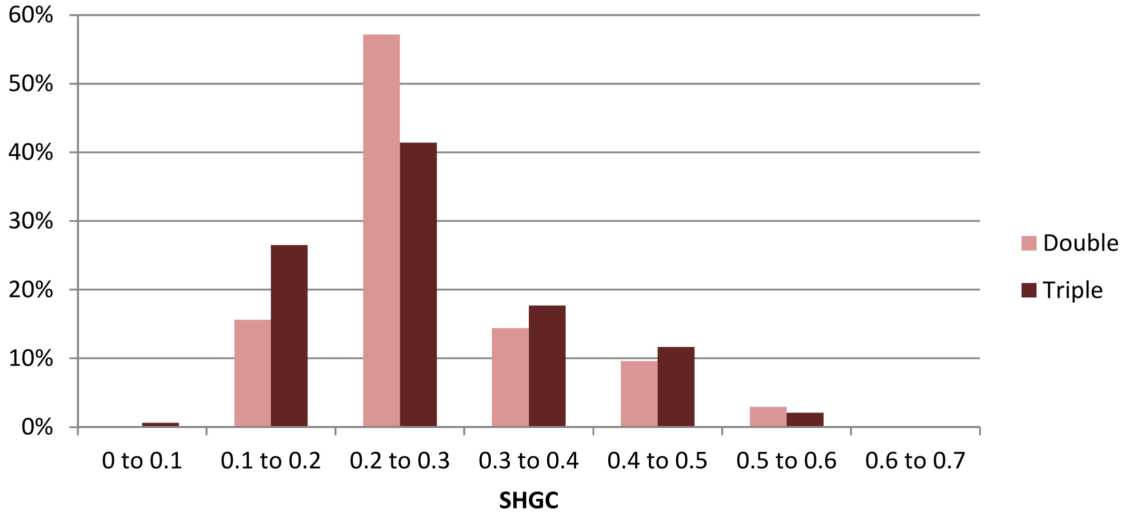


Fig.6.12 Distribution of SHGCs for double and triple glazed windows.

6.3. Typical New and Existing Windows

The thermal performance of existing windows in a house will depend on the age of the house, the location, and whether the windows have been replaced. Most parts of Canada will have at least double glazed windows with vinyl or wood frames. Windows that have been replaced may incorporate low-e coatings, low conductivity edge spacers and argon gas fill. Mild climates such as south-western British Columbia still have a large number of single glazed windows. Typical existing windows are included in the configurations for simulation for comparison.

For windows in new houses, most jurisdictions have building code energy performance requirements for windows. These minimum standards were presented in Section 4 (see Table 4.5). The proposed NBCC 2012 changes would bring the minimum U-value requirements for new houses more in line with current ENERGY STAR® requirements.

6.4. High Performance Glazing Technology

Lower U-values are possible with high performance glazing technologies, however, these products are less common in the current fenestration market. High performance glazing products can include quadruple glazed or higher, heat mirror products, and Vacuum Insulated Glazing (VIG). Heat mirror products incorporate thin plastic films instead of additional layers of glass to create multiple cavities with less thickness and weight. The heat mirror films can also include low-e coatings.

The ENERGY STAR® database contains 845 products with four layers of glazing, however, most of these are not traditional quadruple glazed IGUs, but rather, a combination of double/double or triple/single IGUs in separate framing systems. A few products in the database have sealed quadruple glazed units with heat mirror technology. The quadruple glazed product with the lowest U-value has U_{SI}-0.68 (U-0.12), quadruple glazed with heat mirror, foam-filled fibreglass frame, and Krypton gas fill. This product has an ER of 39, a SHGC of 0.23 to 0.25, and an air leakage rate of 0.048 m^3/h/m.

Vacuum insulated glazing (VIG) or evacuated glazing can have significantly higher centre of glazing R-values. These IGUs have a thin evacuated space between two layers of glass. The vacuum minimizes heat transfer by conduction and convection. Low-e coatings are still used to control radiative heat transfer. The glass layers are separated by small spacers to prevent the cavity from collapsing, and the edges of the IGU are glass welded. These units claim a centre of glass U-value of approximately U_{SI}-0.47 or U-0.08 (R_{SI}-2.11 or R-12), and one unit is 6 to 11 mm thick. Lower U-values can be achieved by using two VIG panels in a traditional double glazed style frame to create centre of glass R-values upwards of R_{SI}-4.40 or R-25 (U_{SI}-0.23 or U-0.04) (compared to a typical triple glazed centre of glass R-value R_{SI}-1.23 or R-7; U_{SI}-0.79 or U-0.14).

VIGs have the potential for very low centre of glazing U-values, however, the overall window U-value would be higher due to the frame and edge losses with current frame technology. An area weighted calculation (similar to the method used in NFRC 100) can be performed in order determine a general overall product U-value for a VIG fenestration system in a low conductivity frame. For example, assume an IGU with two VIG units in a foam filled fibreglass frame has a centre of glass U_{SI}-0.23 (U-0.04), a frame that is U_{SI}-1.14 or U-0.2 (R_{SI}-0.88 or R-5) and an edge of glass U_{SI}-0.57 or U-0.1 (R_{SI}-1.76 or R-10) (note this is a theoretical product and, therefore, general values are selected in order to get a sense of an overall VIG product U-value, including edge and frame losses). Using an area-weighted calculation for a standard size fixed window (1200 mm by 1500 mm) gives an overall product U_{SI}-0.45 (U-0.08).

6.5. Window Configurations for Simulations

The energy simulations completed in this study should examine a range of window products, including typical existing and new windows (for comparison), as well as a range of ENERGY STAR® windows. It is also important to look at a range of U-value and SHGC combinations, including high and low SHGC with high and low U-values, as well as average values. A high performance window product will also be included in the analysis to view the results of a future product compared to current technology.

A list of window configurations was developed using the data analysis presented in the previous sub-sections (Table 6.10). Windows are identified by their U-value and SHGC. An air leakage rate of 0.25 m^3/h/m is used for the ER calculation (A440 fixed window) since 66% of ENERGY STAR® windows have an air leakage rate below this level (note the air leakage rate has a relatively minor impact on the ER). The resulting ER calculated from the window parameters is also shown in Table 6.10.

The majority of double glazed U-values range from U_{SI}-1.4 (U-0.25) to U_{SI}-2.0 (U-0.35), while triple glazed windows range from U_{SI}-0.8 (U-0.14) to U_{SI}-2.0 (U-0.35) with the majority between U_{SI}-1.0 (U-0.18) and U_{SI}-1.6 (U-0.28). A range of high, medium and low double glazed window U-values will be simulated. For triple glazed windows, a high U-value triple glazed window could be the same as a double glazed product from an energy simulation standpoint. Therefore, two triple glazed U-values are included, low and medium (i.e. a high triple glazed U-value would have the same thermal performance characteristics as a low U-value double glazed window).

SHGC values in the table below for the ENERGY STAR® windows were determined based on the distribution of SHGCs by climate zone (Fig.6.5). The double versus triple glazing analysis showed that both double and triple glazed windows have relatively similar distribution of SHGC values, and triple glazed windows with high SHGC are available. Therefore, the same low, medium and high SHGCs are used for both double and triple glazing.

The “Advanced Glazing” window is a theoretical window based on the VIG product discussed in Section 0 (two VIG units in a low conductivity frame). This product does not currently exist in the residential market in Canada, however, with future glazing technology developments this product may be realized.

Table 6.10 Window configurations for energy simulations.

Window	Representative Window	U-Value, W/m^2-K (Btu/h-ft^2-F)	SHGC	ER	ENERGY STAR® Zones, U-Value Path	ENERGY STAR® Zones, ER Path
W1	Single glazed, clear, wood or vinyl frame (existing house in mild climate)[13]	5.58 (0.98)	0.74	-39	None	None
W2	Double glazed, clear, air fill, wood or vinyl frame (existing house in cold climate)[13]	2.83 (0.50)	0.64	14	None	None
W3	Double glazed, low-e, argon fill, metal spacer (typical replacement window that does not meet ENERGY STAR®)[13]	2.27 (0.40)	0.55	22	None	None
W4	Double glazed, very high SHGC	2.00 (0.35)	0.65	34	None	ABCD
W5	Double glazed, high U, high SHGC	2.00 (0.35)	0.50	26	None	AB
W6	Double glazed, medium U, high SHGC	1.75 (0.31)	0.50	30	A	ABC
W7	Double glazed, low U, high SHGC	1.50 (0.26)	0.50	37	AB	ABCD
W8	Double glazed, high U, med SHGC	2.00 (0.35)	0.35	17	None	None
W9	Double glazed, medium U, med SHGC	1.75 (0.31)	0.35	22	A	A
W10	Double glazed, low U, med SHGC	1.50 (0.26)	0.35	28	AB	AB
W11	Double glazed, high U, low SHGC	2.00 (0.35)	0.20	8	None	None
W12	Double glazed, medium U, low SHGC	1.75 (0.31)	0.20	13	A	None
W13	Double glazed, low U, low SHGC	1.50 (0.26)	0.20	19	AB	None
W14	Triple glazed, medium U, high SHGC	1.2 (0.21)	0.50	43	ABCD	ABCD
W15	Triple glazed, low U, high SHGC	0.9 (0.16)	0.50	49	ABCD	ABCD
W16	Triple glazed, medium U, medium SHGC	1.2 (0.21)	0.35	34	ABCD	ABCD
W17	Triple glazed, low U, medium SHGC	0.9 (0.16)	0.35	41	ABCD	ABCD
W18	Triple glazed, medium U, low SHGC	1.2 (0.21)	0.20	25	ABCD	AB
W19	Triple glazed, low U, low SHGC	0.9 (0.16)	0.20	32	ABCD	ABC
W20	Triple glazed, very low SHGC	0.9 (0.16)	0.15	29	ABCD	ABC
W21	Advanced Glazing, high SHGC	0.45 (0.08)	0.50	59	ABCD	ABCD
W22	Advanced Glazing, medium SHGC	0.45 (0.08)	0.35	50	ABCD	ABCD
W23	Advanced Glazing, low SHGC	0.45 (0.08)	0.20	42	ABCD	ABCD

6.5.2 Window Configurations and the ENERGY STAR® Database

To confirm that the windows for energy simulation are realistic and represent a wide range of existing windows, the windows that qualify for ENERGY STAR® were compared to products in the ENERGY STAR® database. The results of this comparison are shown in Table 6.11.

Nine of the 13 ENERGY STAR® windows have at least one window available in the database with the exact matching U-value and SHGC, however many more products have properties that are close. All of the configurations have corresponding products in

[13] U-Value and SHGC from 2009 ASHRAE Handbook – Fundamentals

the database with a U-value and SHGC within +/- 5%. Overall, 20% of the database is within +/- 5% of the windows. Also, 62% of the database is within +/- 10% of the windows. The window configurations for energy simulation appear to represent a good range of ENERGY STAR® windows.

Table 6.11 Window configurations for energy simulation and the ENERGY STAR® database.

W#	Windows with Exact Properties		Windows within +/- 5%	
	#	Type	#	Type
W04	1	Fixed (Picture)	51	Fixed (Picture), Single Slider
W05	6	Double hung, single hung, single slider	4,600	Awning (single), Casement (single), Double hung, Double slider, Dual action (tilt-turn), Fixed (picture), Fixed awning, Fixed casement, Single hung, Single slider
W06	7	Fixed (picture), Fixed Casement	9,966	Awning (single), Casement (single), Double hung, Double slider, Dual action (tilt-turn), Fixed (picture), Fixed awning, Fixed casement, Single hung, Single slider, Triple slider
W07	0		2,568	Awning (single), Casement (single), Double hung, Double slider, Dual action (tilt-turn), Fixed (picture), Fixed awning, Fixed casement, Single hung, Single slider
W08	n/a	(does not meet ENERGY STAR®)	15	Awning (single), Casement (single), Fixed (picture), Fixed casement, Single slider
W09	5	Single hung, Fixed (picture)	16,067	Awning (single), Casement (single), Double hung, Double slider, Dual action (tilt-turn), Fixed (picture), Fixed casement, Single hung, Single slider, Triple slider
W10	3	Fixed (picture)	9,937	Awning (single), Casement (single), Double hung, Double slider, Dual action (tilt-turn), Fixed (picture), Fixed casement, Hopper, Single hung, Single slider
W11	n/a	(does not meet ENERGY STAR®)	9	Fixed (picture)
W12	74	Awning (single), Casement (single), Double hung, Fixed (picture)	20,023	Awning (single), Casement (single), Double hung, Double slider, Dual action (tilt-turn), Fixed (picture), Fixed casement, Hopper, Single hung, Single slider, Triple slider
W13	38	Awning (single), Casement (single), Fixed (picture)	43,634	Awning (single), Casement (single), Double hung, Double slider, Dual action (tilt-turn), Fixed (picture), Fixed casement, Single hung, Single slider, Triple slider
W14	1	Fixed (picture)	439	Awning (single), Casement (single), Double hung, Double slider, Fixed (picture), Fixed casement, Single hung, Single slider
W15	0		35	Fixed (picture), Fixed (casement)
W16	4	Awning (single), Casement (single)	2,033	Awning (double), Awning (single), Casement (single), Double hung, Double slider, Dual action (tilt-turn), Fixed (picture), Fixed casement, Hopper, Single hung, Single slider
W17	0		18	Casement (single), Fixed (picture), Fixed casement
W18	6	Fixed (picture), Casement (single), Awning (single)	4,221	Awning (single), Casement (single), Double hung, Double slider, Dual action (tilt-turn), Fixed (picture), Fixed casement, Hopper, Single hung, Single slider, Triple slider
W19	0		430	Awning (single), Casement (single), Double hung, Double slider, Dual action (tilt-turn), Fixed (picture), Fixed casement
W20	0		264	Awning (single), Casement (single), Double hung, Fixed (picture), Fixed casement, Single hung, Single slider

6.6. References

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7. Energy Simulations

7.1. Methodology

The purpose of this section is to provide complete energy simulation results using the parameters established in Sections 4, 5 and 6. The simulation results will identify whether the ER approach provides consistent rating of window energy consumption for different window and archetype house parameters. The energy simulations were completed using the following methodology.

- Parameters to analyze through energy simulation were identified in Sections 4, 5 and 6. These are summarized for reference in Table 7.1.
- A baseline energy simulation (using the program DesignBuilder) was run for Vancouver, Toronto and Winnipeg to ensure the energy consumption simulated by the program is representative of actual household energy consumption in Canada. The baseline simulation was created for the single-storey archetype using a gas furnace. The simulation results are compared to HOT2000 simulations since this program is more commonly used to model energy consumption of Canadian houses. The results are also compared to Canada-wide statistics from NRCan. This comparison is presented in Section 7.2.
- The single-storey archetype simulation was run for all locations and all window types. The results are shown in graphic and tabular format, and initial observations regarding the use of the ER to rank window energy consumptions are noted. This analysis is shown in Section 7.3.
- The archetype house parameters that are not directly related to windows (e.g. size, mechanical system, etc.) are run for all locations and all window types. This analysis is shown in Section 7.4.
- The archetype house parameters that are directly related to windows (window to wall ratio, orientation, and shading) are run for five locations and all window types. This analysis is shown in Section 7.5.
- Modeling of additional scenarios based on comments received will be presented in Section 7.6.
- Summary and conclusions from the energy simulations in this Section are presented in Section 7.7.

Table 7.1 Archetype house variables to study in energy simulations.

Variable	Parameters
Not directly related to windows	
Size of house	Single-storey, two-storey, large two-storey
Basement	Basement without fenestration, no basement, walkout basement with fenestration
Enclosure Thermal Performance	Existing, new
Mechanical System	Gas/oil furnace (central thermostat), electric baseboards (zoned thermostat), central air conditioning
Natural Ventilation	With or without natural ventilation to offset cooling energy
Lights and plug loads	Average and high internal gains
Shading	No shading, typical roof overhang, fixed exterior shades (various sizes), operable exterior shades
Thermal Mass	Normal (wood framing) and high thermal mass
Directly related to windows	
Window to Wall Ratio	5% to 30%, in 5% increments
Orientation	Equal distribution, greater distribution in each cardinal direction, greater distribution north-south and east-west
Shading	None, fixed exterior shades, operable exterior shades

7.2. Energy Simulation Set-Up

7.2.1 Energy Simulation Program

There are many building energy simulation programs available to choose from for the energy modeling performed for this project. HOT2000 is widely used to simulate energy consumption of houses in Canada. This program uses the bin method to calculate annual energy consumption. The bin method is a simple method of estimating energy consumption without performing hourly calculations. This method does not accurately simulate dynamic effects, including hourly solar radiation and dynamic thermal storage. These effects (particularly hourly solar radiation) are paramount to this study of the Energy Rating for windows. Therefore a program capable of hourly energy simulations should be used for the simulations rather than HOT2000. This is supported by research findings from the literature review.

A number of different hourly energy simulation programs are available to model building energy consumption. The hourly simulation program ESP-r is used as the engine for the new HOT3000 program, which will replace HOT2000, however HOT3000 is still under development. Another common hourly energy modeling program is eQuest, which uses the DOE-2.2 simulation engine. The DOE-2 engine performs hourly energy calculations, but still uses some simplified methodologies, particularly to account for thermal storage effects. EnergyPlus is a newer program that was developed to improve upon the DOE-2 engine. EnergyPlus performs hourly energy calculations using more comprehensive calculation methodologies to account for dynamic effects. A program called DesignBuilder is a user interface that utilizes the EnergyPlus engine to provide a more user-friendly simulation platform. DesignBuilder is used for the modeling in this study.

While hourly energy simulations are important for the analysis in this study, it is important to recognize that hourly energy simulations are not traditionally performed for houses, and there are a few challenges that must be worked out in order to build accurate, meaningful models. These issues will be discussed in the following sections. Since the program HOT2000 has been well calibrated to energy consumption of typical Canadian houses, the initial archetype house hourly simulation results were compared to HOT2000 results to view the difference in calculated energy consumption between the two programs. The simulation results were also compared to statistical data of household energy consumption in Canada to ensure the program provides reasonable and representative results.

7.2.2 Energy Simulation Verification

An energy simulation was created for the single-storey house with the following parameters:

- 15% window to wall ratio, equally distributed in all cardinal directions
- Typical existing house performance level
- Heated basement (no windows to the basement)
- Natural gas furnace and central air conditioning
- Ventilation through intermittent kitchen and bathroom exhaust fans, plus furnace and air conditioner fan
- Internal gains of 14 kWh/d (lighting and appliance/plug loads)
- 0.5 m roof overhang, no additional exterior shading of windows. For the two-storey archetype, first floor windows do not have any shading.
- Standard thermal mass (wood-frame construction, concrete foundation)
- No natural ventilation

A complete list of model inputs can be found in Appendix B.

The archetype house energy consumption should be representative of typical Canadian houses. To verify that the energy simulations are providing representative household energy consumption, the simulation output from three cities for the baseline house is examined. The simulation was initially run in Vancouver, Toronto and Winnipeg in order to look at the energy consumption results in a range of Canadian climates.

The energy consumption of the single-storey house in Vancouver using the “mild climate” archetype parameters and single-glazed windows (type W01 in Table 6.10, U_{SI}-5.88 (U-0.98) and SHGC-0.74) is shown in Fig.7.1. The total annual household energy consumption is 26,800 kWh, an energy intensity of 268 kWh/m^2 not including the basement floor area, or 134 kWh/m^2 including basement floor area. Space heating energy consumption accounts for 46% of total energy consumption in this house.

Cooling energy accounts for 3% of total annual energy consumption in this simulation. It is important to note that the house was simulated assuming no natural ventilation in the summer (i.e. windows remain closed at all times). This was done to view the worst-case scenario of the highest possible cooling energy, as if the windows and doors of the house were kept closed throughout the summer. If natural ventilation was allowed through the summer, cooling energy would be much lower in most Canadian climates. This case will also be studied through simulations in a later section.

Note that fan energy in this chart includes furnace fan power, air conditioner fan power, and intermittent kitchen and bathroom exhaust fan power. The simulation program reports fan power for these three end-uses together.

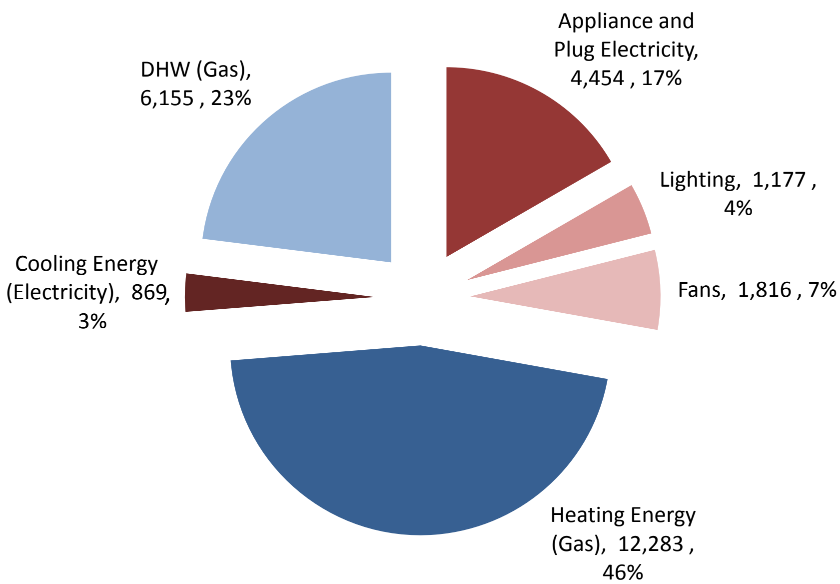


Fig.7.1 Distribution of simulation household energy consumption in Vancouver, kWh_e and percent of total.

The distribution of heat loss through the enclosure in the simulation can also be examined. For the Vancouver simulation, Fig.7.2 shows the distribution of heat loss by enclosure component and Fig.7.3 shows the monthly heat transfer by enclosure component. In this simulation, fenestration accounts for the greatest proportion of heat loss, though it is important to note this case has single glazed windows. The monthly heat transfer plot shows that the attic results in net heat gains to the space in the summer months, but all other enclosure components, including the windows, have a net heat loss in each month.

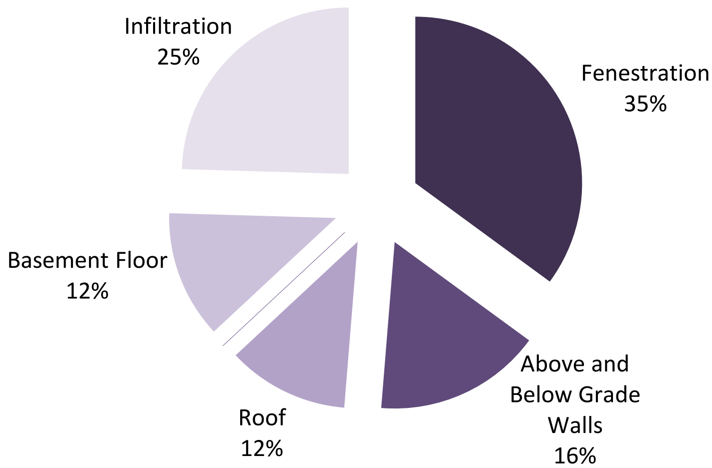


Fig.7.2 Distribution of annual heat loss through the enclosure in Vancouver.

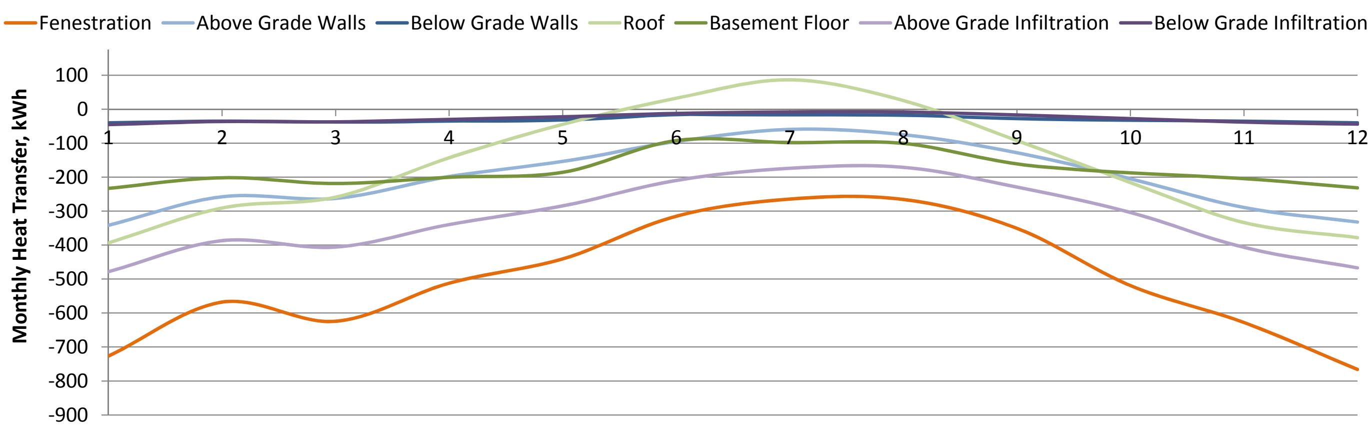


Fig.7.3 Monthly heat loss and gains by enclosure component in Vancouver.

The energy consumption of the single-storey house in Toronto using the “cold climate” archetype parameters (see Section 4 or Appendix B) and double glazed windows (type W02 in Table 6.10, U_{SI}-2.83 (U-0.50) and SHGC-0.64) is shown in Fig.7.4. The total annual household energy consumption is 27,700 kWh, an energy intensity of 277 kWh/m^2 not including the basement floor area, or 138 kWh/m^2 including the basement floor area. It is important to note that this archetype has a better enclosure than the Vancouver archetype when comparing the energy consumption of the two models. Space heating energy consumption accounts for 46% of the total energy consumption in this house. The energy end-use distribution (Fig.7.4) is very similar to the house in Vancouver, with a slightly higher percentage of energy consumption for cooling.

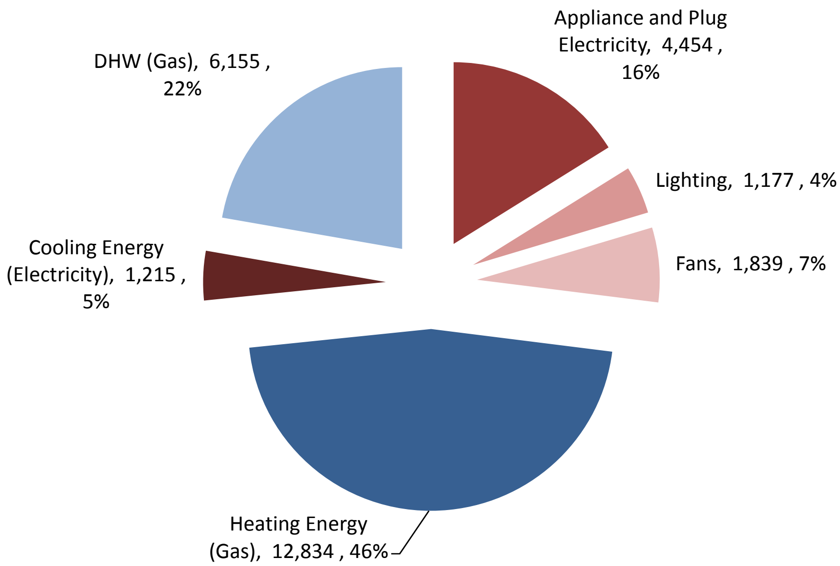


Fig.7.4 Distribution of simulation household energy consumption in Toronto, kWh_e and percent of total.

The energy consumption of the single-storey house in Winnipeg using the "cold climate" archetype parameters with double glazed windows (type W02 in Table 6.10, U_{SI}-2.83 (U-0.50) and SHGC-0.64) is shown in Fig.7.5. The total annual household energy consumption is 34,500 kWh, which equals 345 kWh/m^2 not including the basement floor area, or 173 kWh/m^2 including the basement floor area. Space heating energy consumption accounts for 57% of total energy consumption in this house. As expected, the house in Winnipeg has a greater portion of space heat energy consumption than in Toronto and Vancouver.

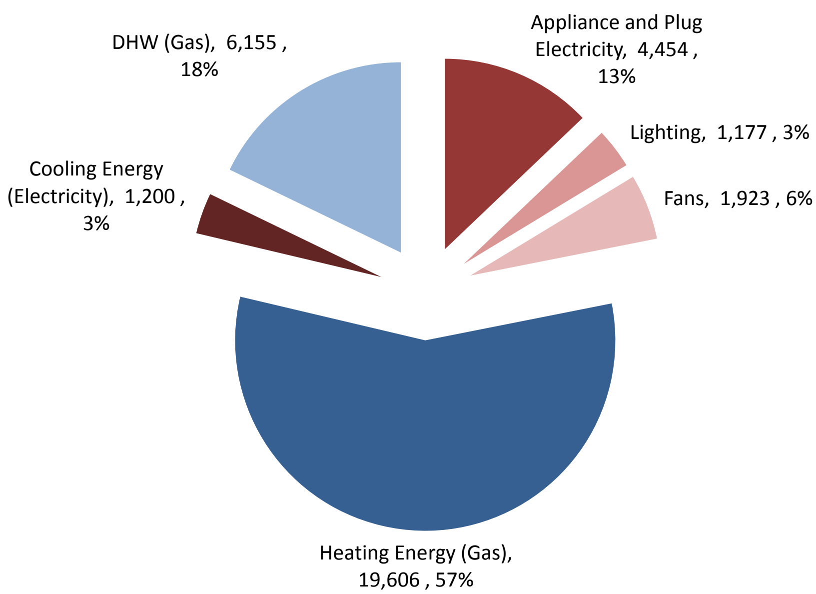


Fig.7.5 Distribution of simulation household energy consumption in Winnipeg, kWh and percent of total.

Fig.7.6 shows the distribution of heat loss by enclosure component and Fig.7.7 shows the monthly heat transfer by enclosure component for the Winnipeg archetype house. Fenestration accounts for the greatest proportion of heat loss in this simulation. The monthly heat transfer plot shows that the attic results in net heat gains to the space in the summer months, but all other enclosure components, including the windows, have a net heat loss in each month.

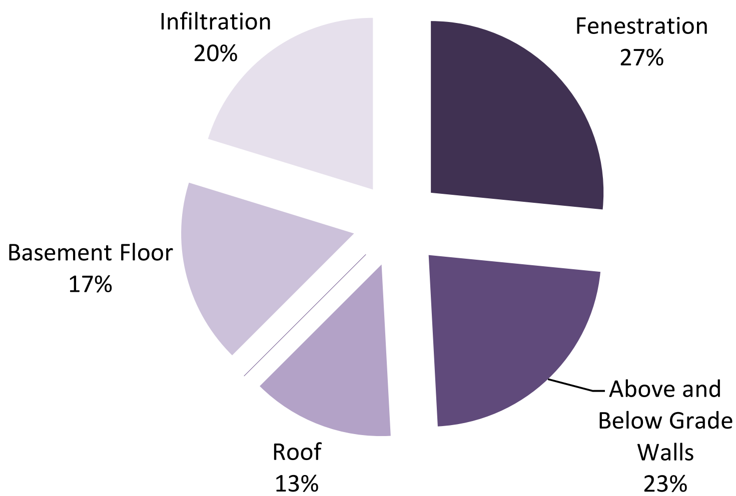


Fig.7.6 Distribution of annual heat loss through the enclosure in Winnipeg.

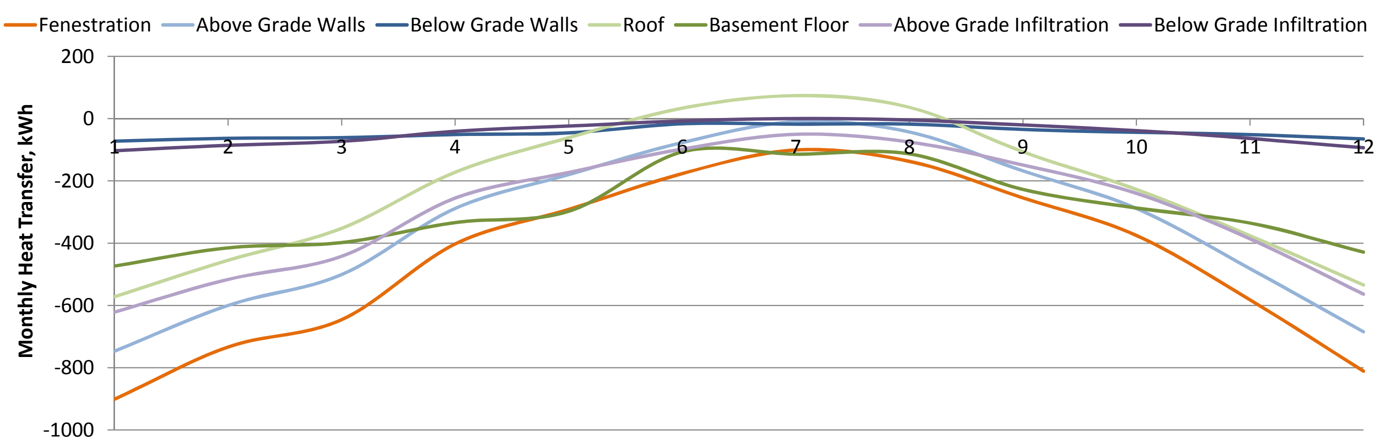


Fig.7.7 Monthly heat loss and gains by enclosure component in Winnipeg.

The energy consumption of the archetype house simulations can be compared to statistical data on household energy consumption, particularly for space heating energy, to verify that the simulations are representative of typical Canadian houses. Data from Natural Resources Canada (NRCan) on residential sector energy consumption shows that the average energy intensity of Canadian single detached houses was 229 kWh/m^2 in 2009. This is between the energy consumption of the baseline archetype house simulations, including and excluding the basement floor area. Including the basement area, the energy intensities are 268 kWh/m^2 in Vancouver, 277 kWh/m^2 in Toronto, and 345 kWh/m^2 in Winnipeg. Excluding the basement area, the energy intensities are 134 kWh/m^2 in Vancouver, 138 kWh/m^2 in Toronto and 173 kWh/m^2 in Winnipeg.

The simulation energy intensity is reported exclusive of the basement floor area because although the basement is heated, the other loads are much lower over the basement floor area. Lighting and plug loads were assumed to be 15% of the main floor area in the basement, following the EnerGuide standard simulation conditions. This would be representative of a basement that is used less frequently than the main floor area. Domestic hot water also has the same load regardless of whether or not a basement is present, and the basement typically does not require any cooling energy due to ground temperatures that are cooler than outdoor air in the summer. In other words, although the basement results in greater heating energy, the other energy consumption loads on the house tend to be the same or only slightly higher with a basement, and therefore representing energy intensity as a function of total (including basement) floor area can result in misleadingly low energy intensities. Of course, this would also be reflected in the energy intensity statistics from NRCan, however, the statistics comprise a much larger range of data that includes houses where the basement is used more frequently, houses with fully occupied basement apartments, and houses that do not have a basement. The statistical energy consumption should be relied upon only as a general comparison to the simulated energy consumption.

Fig.7.8 shows the distribution of residential energy consumption by end-use in 2008 from Natural Resources Canada data. The data shows that space heating accounts for an average of 63% of energy consumption in Canadian houses. This is higher than the percentage of space heating energy consumption in the three simulations presented above, but close to the Winnipeg simulation.

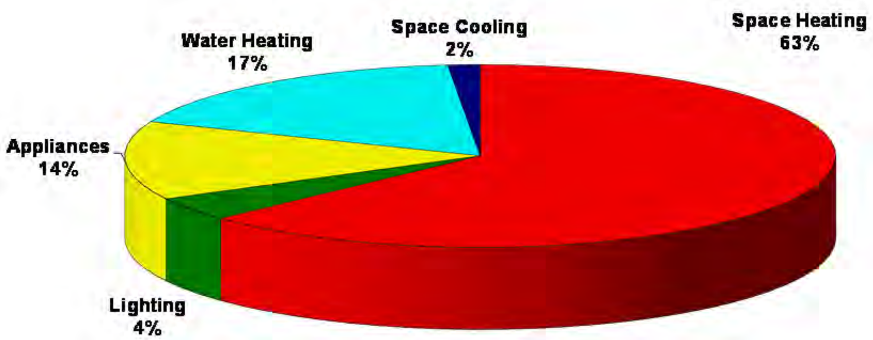


Fig.7.8 Residential Energy Consumption by End-Use, 2008 (Natural Resources Canada).

Another means of verifying the hourly energy simulations is to compare the simulation results to the same house modeled using the program HOT2000, which is more commonly used to simulate energy consumption of houses in Canada. The results of this comparison are shown in Fig.7.8 for a house in Vancouver, Toronto and Winnipeg. With this analysis it is important to recognize that the two programs use very different methods of calculating energy consumption and each program has its own limitations in different areas.

Table 7.2 Summary of energy consumption simulated in HOT2000 and DesignBuilder (DB).

	Vancouver			Toronto			Winnipeg		
End-Use	HOT2000	DB	Percent Difference	HOT2000	DB	Percent Difference	HOT2000	DB	Percent Difference
Space Heating	12,362	12,283	0.6%	11,168	12,834	14.9%	18,950	19,606	3.5%
Fan Power	1,928	1,816	5.8%	1,737	1,839	5.9%	1,912	1,923	0.6%
Cooling	930	869	6.6%	1,587	1,215	23.5%	1,400	1,200	14.3%

Space heating and cooling energy compare well between the two programs. Although the cooling energy consumption has a higher percent difference, the cooling numbers are fairly small and the absolute difference is low. Looking at the monthly heating and cooling energy consumption shows that the simulation results from the two programs compare well.

Fig.7.9 and Fig.7.10 show the monthly heating and cooling energy consumption simulated in HOT2000 and DesignBuilder for the “mild” archetype house in Vancouver. The monthly data shows that the two programs line up fairly well, with different amounts of monthly variation (i.e. not a consistent difference each month). The variations are likely attributable to different schedules (for example, DesignBuilder simulates cooling in April but not October, while HOT2000 is the opposite), different weather data and different calculation methods.

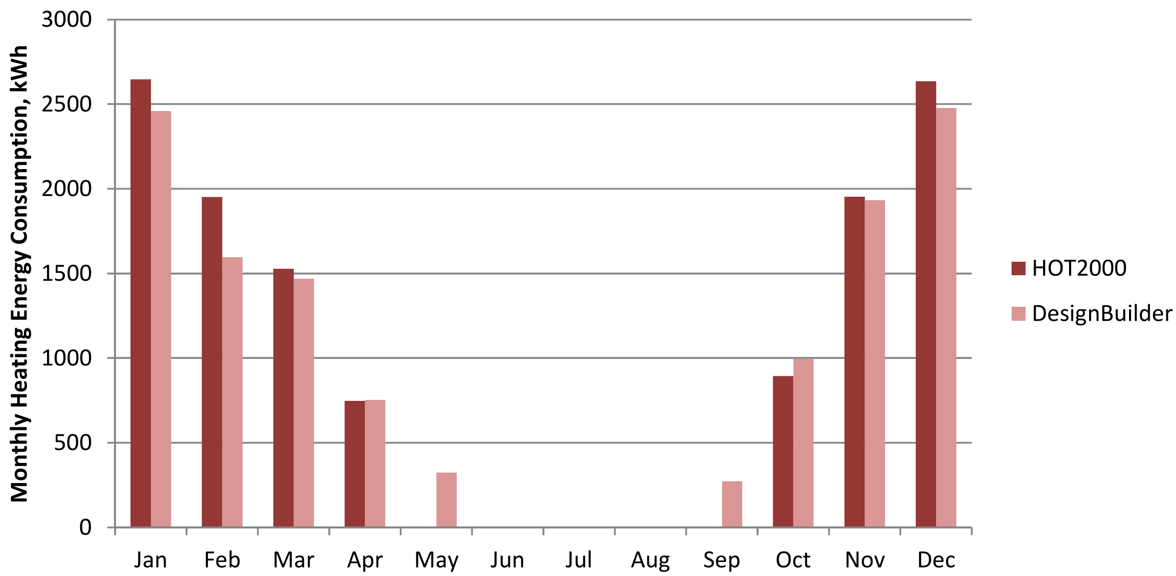


Fig.7.9 Monthly heating energy simulated in HOT2000 and DesignBuilder in Vancouver.

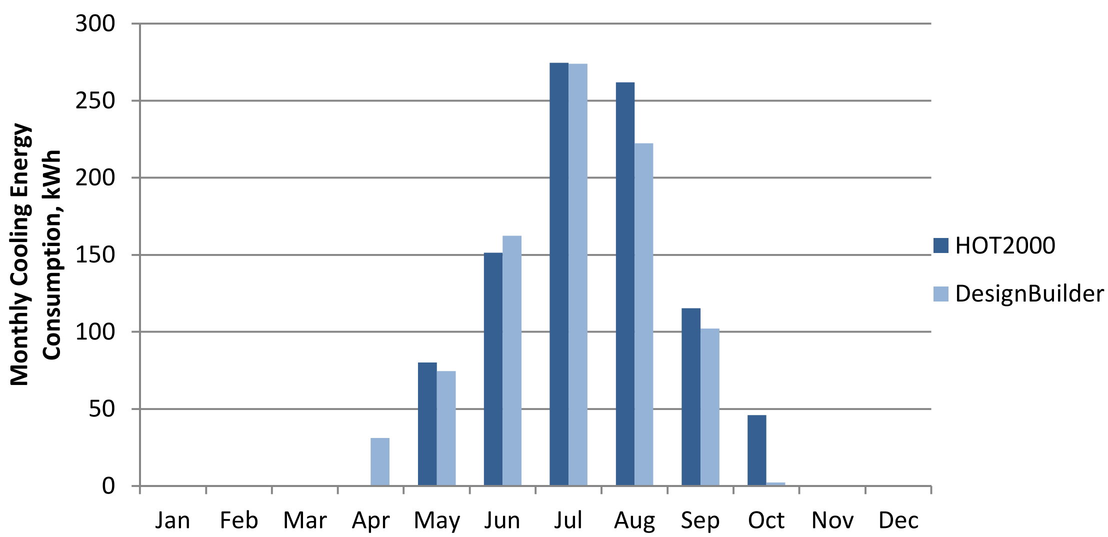


Fig.7.10 Monthly cooling energy simulated in HOT2000 and DesignBuilder in Vancouver.

Fig.7.11 and Fig.7.12 show the heating and cooling energy simulated in HOT2000 and DesignBuilder for the "cold" archetype house in Toronto. As with the Vancouver comparison, the two programs provide similar results with different amounts of monthly variability. DesignBuilder simulates slightly more heating energy and less cooling energy than HOT2000 in this scenario.

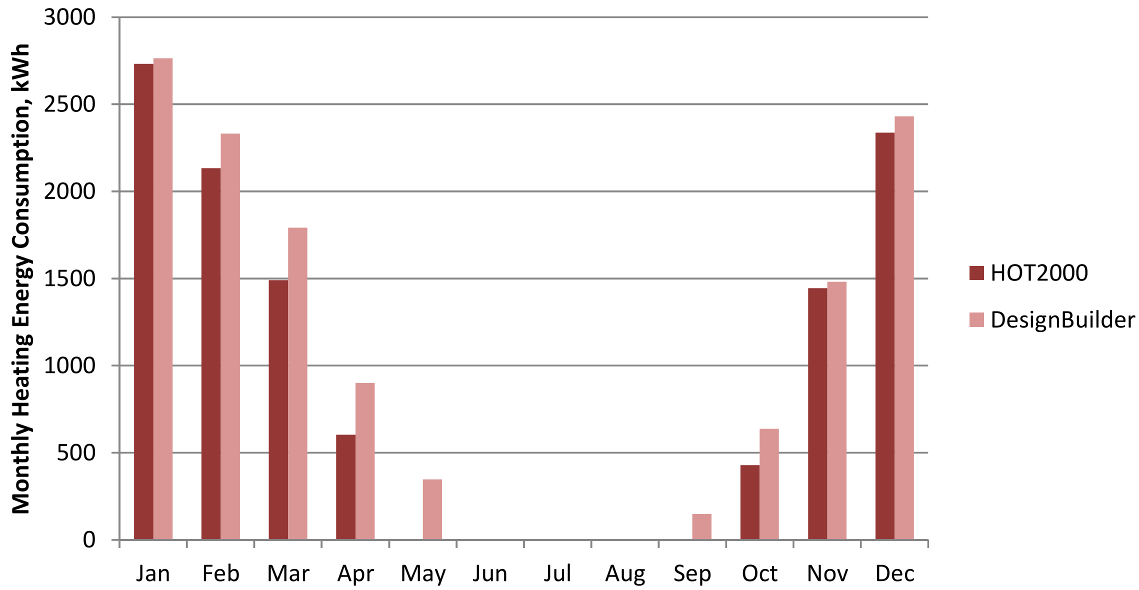


Fig.7.11 Monthly heating energy simulated in HOT2000 and DesignBuilder in Toronto.

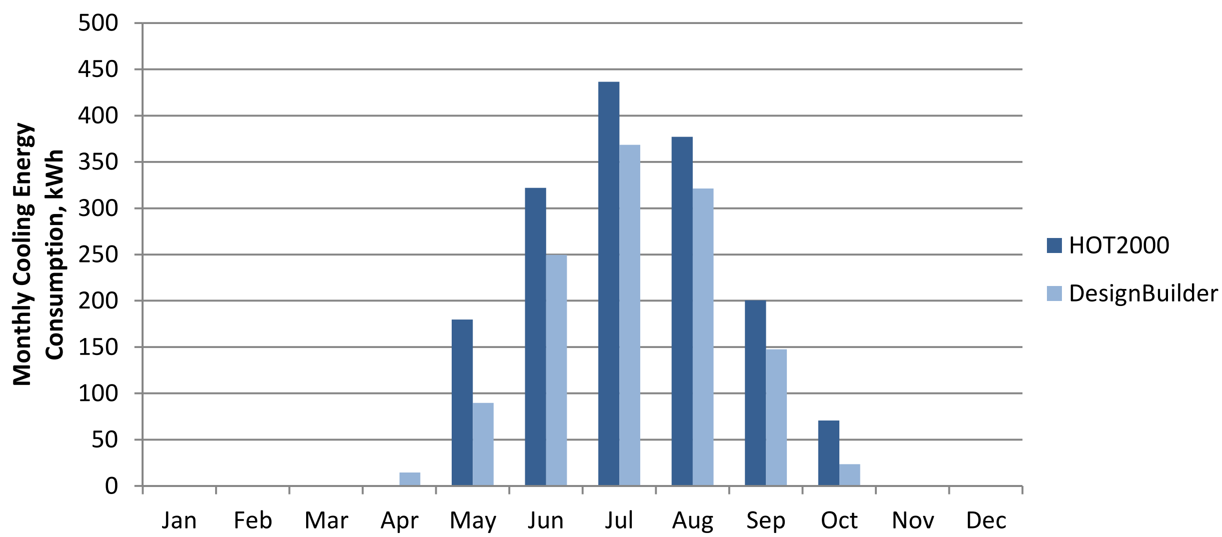


Fig.7.12 Monthly cooling energy simulated in HOT2000 and DesignBuilder in Toronto.

Fig.7.13 and Fig.7.14 show the monthly heating and cooling energy simulated in HOT2000 and DesignBuilder for the "cold" archetype house in Winnipeg. As with the Vancouver and Toronto comparisons, the two programs provide similar results with different amounts of monthly variability.

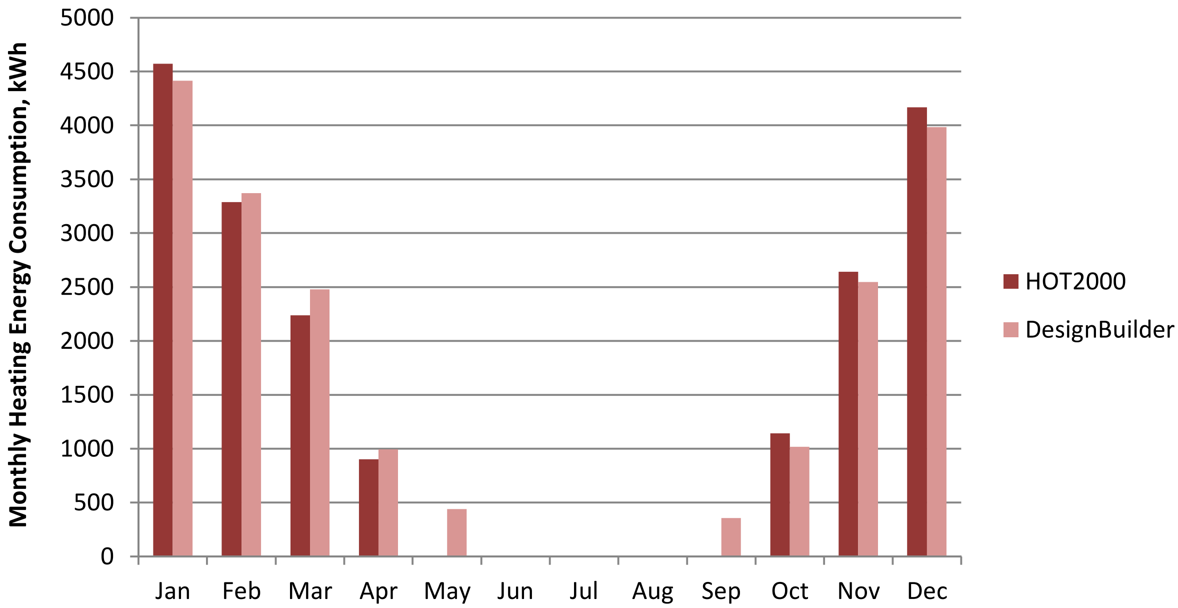


Fig.7.13 Monthly heating energy simulated in HOT2000 and DesignBuilder in Winnipeg.

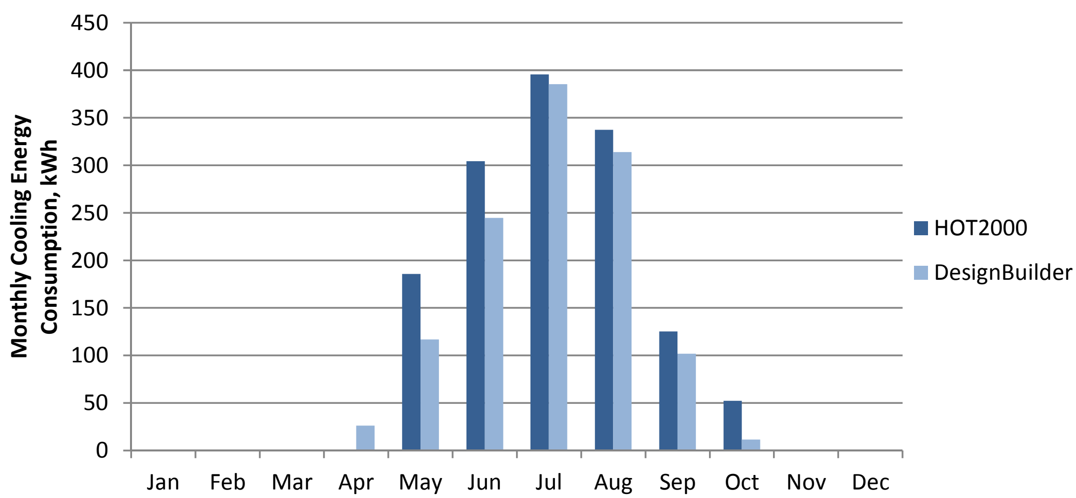


Fig.7.14 Monthly cooling energy simulated in HOT2000 and DesignBuilder in Winnipeg.

7.3. Baseline Energy Simulation Results

The single-storey archetype house (gas furnace, central air conditioning, existing house enclosure inputs) was simulated with each of the 23 windows established in Section 6. Simulations were performed for this archetype for the 13 cities identified in Section 5. It should be noted that the same archetype was simulated for Yellowknife even though houses in the far north typically do not have basements. This was done so that Yellowknife energy consumption results could be compared to the other cities. The following plots show results for three cities with different climates: Vancouver, Toronto and Winnipeg.

Fig.7.15, Fig.7.16 and Fig.7.17 show the annual heating, cooling and total energy, respectively, for the house in Vancouver with each window type. Refer to Table 6.10 for the U-value and SHGC parameters associated with each window type. The data in each plot is ordered from lowest to highest ER. The plots show that a higher ER does not necessarily correspond to lower energy consumption in heating, cooling and total energy consumption. The overall trend is that higher ERs trend towards lower heating and total energy consumption. However, within ERs that are close there are a number of cases where the ER of window A may be higher than window B, but window B uses more energy than window A. For cooling energy, windows with a lower SHGC have less cooling energy consumption, since solar heat gain is reduced. There is a slight tendency for windows with a higher ER to have more cooling energy consumption, though there is no regular pattern to this. The poor correlation between ER and cooling energy is expected since the ER was developed based on reducing heating energy.

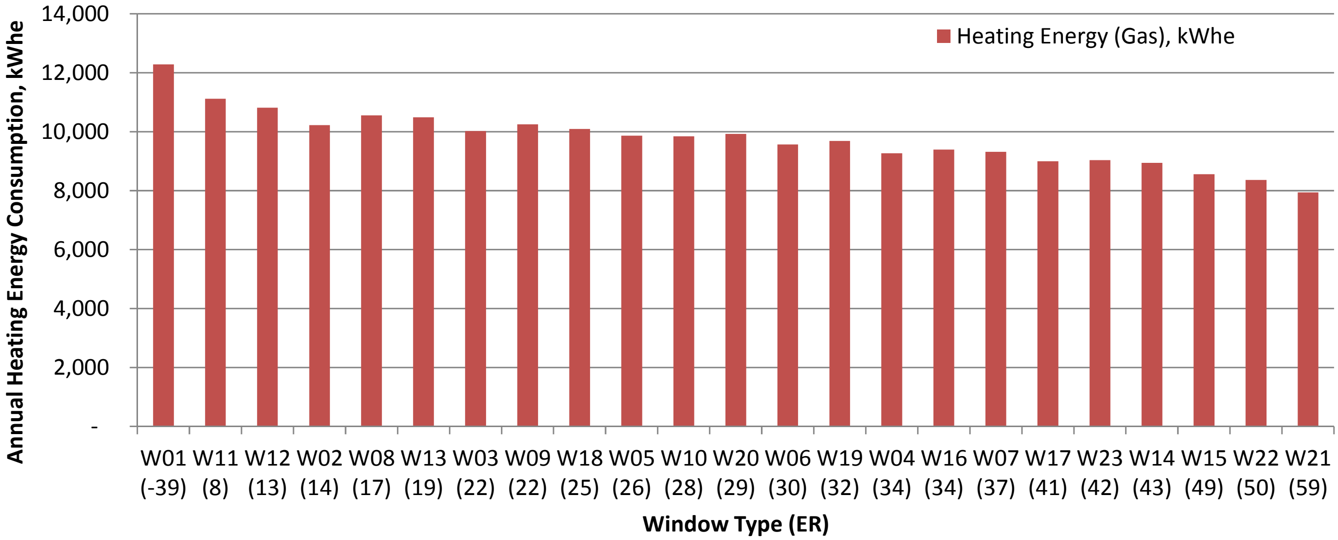


Fig.7.15 Annual heating energy consumption in Vancouver, kWh_e.

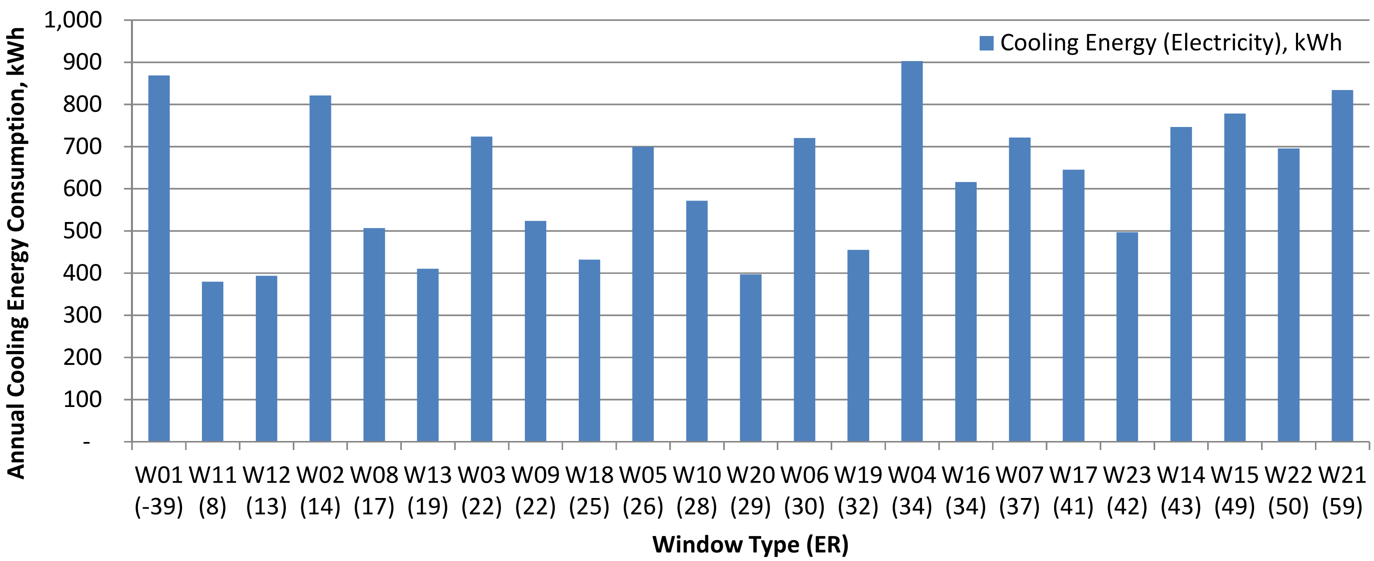


Fig.7.16 Annual cooling energy consumption in Vancouver, kWh.

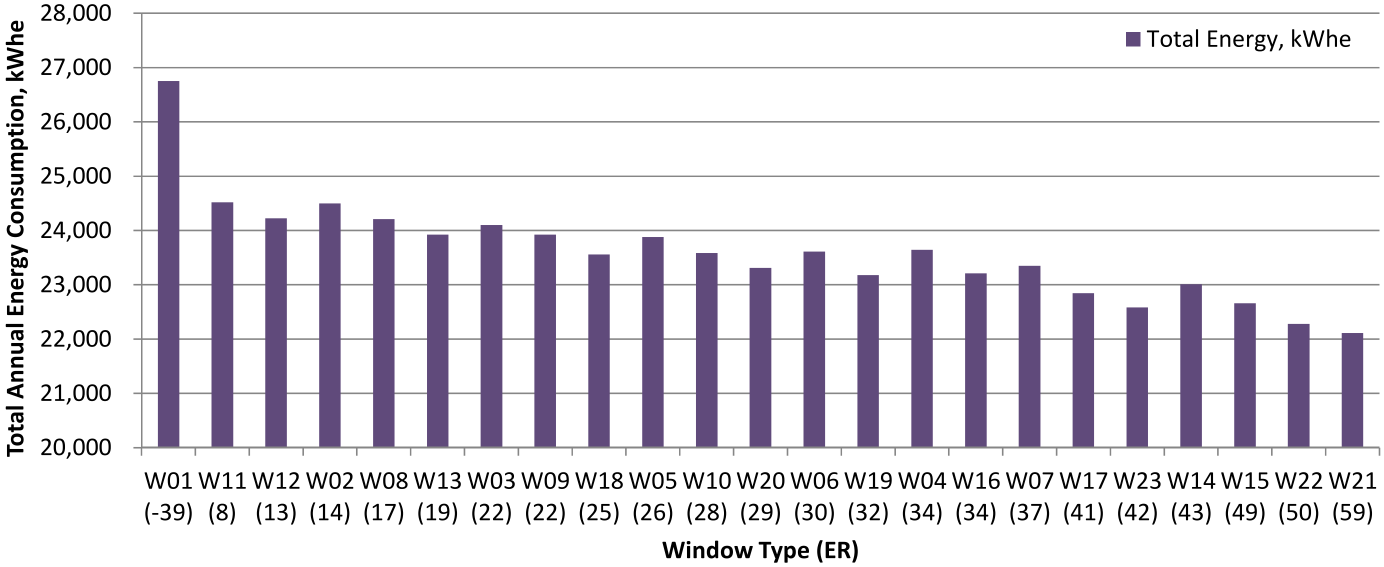


Fig.7.17 Total annual household energy consumption in Vancouver, kWh_e.

Fig.7.18, Fig.7.19 and Fig.7.20 show the annual heating, cooling and total energy, respectively, for the house in Toronto with each window type. The data in each plot is ordered from lowest to highest ER. The results are similar to the Vancouver plots. Overall, a higher ER generally results in lower energy consumption. However, within ER values that are close there are a number of cases where a window with a higher ER uses more heating or total energy.

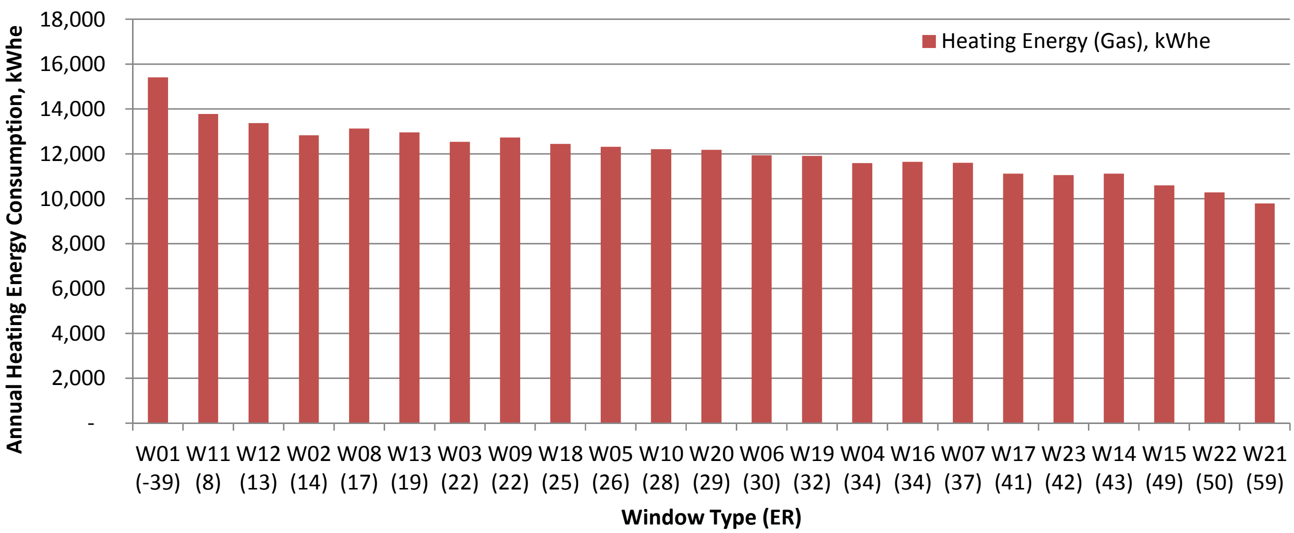


Fig.7.18 Annual heating energy consumption in Toronto, kWh_e.

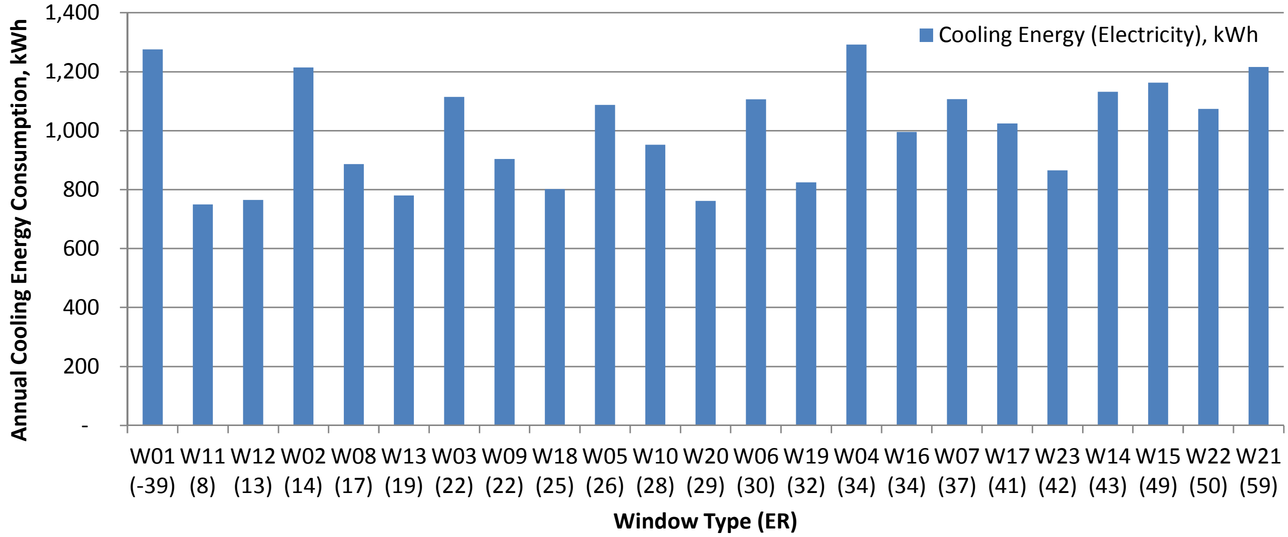


Fig.7.19 Annual cooling energy consumption in Toronto, kWh.

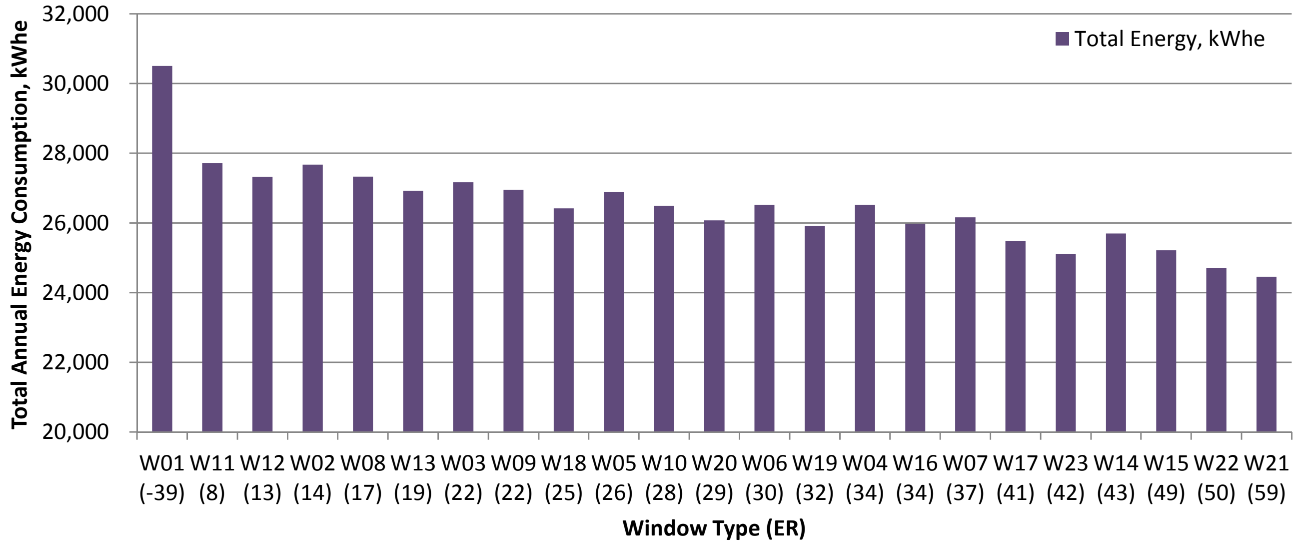


Fig.7.20 Total annual household energy consumption in Toronto, kWh_e.

Fig.7.21, Fig.7.22 and Fig.7.23 show the annual heating, cooling and total energy, respectively, for the house in Winnipeg with each window type. The data in each plot is ordered from lowest to highest ER. The results are similar to the Vancouver and Toronto plots. Overall, a higher ER generally results in lower energy consumption. However, within ER values that are close there are a number of cases where a window with a higher ER uses more heating or total energy.

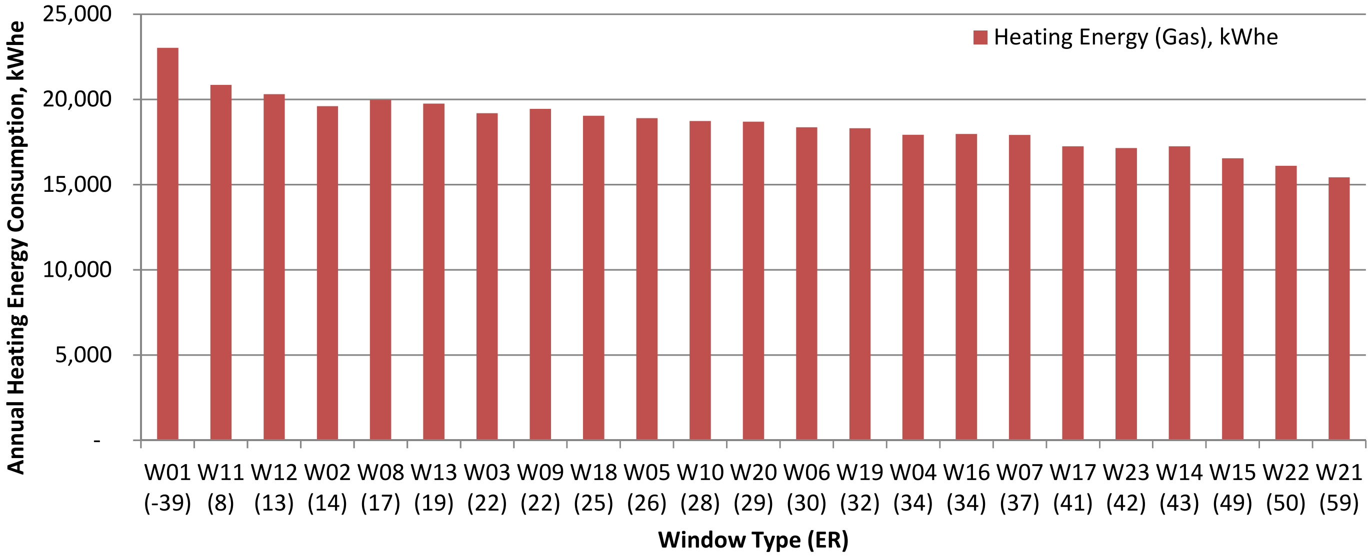


Fig.7.21 Annual heating energy consumption in Winnipeg, kWh_e.

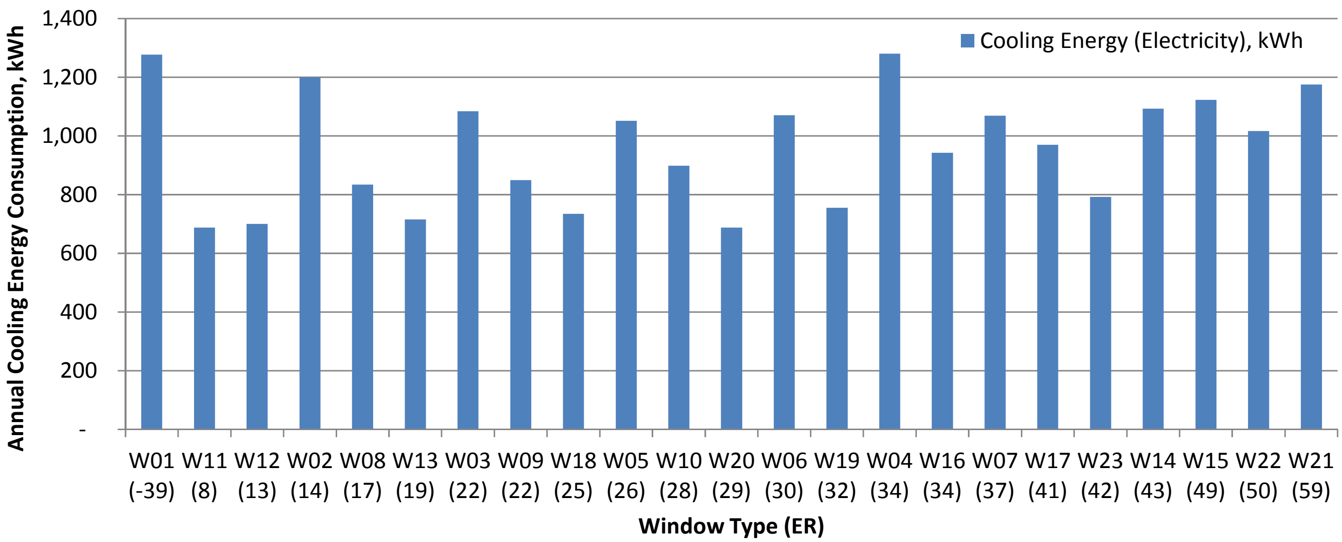


Fig.7.22 Annual cooling energy consumption in Winnipeg, kWh.

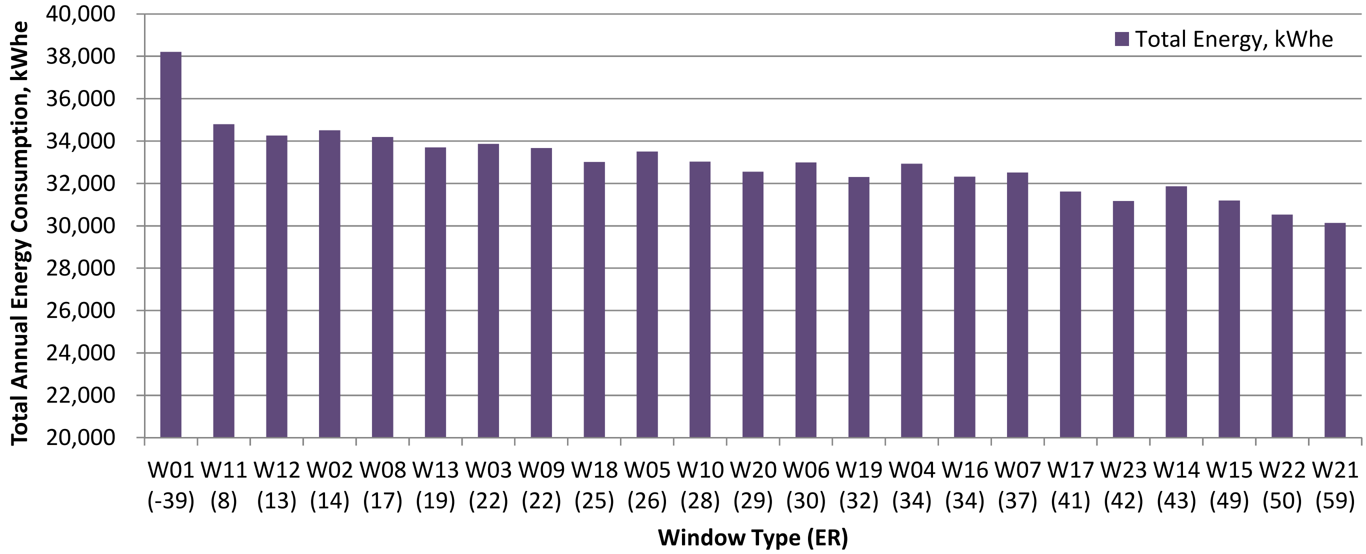


Fig.7.23 Total annual household energy consumption in Winnipeg, kWh_e.

It is also helpful to plot this data as a line plot, to view the results from all cities on a single plot and identify anomalies. Fig.7.24, Fig.7.25, and Fig.7.26 show the annual heating, cooling and total energy consumption, respectively, for all window types in all geographic locations. These plots are useful to compare the difference between geographic locations.

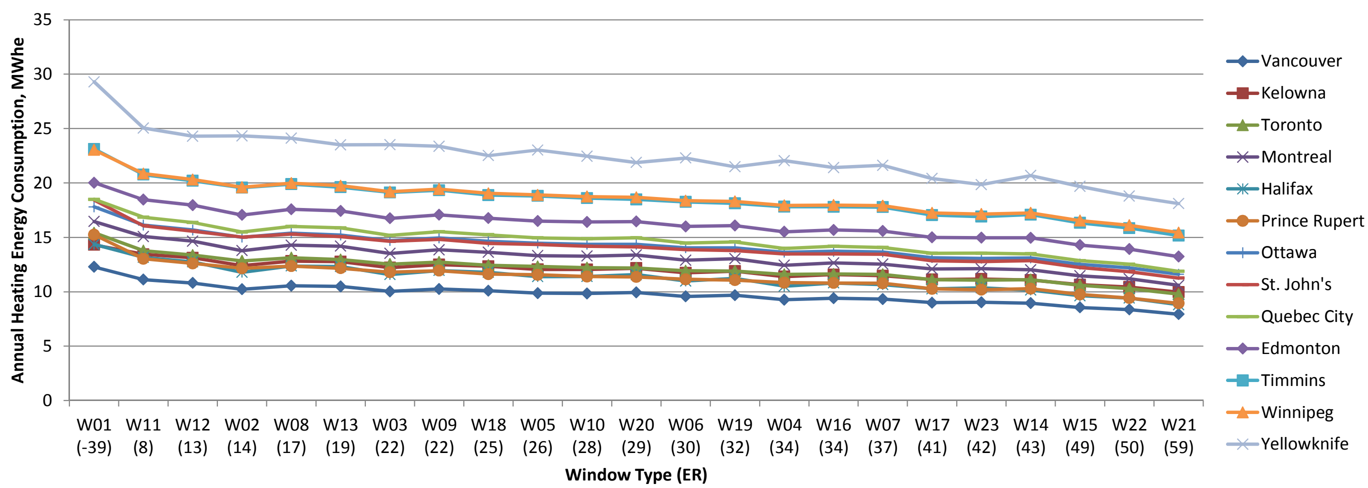


Fig.7.24 Annual heating energy consumption, MWh_e.

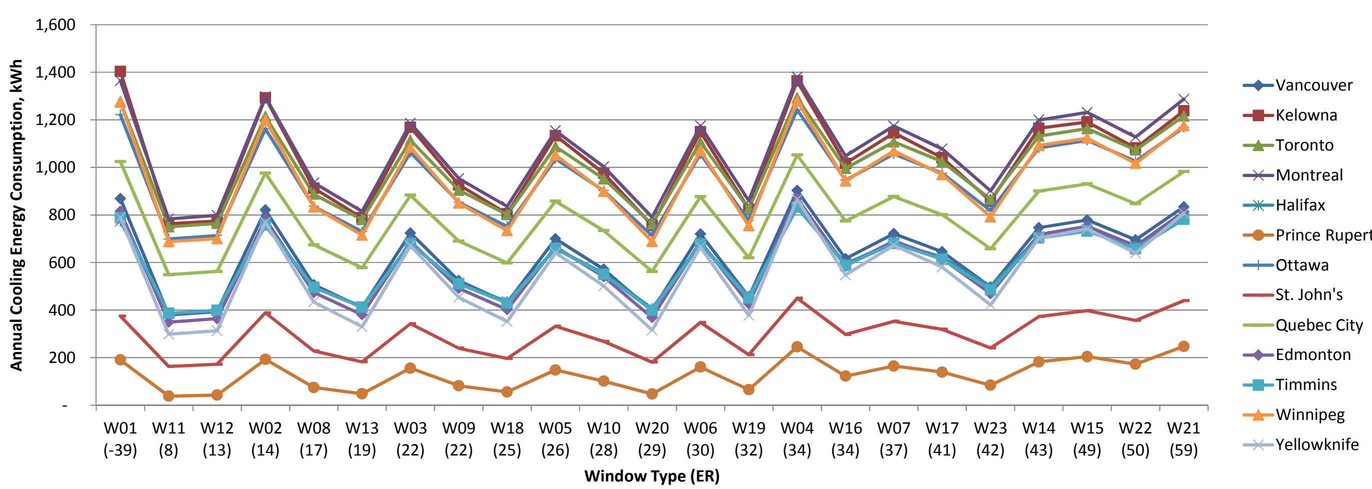


Fig.7.25 Annual cooling energy consumption, kWh.

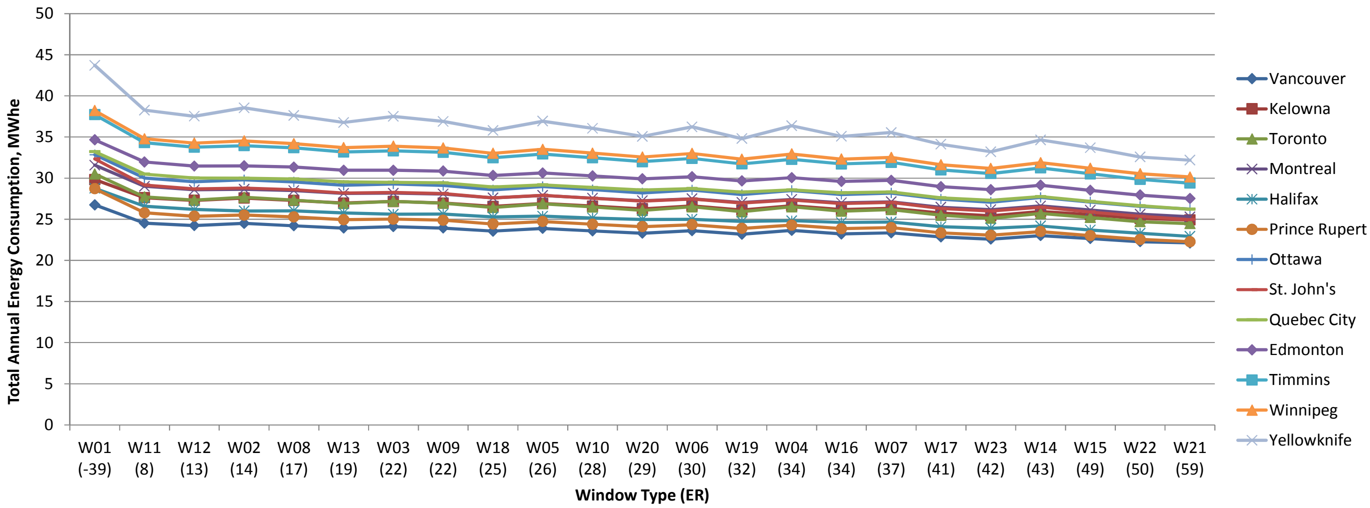


Fig.7.26 Total annual energy consumption, MWh_e.

The results can also be shown in tabular format. Annual space heat energy consumption for all of the locations simulated is shown in Table 7.3 and Table 7.4. Annual cooling energy for each location is shown in Table 7.5 and Table 7.6, and total household energy consumption is shown in Table 7.7. Each row in the table is formatted by colour on a scale of red to green, with the highest energy consumption in red. It is noteworthy that the ordering by ER (Table 7.3) shows a better trend than the ordering by U-value (Table 7.4).

Table 7.3 Annual Space Heating Energy Consumption, MWh_e, ordered lowest to highest ER.

	W01 (-39)	W11 (8)	W12 (13)	W02 (14)	W08 (17)	W13 (19)	W03 (22)	W09 (22)	W18 (25)	W05 (26)	W10 (28)	W20 (29)	W06 (30)	W19 (32)	W04 (34)	W16 (34)	W07 (37)	W17 (41)	W23 (42)	W14 (43)	W15 (49)	W22 (50)	W21 (59)
U-Value	*5.58*	*2.00*	*1.75*	*2.83*	*2.00*	*1.50*	*2.27*	*1.75*	*1.20*	*2.00*	*1.50*	*0.90*	*1.75*	*0.90*	*2.00*	*1.20*	*1.50*	*0.90*	*0.45*	*1.20*	*0.90*	*0.45*	*0.45*
SHGC	*0.74*	*0.20*	*0.20*	*0.64*	*0.35*	*0.20*	*0.55*	*0.35*	*0.20*	*0.50*	*0.35*	*0.15*	*0.50*	*0.20*	*0.65*	*0.35*	*0.50*	*0.35*	*0.20*	*0.50*	*0.50*	*0.35*	*0.50*
Vancouver	12.3	11.1	10.8	10.2	10.6	10.5	10.0	10.2	10.1	9.9	9.8	9.9	9.6	9.7	9.3	9.4	9.3	9.0	9.0	8.9	8.6	8.4	7.9
Kelowna	14.3	13.4	13.1	12.4	12.8	12.8	12.2	12.5	12.3	12.1	12.0	12.2	11.7	11.9	11.4	11.6	11.5	11.1	11.2	11.1	10.6	10.4	10.0
Toronto	15.4	13.8	13.4	12.8	13.1	13.0	12.5	12.7	12.4	12.3	12.2	12.2	11.9	11.9	11.6	11.6	11.6	11.1	11.1	11.1	10.6	10.3	9.8
Montreal	16.5	15.1	14.6	13.8	14.3	14.2	13.5	13.9	13.6	13.3	13.3	13.4	12.9	13.0	12.4	12.7	12.5	12.1	12.1	12.0	11.5	11.2	10.6
Halifax	14.4	13.2	12.7	11.8	12.4	12.3	11.6	12.0	11.8	11.4	11.4	11.6	11.0	11.2	10.5	10.8	10.7	10.3	10.4	10.2	9.6	9.4	8.8
Prince Rupert	15.2	13.0	12.6	12.2	12.4	12.2	11.8	11.9	11.6	11.5	11.4	11.4	11.1	11.1	10.8	10.8	10.8	10.3	10.2	10.3	9.8	9.4	8.9
Ottawa	17.8	16.1	15.7	15.0	15.4	15.2	14.7	14.9	14.6	14.5	14.4	14.3	14.0	14.0	13.6	13.7	13.7	13.1	13.1	13.1	12.5	12.2	11.6
St. John's	18.4	16.1	15.6	15.0	15.3	15.1	14.6	14.8	14.4	14.3	14.2	14.1	13.9	13.8	13.5	13.5	13.5	12.9	12.8	12.9	12.2	11.9	11.3
Quebec City	18.5	16.8	16.4	15.5	16.0	15.9	15.2	15.5	15.2	14.9	14.9	15.0	14.5	14.6	14.0	14.2	14.1	13.5	13.5	13.5	12.9	12.5	11.9
Edmonton	20.0	18.5	18.0	17.1	17.6	17.4	16.7	17.1	16.8	16.5	16.4	16.5	16.0	16.1	15.5	15.7	15.6	15.0	15.0	15.0	14.3	13.9	13.2
Timmins	23.1	20.8	20.2	19.6	19.9	19.6	19.1	19.3	18.9	18.8	18.6	18.5	18.3	18.1	17.8	17.8	17.8	17.0	16.9	17.1	16.3	15.8	15.2
Winnipeg	23.0	20.9	20.3	19.6	20.0	19.7	19.2	19.4	19.0	18.9	18.7	18.7	18.4	18.3	17.9	18.0	17.9	17.2	17.1	17.2	16.5	16.1	15.4
Yellowknife	29.3	25.0	24.3	24.3	24.1	23.5	23.5	23.4	22.5	23.0	22.5	21.9	22.3	21.5	22.0	21.4	21.6	20.4	19.8	20.7	19.7	18.8	18.1

Table 7.4 Annual Space Heating Energy Consumption, MWh_e, ordered highest to lowest U-value.

	W01 (-39)	W02 (14)	W03 (22)	W11 (8)	W08 (17)	W05 (26)	W04 (34)	W12 (13)	W09 (22)	W06 (30)	W13 (19)	W10 (28)	W07 (37)	W18 (25)	W16 (34)	W14 (43)	W20 (29)	W19 (32)	W17 (41)	W15 (49)	W23 (42)	W22 (50)	W21 (59)
U-Value	*5.58*	*2.83*	*2.27*	*2.00*	*2.00*	*2.00*	*2.00*	*1.75*	*1.75*	*1.75*	*1.50*	*1.50*	*1.50*	*1.20*	*1.20*	*1.20*	*0.90*	*0.90*	*0.90*	*0.90*	*0.45*	*0.45*	*0.45*
SHGC	*0.74*	*0.64*	*0.55*	*0.20*	*0.35*	*0.50*	*0.65*	*0.20*	*0.35*	*0.50*	*0.20*	*0.35*	*0.50*	*0.20*	*0.35*	*0.50*	*0.15*	*0.20*	*0.35*	*0.50*	*0.20*	*0.35*	*0.50*
Vancouver	12.3	10.2	10.0	11.1	10.6	9.9	9.3	10.8	10.2	9.6	10.5	9.8	9.3	10.1	9.4	8.9	9.9	9.7	9.0	8.6	9.0	8.4	7.9
Kelowna	14.3	12.4	12.2	13.4	12.8	12.1	11.4	13.1	12.5	11.7	12.8	12.0	11.5	12.3	11.6	11.1	12.2	11.9	11.1	10.6	11.2	10.4	10.0
Toronto	15.4	12.8	12.5	13.8	13.1	12.3	11.6	13.4	12.7	11.9	13.0	12.2	11.6	12.4	11.6	11.1	12.2	11.9	11.1	10.6	11.1	10.3	9.8
Montreal	16.5	13.8	13.5	15.1	14.3	13.3	12.4	14.6	13.9	12.9	14.2	13.3	12.5	13.6	12.7	12.0	13.4	13.0	12.1	11.5	12.1	11.2	10.6
Halifax	14.4	11.8	11.6	13.2	12.4	11.4	10.5	12.7	12.0	11.0	12.3	11.4	10.7	11.8	10.8	10.2	11.6	11.2	10.3	9.6	10.4	9.4	8.8
Prince Rupert	15.2	12.2	11.8	13.0	12.4	11.5	10.8	12.6	11.9	11.1	12.2	11.4	10.8	11.6	10.8	10.3	11.4	11.1	10.3	9.8	10.2	9.4	8.9
Ottawa	17.8	15.0	14.7	16.1	15.4	14.5	13.6	15.7	14.9	14.0	15.2	14.4	13.7	14.6	13.7	13.1	14.3	14.0	13.1	12.5	13.1	12.2	11.6
St. John's	18.4	15.0	14.6	16.1	15.3	14.3	13.5	15.6	14.8	13.9	15.1	14.2	13.5	14.4	13.5	12.9	14.1	13.8	12.9	12.2	12.8	11.9	11.3
Quebec City	18.5	15.5	15.2	16.8	16.0	14.9	14.0	16.4	15.5	14.5	15.9	14.9	14.1	15.2	14.2	13.5	15.0	14.6	13.5	12.9	13.5	12.5	11.9
Edmonton	20.0	17.1	16.7	18.5	17.6	16.5	15.5	18.0	17.1	16.0	17.4	16.4	15.6	16.8	15.7	15.0	16.5	16.1	15.0	14.3	15.0	13.9	13.2
Timmins	23.1	19.6	19.1	20.8	19.9	18.8	17.8	20.2	19.3	18.3	19.6	18.6	17.8	18.9	17.8	17.1	18.5	18.1	17.0	16.3	16.9	15.8	15.2
Winnipeg	23.0	19.6	19.2	20.9	20.0	18.9	17.9	20.3	19.4	18.4	19.7	18.7	17.9	19.0	18.0	17.2	18.7	18.3	17.2	16.5	17.1	16.1	15.4
Yellowknife	29.3	24.3	23.5	25.0	24.1	23.0	22.0	24.3	23.4	22.3	23.5	22.5	21.6	22.5	21.4	20.7	21.9	21.5	20.4	19.7	19.8	18.8	18.1

Table 7.5 Annual Space Cooling Energy Consumption, kWh, ordered lowest to highest ER.

	W01 (-39)	W11 (8)	W12 (13)	W02 (14)	W08 (17)	W13 (19)	W03 (22)	W09 (22)	W18 (25)	W05 (26)	W10 (28)	W20 (29)	W06 (30)	W19 (32)	W04 (34)	W16 (34)	W07 (37)	W17 (41)	W23 (42)	W14 (43)	W15 (49)	W22 (50)	W21 (59)
U-Value	*5.58*	*2.00*	*1.75*	*2.83*	*2.00*	*1.50*	*2.27*	*1.75*	*1.20*	*2.00*	*1.50*	*0.90*	*1.75*	*0.90*	*2.00*	*1.20*	*1.50*	*0.90*	*0.45*	*1.20*	*0.90*	*0.45*	*0.45*
SHGC	*0.74*	*0.20*	*0.20*	*0.64*	*0.35*	*0.20*	*0.55*	*0.35*	*0.20*	*0.50*	*0.35*	*0.15*	*0.50*	*0.20*	*0.65*	*0.35*	*0.50*	*0.35*	*0.20*	*0.50*	*0.50*	*0.35*	*0.50*
Vancouver	869	379	394	821	507	410	724	524	432	699	572	397	720	455	903	616	721	645	497	747	779	695	834
Kelowna	1,403	763	775	1,293	913	788	1,169	926	805	1,134	975	756	1,150	824	1,364	1,016	1,145	1,040	858	1,164	1,191	1,081	1,237
Toronto	1,275	750	764	1,215	887	780	1,114	904	801	1,087	952	761	1,107	825	1,292	996	1,107	1,024	866	1,132	1,163	1,073	1,216
Montreal	1,365	783	798	1,297	936	815	1,185	953	836	1,154	1,003	791	1,174	860	1,380	1,049	1,174	1,078	901	1,199	1,231	1,128	1,287
Halifax	774	386	399	755	496	415	679	513	436	660	555	407	679	459	832	595	684	623	499	709	740	671	793
Prince Rupert	191	38	43	193	75	48	156	82	56	148	101	47	161	65	245	122	165	139	84	182	205	173	247
Ottawa	1,222	699	714	1,163	836	730	1,062	853	752	1,036	902	713	1,056	776	1,243	946	1,057	975	818	1,082	1,114	1,025	1,168
St. John's	375	163	172	388	228	183	343	240	197	332	269	181	348	213	450	298	353	319	241	373	397	356	440
Quebec City	1,025	549	563	976	674	578	883	690	598	858	734	563	876	620	1,052	774	877	801	658	901	930	847	982
Edmonton	815	350	364	783	474	381	690	492	402	665	540	368	687	427	870	585	691	616	469	718	753	670	813
Timmins	788	387	399	760	496	412	680	510	430	659	550	400	677	450	833	588	680	614	486	703	732	659	782
Winnipeg	1,277	688	701	1,200	834	715	1,085	850	734	1,052	899	688	1,071	755	1,280	943	1,069	970	792	1,092	1,123	1,017	1,175
Yellowknife	789	298	313	769	435	330	671	453	352	641	501	316	665	377	866	547	672	581	422	703	741	640	807

Table 7.6 Annual Space Cooling Energy Consumption, kWh, ordered highest to lowest SHGC.

	W01 (-39)	W04 (34)	W02 (14)	W03 (22)	W05 (26)	W06 (30)	W07 (37)	W14 (43)	W15 (49)	W21 (59)	W08 (17)	W09 (22)	W10 (28)	W16 (34)	W17 (41)	W22 (50)	W11 (8)	W12 (13)	W13 (19)	W18 (25)	W19 (32)	W23 (42)	W20 (29)
U-Value	*5.58*	*2.00*	*2.83*	*2.27*	*2.00*	*1.75*	*1.50*	*1.20*	*0.90*	*0.45*	*2.00*	*1.75*	*1.50*	*1.20*	*0.90*	*0.45*	*2.00*	*1.75*	*1.50*	*1.20*	*0.90*	*0.45*	*0.90*
SHGC	*0.74*	*0.65*	*0.64*	*0.55*	*0.50*	*0.50*	*0.50*	*0.50*	*0.50*	*0.50*	*0.35*	*0.35*	*0.35*	*0.35*	*0.35*	*0.35*	*0.20*	*0.20*	*0.20*	*0.20*	*0.20*	*0.20*	*0.15*
Vancouver	869	903	821	724	699	720	721	747	779	834	507	524	572	616	645	695	379	394	410	432	455	497	397
Kelowna	1403	1364	1293	1169	1134	1150	1145	1164	1191	1237	913	926	975	1016	1040	1081	763	775	788	805	824	858	756
Toronto	1275	1292	1215	1114	1087	1107	1107	1132	1163	1216	887	904	952	996	1024	1073	750	764	780	801	825	866	761
Montreal	1365	1380	1297	1185	1154	1174	1174	1199	1231	1287	936	953	1003	1049	1078	1128	783	798	815	836	860	901	791
Halifax	774	832	755	679	660	679	684	709	740	793	496	513	555	595	623	671	386	399	415	436	459	499	407
Prince Rupert	191	245	193	156	148	161	165	182	205	247	75	82	101	122	139	173	38	43	48	56	65	84	47
Ottawa	1222	1243	1163	1062	1036	1056	1057	1082	1114	1168	836	853	902	946	975	1025	699	714	730	752	776	818	713
St. John's	375	450	388	343	332	348	353	373	397	440	228	240	269	298	319	356	163	172	183	197	213	241	181
Quebec City	1025	1052	976	883	858	876	877	901	930	982	674	690	734	774	801	847	549	563	578	598	620	658	563
Edmonton	815	870	783	690	665	687	691	718	753	813	474	492	540	585	616	670	350	364	381	402	427	469	368
Timmins	788	833	760	680	659	677	680	703	732	782	496	510	550	588	614	659	387	399	412	430	450	486	400
Winnipeg	1277	1280	1200	1085	1052	1071	1069	1092	1123	1175	834	850	899	943	970	1017	688	701	715	734	755	792	688
Yellowknife	789	866	769	671	641	665	672	703	741	807	435	453	501	547	581	640	298	313	330	352	377	422	316

Table 7.7 Total Annual Household Energy Consumption, MWh_e, ordered lowest to highest ER.

	W01 (-39)	W11 (8)	W12 (13)	W02 (14)	W08 (17)	W13 (19)	W03 (22)	W09 (22)	W18 (25)	W05 (26)	W10 (28)	W20 (29)	W06 (30)	W19 (32)	W04 (34)	W16 (34)	W07 (37)	W17 (41)	W23 (42)	W14 (43)	W15 (49)	W22 (50)	W21 (59)
U-Value	*5.58*	*2.00*	*1.75*	*2.83*	*2.00*	*1.50*	*2.27*	*1.75*	*1.20*	*2.00*	*1.50*	*0.90*	*1.75*	*0.90*	*2.00*	*1.20*	*1.50*	*0.90*	*0.45*	*1.20*	*0.90*	*0.45*	*0.45*
SHGC	*0.74*	*0.20*	*0.20*	*0.64*	*0.35*	*0.20*	*0.55*	*0.35*	*0.20*	*0.50*	*0.35*	*0.15*	*0.50*	*0.20*	*0.65*	*0.35*	*0.50*	*0.35*	*0.20*	*0.50*	*0.50*	*0.35*	*0.50*
Vancouver	26.8	24.5	24.2	24.5	24.2	23.9	24.1	23.9	23.6	23.9	23.6	23.3	23.6	23.2	23.6	23.2	23.3	22.8	22.6	23.0	22.7	22.3	22.1
Kelowna	29.8	27.6	27.3	27.6	27.3	27.0	27.2	27.0	26.6	26.9	26.6	26.3	26.6	26.1	26.7	26.2	26.3	25.8	25.4	25.9	25.5	25.1	24.9
Toronto	30.5	27.7	27.3	27.7	27.3	26.9	27.2	26.9	26.4	26.9	26.5	26.1	26.5	25.9	26.5	26.0	26.2	25.5	25.1	25.7	25.2	24.7	24.5
Montreal	31.6	29.0	28.6	28.6	28.5	28.1	28.2	28.1	27.6	27.9	27.6	27.3	27.5	27.0	27.4	27.0	27.1	26.5	26.2	26.6	26.1	25.6	25.3
Halifax	28.8	26.6	26.2	26.0	26.0	25.8	25.6	25.6	25.3	25.4	25.1	25.0	25.0	24.7	24.8	24.6	24.7	24.1	23.9	24.2	23.7	23.3	22.9
Prince Rupert	28.7	25.8	25.4	25.5	25.3	24.9	25.0	24.9	24.4	24.7	24.4	24.1	24.3	23.9	24.3	23.8	24.0	23.3	23.1	23.5	23.0	22.6	22.3
Ottawa	32.8	30.0	29.6	29.8	29.5	29.1	29.3	29.1	28.6	29.0	28.6	28.2	28.6	28.0	28.5	28.0	28.2	27.4	27.1	27.6	27.1	26.6	26.2
St. John's	32.3	29.2	28.7	28.8	28.6	28.2	28.2	28.1	27.6	27.9	27.6	27.2	27.5	27.0	27.3	26.9	27.0	26.3	26.0	26.5	25.9	25.4	25.0
Quebec City	33.2	30.5	30.0	30.0	29.9	29.5	29.5	29.4	28.9	29.2	28.9	28.6	28.7	28.3	28.6	28.2	28.3	27.6	27.3	27.8	27.2	26.6	26.2
Edmonton	34.7	32.0	31.5	31.5	31.3	31.0	31.0	30.9	30.3	30.6	30.3	29.9	30.2	29.7	30.0	29.6	29.7	29.0	28.6	29.1	28.5	27.9	27.5
Timmins	37.7	34.3	33.8	33.9	33.7	33.2	33.3	33.1	32.5	32.9	32.5	32.0	32.4	31.7	32.3	31.7	31.9	31.0	30.6	31.2	30.5	29.8	29.4
Winnipeg	38.2	34.8	34.3	34.5	34.2	33.7	33.9	33.7	33.0	33.5	33.0	32.6	33.0	32.3	32.9	32.3	32.5	31.6	31.2	31.9	31.2	30.5	30.1
Yellowknife	43.7	38.3	37.5	38.5	37.6	36.8	37.5	36.9	35.8	36.9	36.1	35.1	36.2	34.8	36.4	35.1	35.5	34.1	33.2	34.6	33.7	32.6	32.2

Fig.7.27 shows a plot of annual heating energy consumption versus ER for five Canadian cities. The data shows a good fit to a linear trend line for each location. By comparison, Fig.7.28 shows the annual heating energy consumption versus U-value for the same five cities. The resulting linear trend line does not show as good a fit as the plot by ER; energy consumption for a particular window U-value also varies with the SHGC.

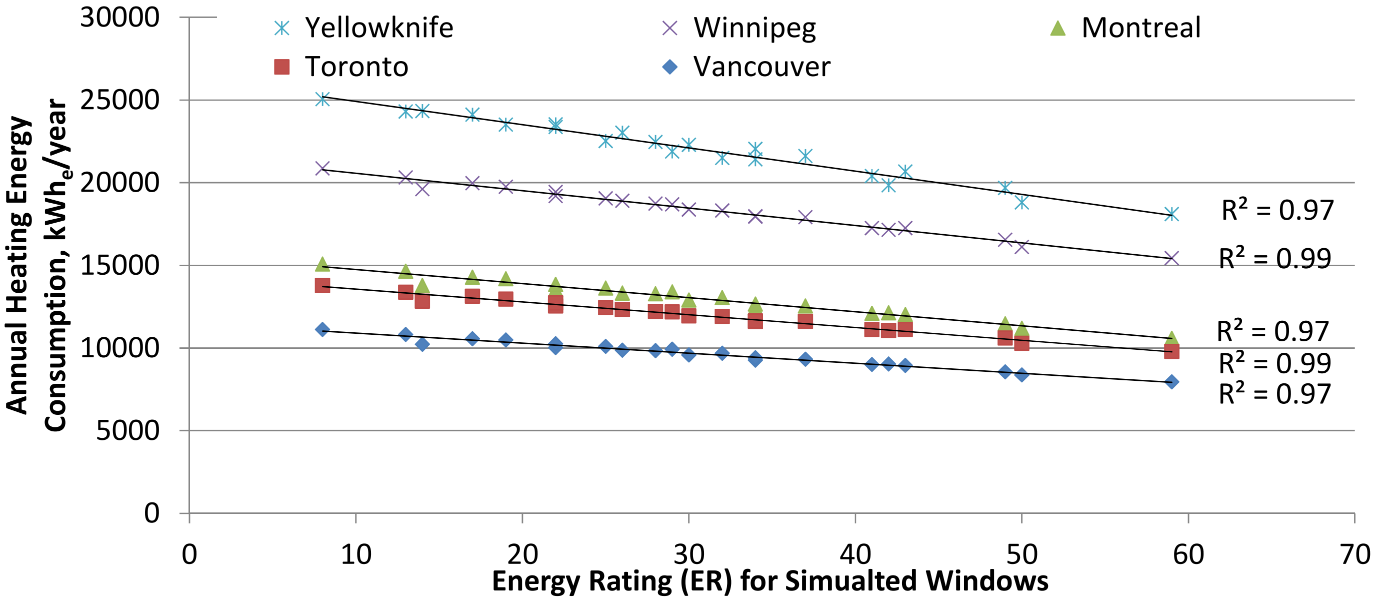


Fig.7.27 Heating energy consumption versus Energy Rating.

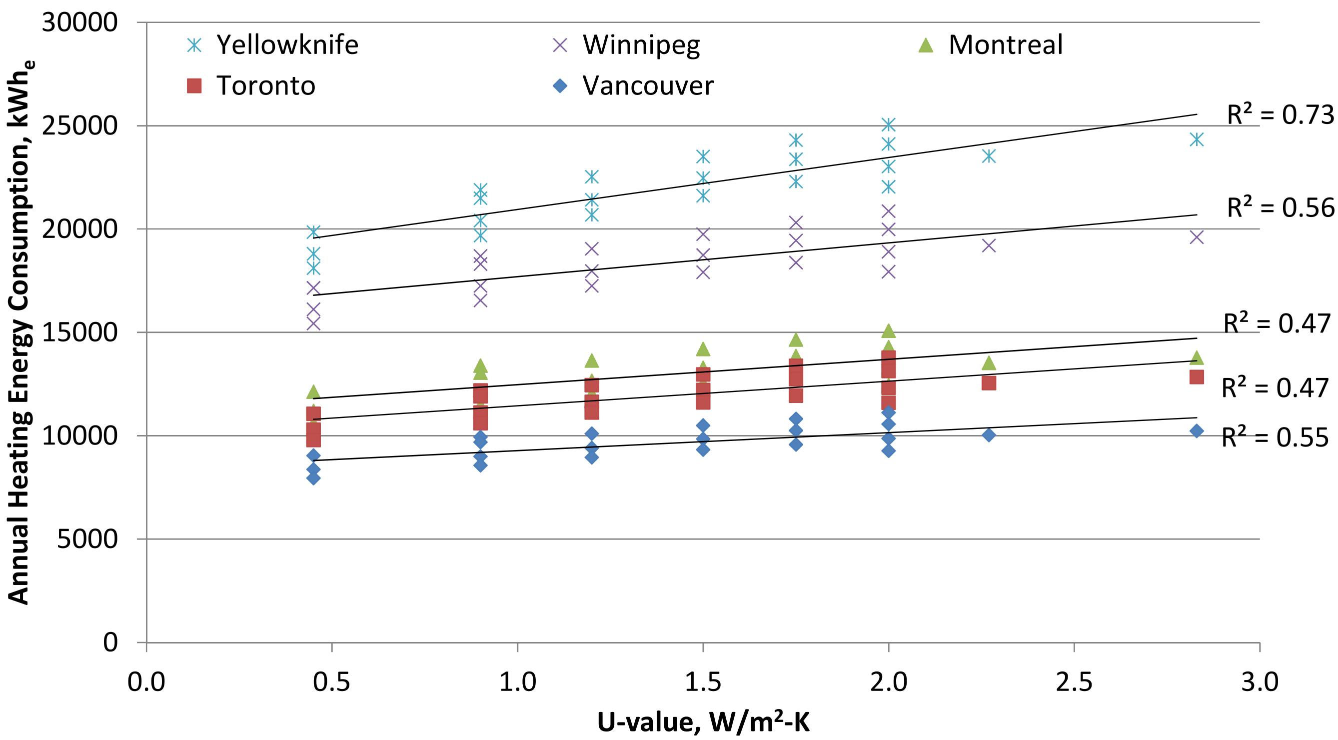


Fig.7.28 Heating energy consumption versus U-value.

7.3.1 Ordering of Energy Consumption and ER

Fig.7.24, Fig.7.25 and Fig.7.26 can be used to examine the order of energy consumption versus ER for different window types. Fig.7.24 shows that heating energy generally decreases as the ER increases, however, there are a number of cases where a higher ER also results in higher heating energy consumption in some or all locations:

- Heating energy increases as ER increases for a number of cases in Yellowknife only. In each of these cases, a double glazed, high SHGC window uses less energy than a triple glazed, low SHGC window in Yellowknife.
  - W18 (U-1.2, SHGC-0.20, ER-25) to W05 (U-2.0, SHGC-0.50, ER-26)
  - W20 (U-0.9, SHGC-0.15, ER-29) to W06 (U-1.75, SHGC-0.50, ER-30)
  - W19 (U-0.9, SHGC-0.20, ER-32) to W04 (U-2.0, SHGC-0.65, ER-34)
  - W16 (U-1.2, SHGC-0.35, ER-34) to W07 (U-1.5, SHGC-0.50, ER-37)
  - W23 (U-0.45, SHGC-0.20, ER-42) to W14 (U-1.2, SHGC-0.50, ER-43)
- Heating energy increases as ER increases for all locations except Yellowknife. High SHGC window uses less energy than low SHGC window.
  - W02 (U-2.83, SHGC-0.64, ER-14) to W08 (U-2.0, SHGC-0.35, ER-17)
- Heating energy increases as ER increases for Vancouver, Kelowna, Montreal, Halifax, Quebec City, Edmonton. High SHGC window uses less energy than low SHGC window.
  - W06 (U-1.75, SHGC-0.50, ER-30) to W19 (U-0.9, SHGC-0.20, ER-32)
- Heating energy increases as ER increases for Kelowna, Halifax. Higher SHGC window uses less energy than lower SHGC window.
  - W17 (U-0.9, SHGC-0.35, ER-41) to W23 (U-0.45, SHGC-0.20, ER-42)
- Heating energy increases as ER increases for Prince Rupert, St. John's, Timmins, Winnipeg, Yellowknife. In this case, a lower U-value (lower SHGC) window uses less energy than a higher U-value (higher SHGC) window in these locations.
  - W23 (U-0.45, SHGC-0.20, ER-42) to W14 (U-1.2, SHGC-0.50, ER-43)
- Windows with the same ER have different energy consumption, with a different trend in Yellowknife than other cities.
  - W03 to W09 (W09 higher than W03 in all locations except Yellowknife)
  - W04 to W16 (W16 the same or higher than W04 in all locations except Yellowknife)

Fig.7.25 shows that the cooling energy ordered from lowest to highest ER is inconsistent since cooling energy depends largely on SHGC. The geographic locations all follow the same general pattern of increasing/decreasing cooling energy for different window types.

Fig.7.26 shows that, like heating energy, total energy consumption generally decreases as the ER increases, however, there are a number of cases where a higher ER also results in higher heating energy consumption in some or all locations. These cases are:

- Total energy increases as ER increases for all locations except Montreal, Halifax, Quebec City and Edmonton. This occurs for low SHGC to high SHGC double glazed windows.
  - W12 (U-1.75, SHGC-0.20, ER-13) to W02 (U-2.83, SHGC-0.64, ER-14)
- Total energy increases as ER increases for all locations except Halifax, St. John's, Quebec City and Edmonton. This occurs for low SHGC to high SHGC double glazed windows.
  - W13 (U-1.50, SHGC-0.20, ER-19) to W03 (U-2.27, SHGC-0.55, ER-22)
- Total energy is the same or higher for all locations. This occurs for low SHGC triple glazed windows to high SHGC double glazed windows.
  - W18 (U-1.2, SHGC-0.20, ER-25) to W05 (U-2.0, SHGC-0.50, ER-26)

- W20 (U-0.9, SHGC-0.15, ER-29) to W06 (U-1.75, SHGC-0.50, ER-30)
- W19 (U-0.9, SHGC-0.20, ER-32) to W04 (U-2.0, SHGC-0.65, ER-34)
- W16 (U-1.2, SHGC-0.35, ER-34) to W07 (U-1.5, SHGC-0.50, ER-37)
- W23 (U-0.45, SHGC-0.20, ER-42) to W14 (U-1.2, SHGC-0.50, ER-43)

Note that Fig.7.26 represents total household energy consumption, including heating, cooling, fan power, and other energy. This data is really only applicable to houses that have both heating and cooling, which is not common in many parts of Canada.

Comparing Table 7.3 and Table 7.4, it is noteworthy that the heating and total energy results ordered by U-value appear to have more anomalies where lower U-value does not result in lower energy consumption compared to the results ordered by ER value. This suggests that although a higher ER does not always result in lower energy consumption, it may be more indicative of lower energy consumption than U-value alone.

7.3.2 Differences between Geographic Locations

Fig.7.24, Fig.7.25 and Fig.7.26 can be used to examine the difference between geographic locations and energy consumption for different window types.

Fig.7.24 shows that with the exception of W01, the order of geographic locations does not change by window type for heating energy consumption. The only exceptions for W01 are where St. John's crosses Ottawa, and Prince Rupert crosses Kelowna and Halifax. This is not a significant finding since W01 (a single glazed window) was used for reference only, and these windows are no longer installed in Canada. For all other window types, the order of heating energy for each window type does not change by geographic location.

Fig.7.25 shows that cooling energy follows the same general pattern for all geographic locations. There are a few areas where the line crosses slightly for some of the cities, however the pattern is consistent. The cities that cross are:

- Kelowna and Montreal: for W11 and W12 Kelowna has lower cooling energy, otherwise Montreal has lower cooling energy.
- Winnipeg and Ottawa cross at multiple points: for low SHGC, Winnipeg tends to have lower energy consumption than Ottawa; for high SHGC, Winnipeg tends to have higher energy consumption than Ottawa. Winnipeg has more summer solar radiation, but Ottawa has higher cooling degree days. It is thought that Winnipeg has higher energy consumption at high SHGC's since there are lower conductive losses at night (since Winnipeg has higher CDDs).
- Edmonton and Timmins cross at multiple points: for low SHGC, Edmonton has lower energy consumption than Timmins; for high SHGC, Edmonton has the same or higher energy consumption than Timmins. Edmonton has slightly more summer solar radiation than Timmins, while Timmins has slightly higher cooling degree days. This is the same pattern as the Winnipeg/Ottawa crossing.

Note that the difference in energy between the lines that cross is very small, and occur for cities that have very close energy consumption.

Fig.7.26 shows that the order of geographic locations does not change by window type for total energy consumption. In other words, a window always has a greater energy consumption in location A than in location B (the lines for each city do not cross). This indicates that the small difference in cooling energy is not large enough to impact the difference in total energy consumption.

7.3.3 Summary of Baseline Simulations

The baseline archetype house simulations indicates that generally, higher ER values result in lower energy consumption, as expected. However, within ER values that are close, there are a number of occurrences where a higher ER window results in higher energy consumption. Generally, this occurs where a higher SHGC window uses less heating or total energy than a lower SHGC window, but has a lower ER rating. Also, this generally occurs more in colder locations, though not always.

7.4. Factors Not Directly Related to Windows

The following simulation cases were run with one variable changed to assess factors that are not directly related to windows. Each simulation case is labeled A# for reference in the plots below. Case A1 is the single-storey house with gas heating, existing construction and other parameters described in Section 7.3.

- A2: Natural ventilation to offset cooling energy
- A3: Electric baseboard heating with zoned thermostat control
- A4: High internal gains (17 kWh/d equipment, 6 kWh/d lights)
- A5: No basement
- A6: New enclosure thermal performance (current code minimum)
- A7: High thermal mass (concrete construction) with new enclosure thermal performance
- A8: Walkout basement with fenestration
- A9: Two-storey house
- A10: Large two-storey house

The following plots show the annual heating and cooling energy consumption simulated for each archetype house case in Vancouver, Toronto, Montreal, Winnipeg and Yellowknife. These locations were selected for analysis here to show a range of climates; complete results for all locations can be found in Appendix C.

7.4.1 Comparing Archetypes

Fig.7.29, Fig.7.30 and Fig.7.31 show the heating, cooling and total energy for the archetype houses in Vancouver. For heating energy, the simulation results show that the archetype does not affect the general ordering of energy consumption by window type. That is, the window types follow the same path of heating energy consumption for each archetype house. This plot suggests that the archetype house does not affect the energy ranking of window types for heating energy. This is also the case for total energy.

For cooling energy, the simulation results show that the general trend of increasing/decreasing energy consumption is consistent across all archetypes, however, the magnitude of the increase or decrease varies for two of the archetypes, the two-storey house (A9) and the large two-storey house (A10). Comparing these two archetypes to the baseline case (A1), the larger houses have much higher cooling energy consumption than the baseline for windows with high solar heat gain (SHGC ≥ 0.50), and the same or lower cooling energy consumption for houses with low solar heat gain (SHGC-0.20). The larger houses likely result in higher cooling energy swings due to the larger window area; all three sizes have the same window to wall ratio in these simulations (15%), however in the larger houses the actual window area is greater. Despite the larger swings, the trends of increasing or decreasing energy consumption across the different window types are consistent in all three house sizes.

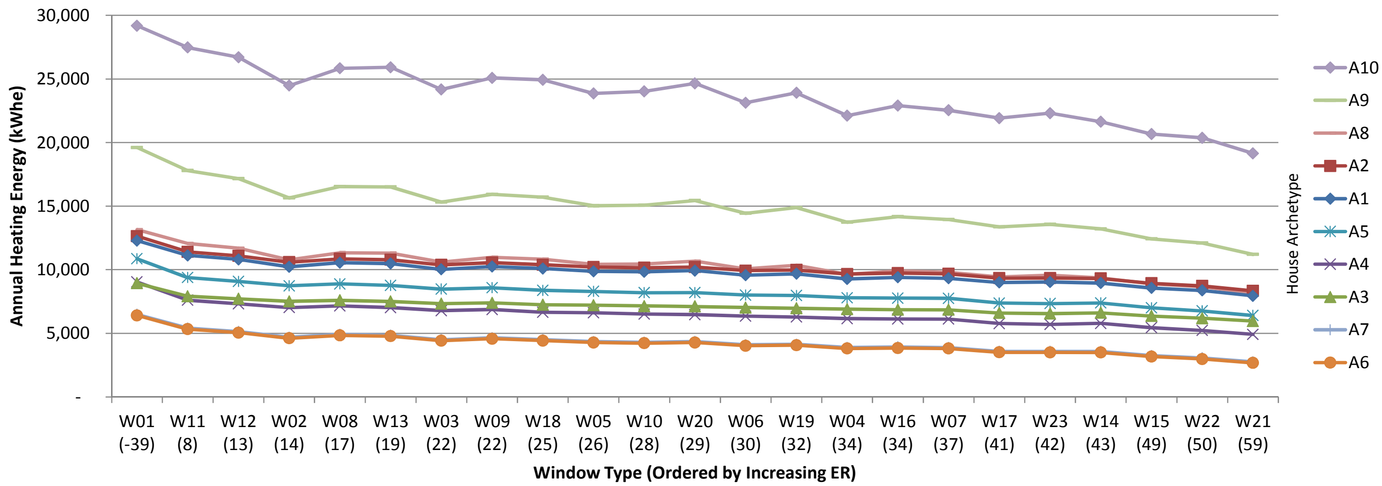


Fig.7.29 Annual heating energy consumption for archetype houses in Vancouver, kWh_e.

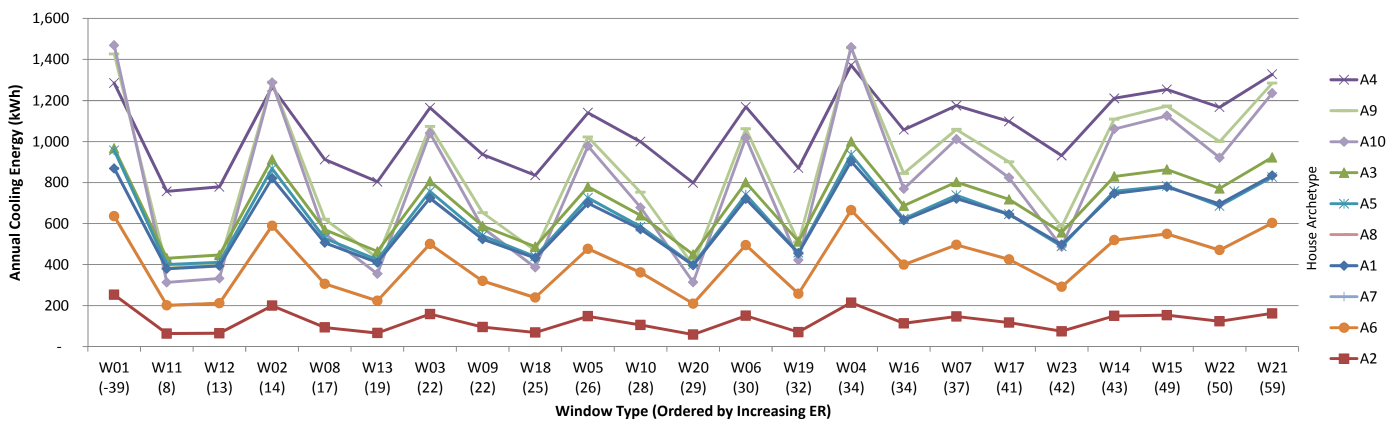


Fig.7.30 Annual cooling energy consumption for archetype houses in Vancouver, kWh.

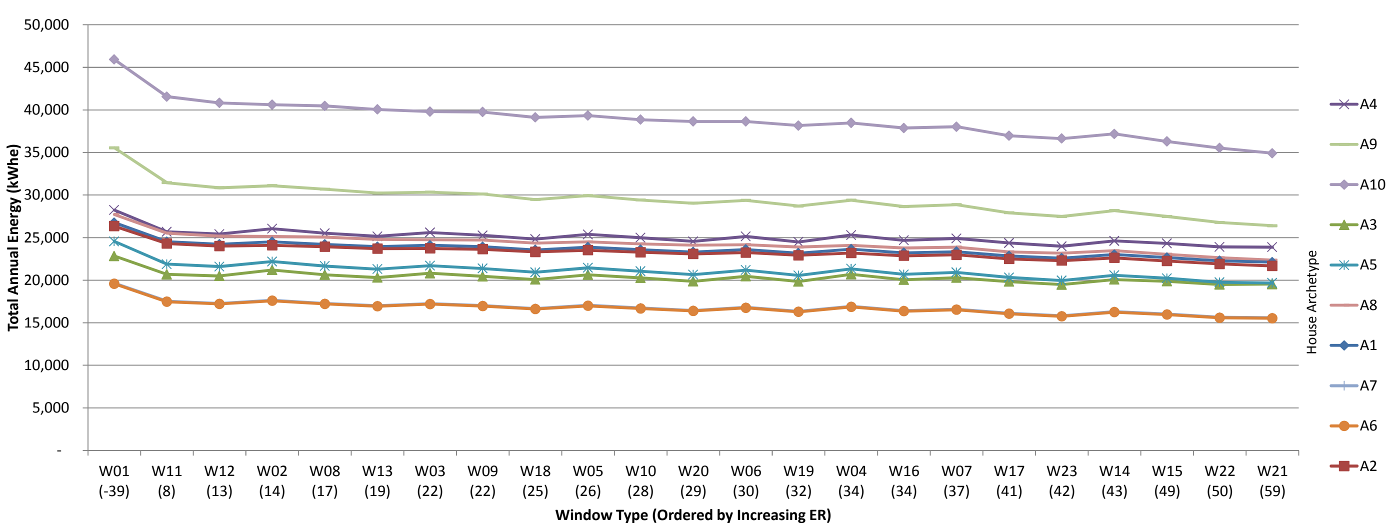


Fig.7.31 Total annual energy consumption for archetype houses in Vancouver, kWh_e.

Fig.7.32, Fig.7.33 and Fig.7.34 show the heating, cooling and total energy for the archetype houses in Toronto. Compared to Vancouver, the Toronto climate has colder winters and warmer (and more humid) summers. Therefore, heating and cooling energy are higher in Toronto. The heating and total energy simulation results show that, like Vancouver, the archetype does not affect the general ordering of energy consumption by window type. Each window type follows the same path of increasing or decreasing energy consumption for each archetype house. This is also the case for total energy.

The cooling plot results are also similar to Vancouver; each archetype follows the same path of increasing or decreasing cooling energy consumption. The two-storey and large two-storey archetypes have greater ranges in energy consumption, while the rest of the archetypes show a similar change in energy across each window type. One difference from the Vancouver cooling energy results is that the case with natural ventilation (A2) does not provide the lowest cooling energy as it did in Vancouver. This is indicative of the fact that natural ventilation is not as effective in the Toronto climate to offset summer cooling requirements, due to higher night-time temperatures.

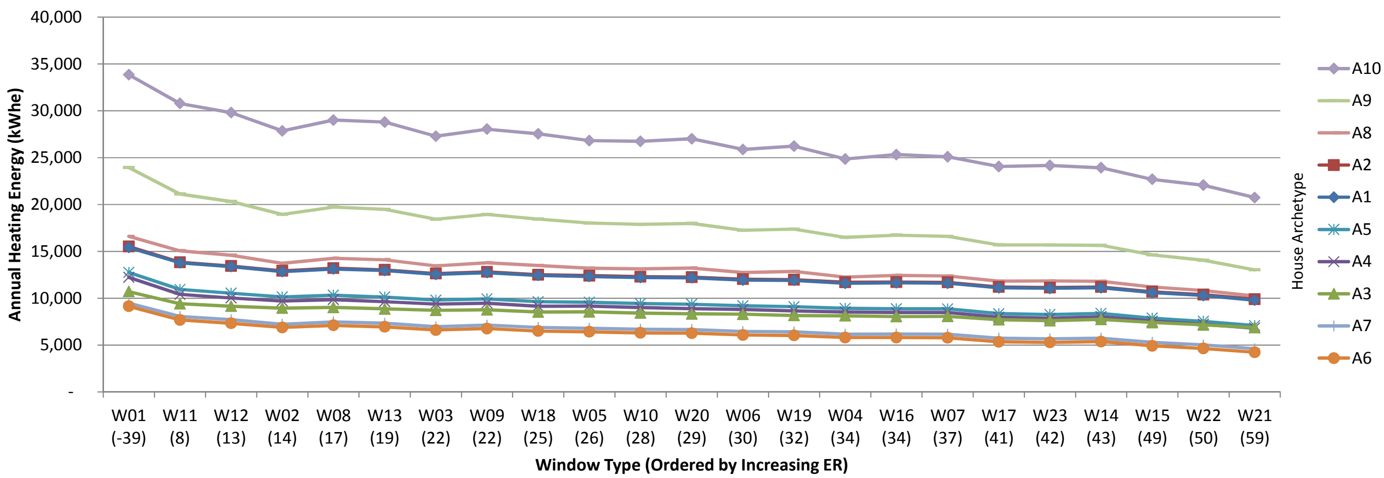


Fig.7.32 Annual heating energy consumption for archetype houses in Toronto, kWh$_e$.

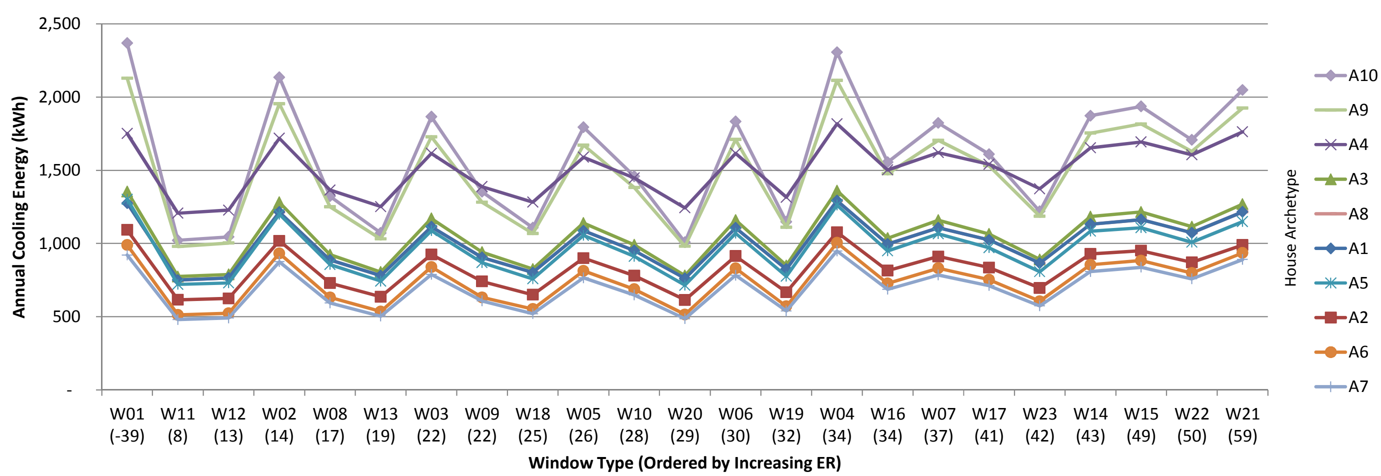


Fig.7.33 Annual cooling energy consumption for archetype houses in Toronto, kWh.

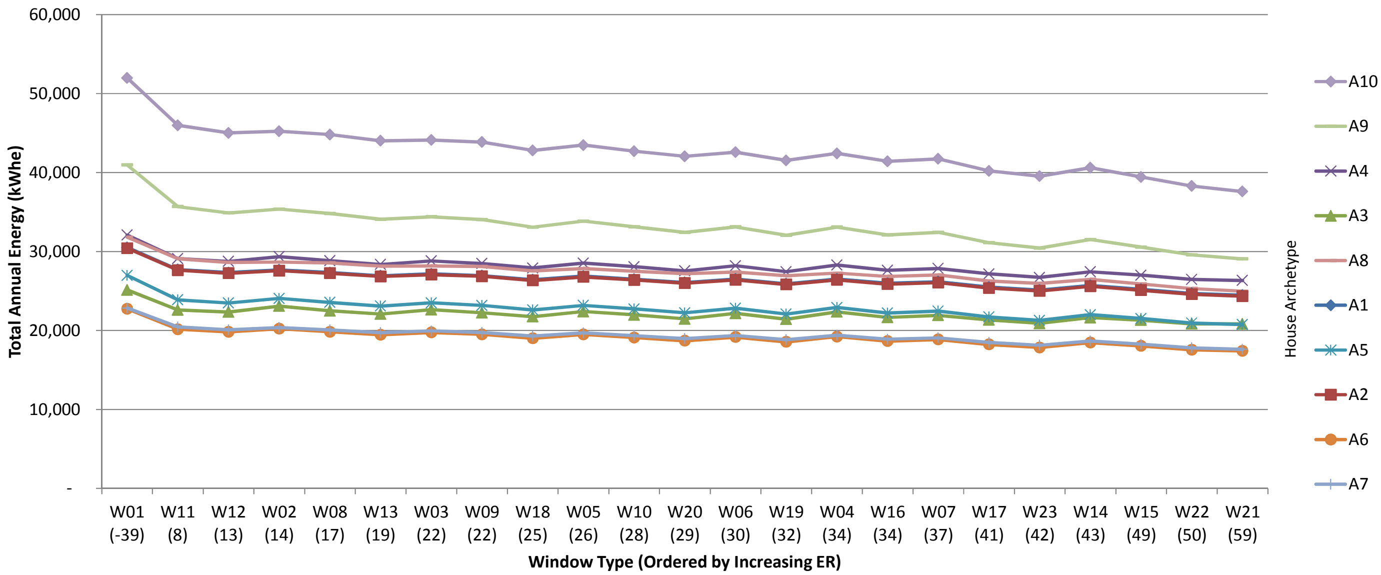


Fig.7.34 Total annual energy consumption for archetype houses in Toronto, kWh$_e$.

Fig.7.35, Fig.7.36 and Fig.7.37 show the heating, cooling and total energy for the archetype houses in Montreal. Like Vancouver and Toronto, the heating simulation results for Montreal show that the archetype does not affect the general ordering of energy consumption by window type. Each window type follows the same path of increasing or decreasing energy consumption for each archetype house. This is also the case for total energy. Similarly with the cooling energy plot, each archetype follows the same path of increasing or decreasing cooling energy. The two-storey and large two-storey archetypes have greater ranges in energy consumption, while the rest of the archetypes show a similar change in energy across each window type.

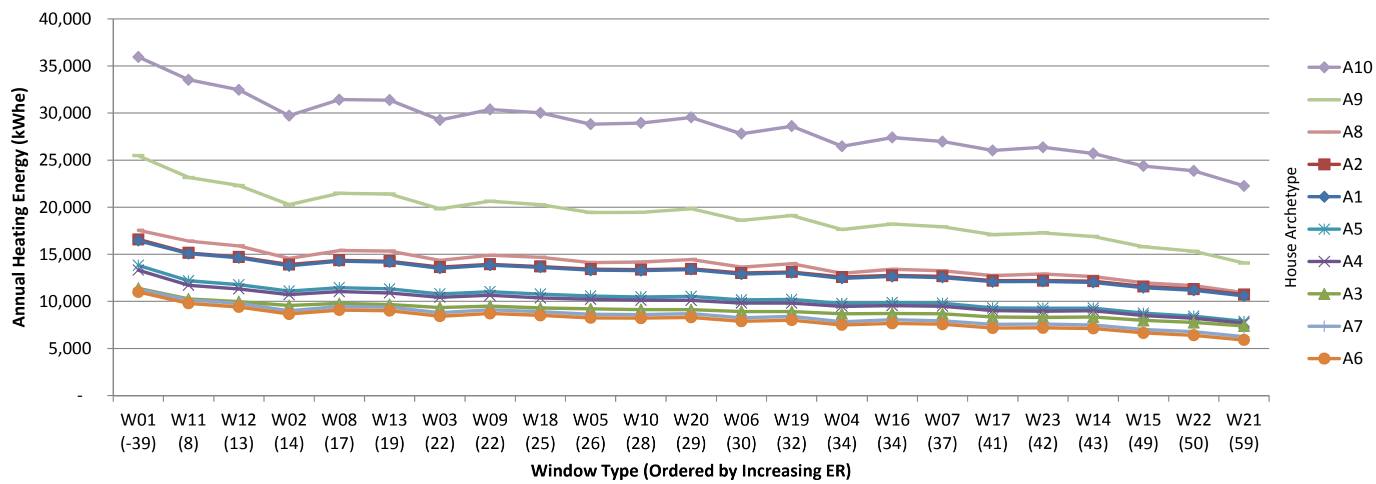


Fig.7.35 Annual heating energy consumption for archetype houses in Montreal, kWh$_e$.

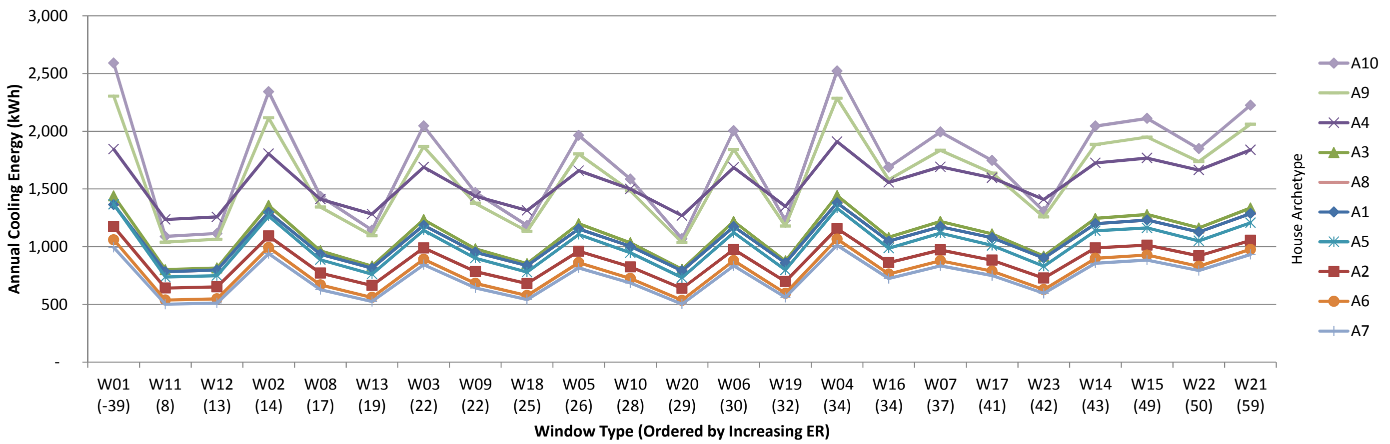


Fig.7.36 Annual cooling energy consumption for archetype houses in Montreal, kWh.

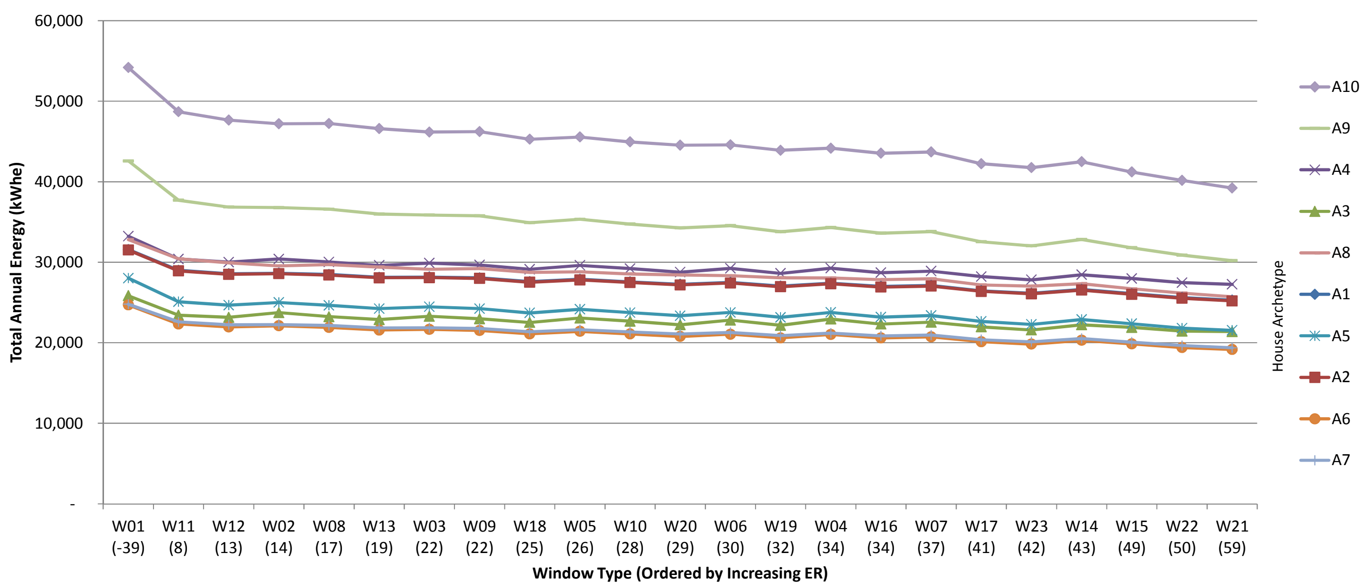


Fig.7.37 Total annual energy consumption for archetype houses in Montreal, kWh_e.

Fig.7.38, Fig.7.39 and Fig.7.40 show the heating, cooling and total energy for the archetype houses in Winnipeg. Like the other cities, both the heating and cooling simulation results for Winnipeg show that each window type follows the same path of increasing or decreasing energy consumption for each archetype house. This is also the case for total energy. The two-storey and large two-storey archetypes have greater ranges in cooling energy consumption, while the rest of the archetypes show a similar change in cooling energy across each window type.

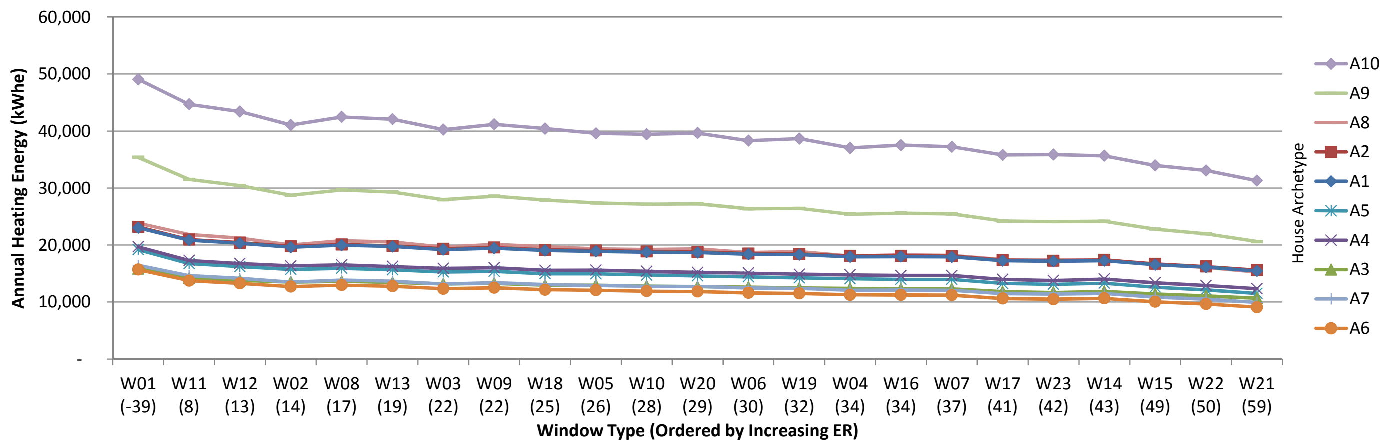


Fig.7.38 Annual heating energy consumption for archetype houses in Winnipeg, kWh_e.

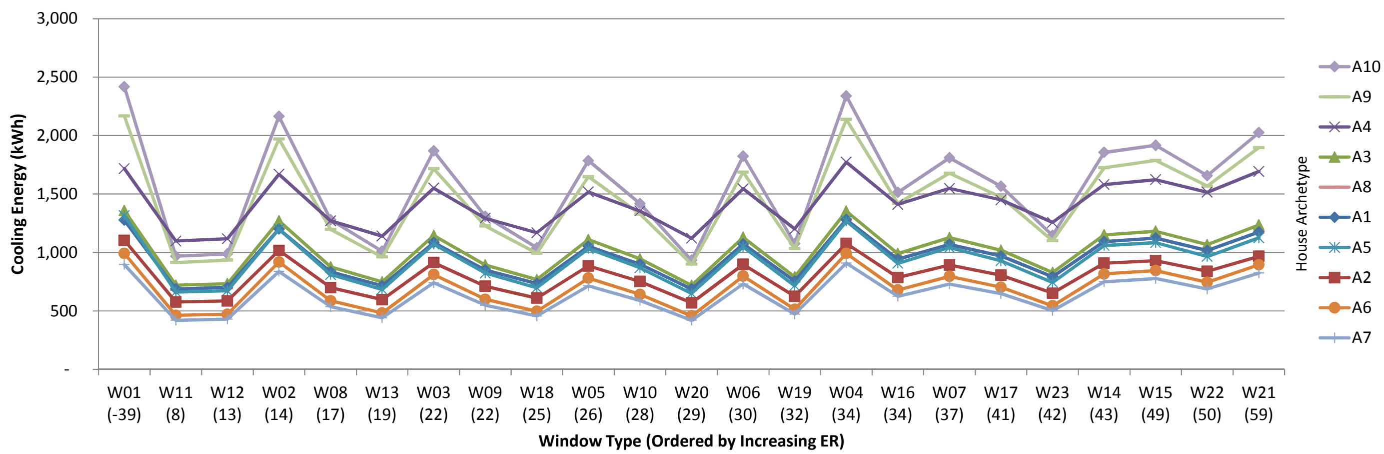


Fig.7.39 Annual cooling energy consumption for archetype houses in Winnipeg, kWh.

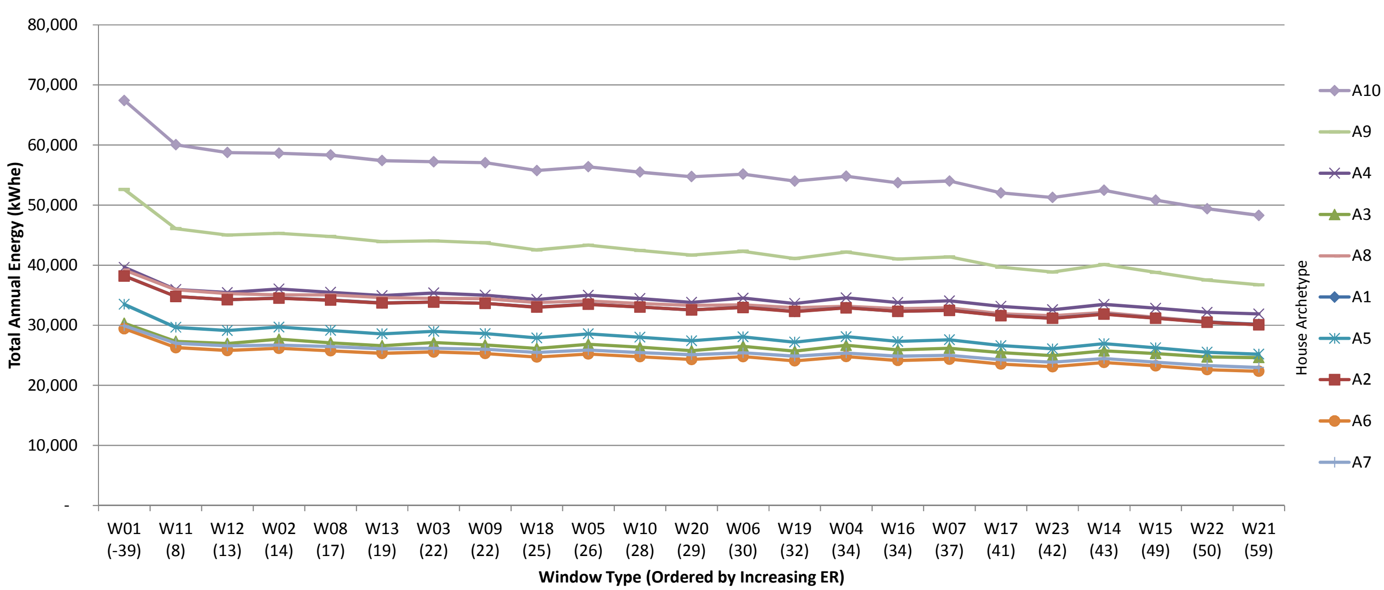


Fig.7.40 Total annual energy consumption for archetype houses in Winnipeg, kWh_e.

Fig.7.41, Fig.7.42 and Fig.7.43 show the heating, cooling and total energy for the archetype houses in Yellowknife. Like the other cities, both the heating, cooling and total simulation results for Yellowknife show that each window type follows the same path of increasing or decreasing energy consumption for each archetype house. The two-storey and large two-storey archetypes have greater ranges in cooling energy consumption, while the rest of the archetypes show a similar change in cooling energy across each window type.

The cooling energy for the case with natural ventilation (A2) is very low, indicating that little cooling energy would be consumed in a house in Yellowknife where natural ventilation is available.

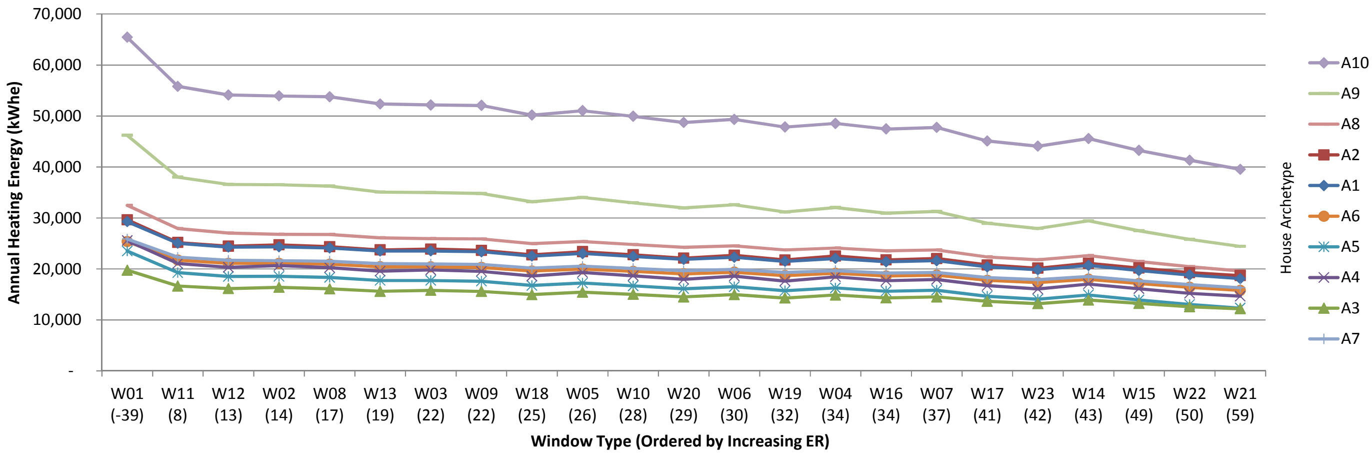


Fig.7.41 Annual heating energy consumption for archetype houses in Yellowknife, kWh_e.

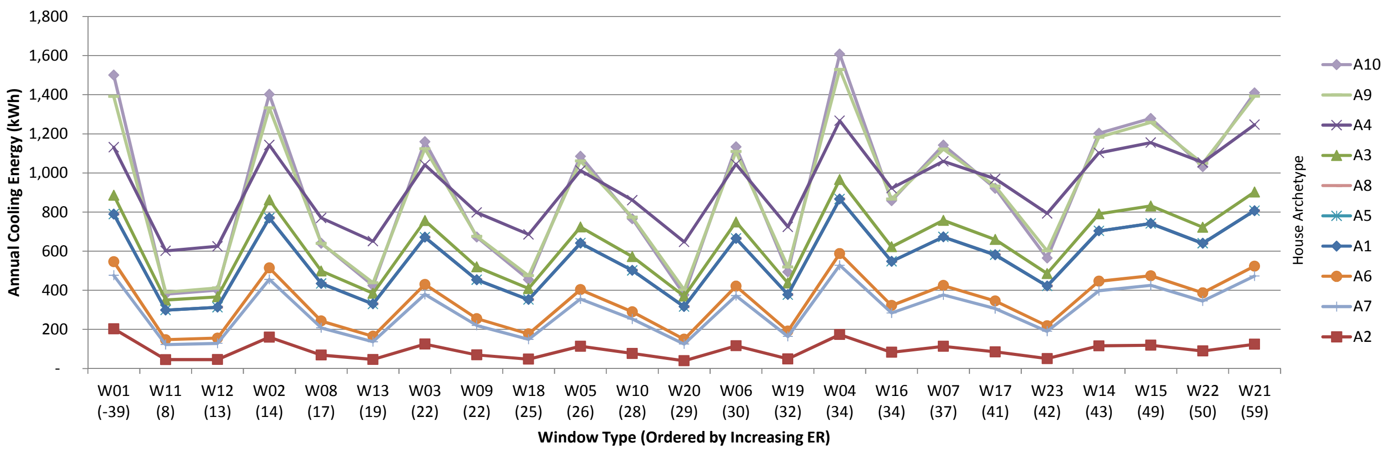


Fig.7.42 Annual cooling energy consumption for archetype houses in Yellowknife, kWh.

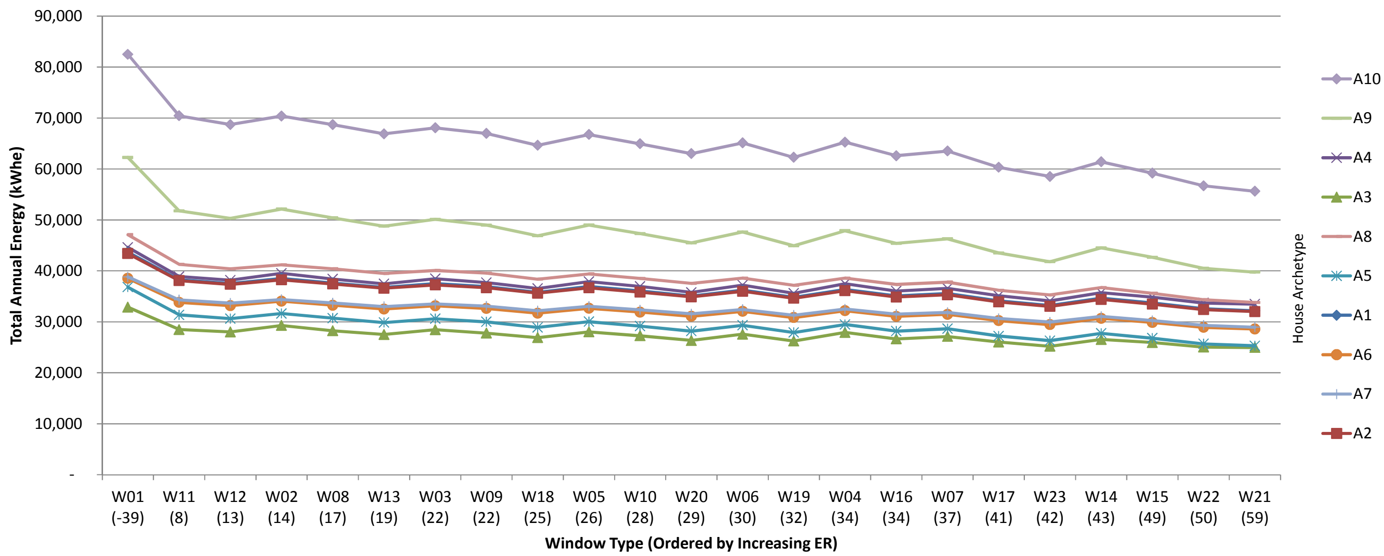


Fig.7.43 Total annual energy consumption for archetype houses in Yellowknife, kWh_e.

7.4.2 Comparing Locations

Comparing the Vancouver, Toronto, Montreal and Winnipeg plots, the ordering of higher and lower energy consumption by window type does not change between these locations. However, the Yellowknife plot shows a different pattern of increasing and decreasing heating energy, as discussed in the previous section.

The following windows show increasing heating energy consumption for a window with a higher ER in Vancouver, Toronto, Montreal and Winnipeg (see Fig.7.29, Fig.7.32, Fig.7.35 and Fig.7.38):

- W02 (U-2.83, SHGC-0.64, ER-14) to W08 (U-2.0, SHGC-0.35, ER-17)
- W03 (U-2.27, SHGC-0.55, ER-22) to W09 (U-1.75, SHGC-0.35, ER-22) (same ER)
- W05 (U-2.0, SHGC-0.5, ER-26) to W10 (U-1.5, SHGC-0.35, ER-28) to W20 (U-0.9, SHGC-0.15, ER-29)
- W06 (U-1.75, SHGC-0.5, ER-30) to W19 (U-0.9, SHGC-0.2, ER-32)
- W04 (U-2.0, SHGC-0.65, ER-34) to W16 (U-1.2, SHGC-0.35, ER-34) (same ER)
- W17 (U-0.9, SHGC-0.35, ER-41) to W23 (U-0.45, SHGC-0.2, ER-42)

The following windows show increasing heating energy consumption for a window with a higher ER in Yellowknife (see Fig.7.41):

- W18 (U-1.2, SHGC-0.2, ER-25) to W05 (U-2.0, SHGC-0.5, ER-26)
- W20 (U-0.9, SHGC-0.15, ER-25) to W06 (U-1.75, SHGC-0.5, ER-30)
- W19 (U-0.9, SHGC-0.2, ER-32) to W04 (U-2.0, SHGC-0.65, ER-34)
- W16 (U-1.2, SHGC-0.35, ER-34) to W07 (U-1.5, SHGC-0.5, ER-37)
- W23 (U-0.45, SHGC-0.2, ER-42) to W14 (U-1.2, SHGC-0.5, ER-43)

The anomaly windows in Vancouver, Toronto, Montreal and Winnipeg all occur where a high U-value, high SHGC window uses less energy than a low U-value, low SHGC window with a higher ER. The opposite is true in Yellowknife: the anomalies occur where a low U-value, low SHGC window uses less energy than a high U-value, high SHGC window with a higher ER. This indicates that in northern climates such as Yellowknife a low U-value is more important than a high SHGC (since the far north sees limited sunlight in the winter). This finding suggests it may be difficult to determine a single ER rating that consistently ranks windows in the far north and windows in the rest of Canada.

7.4.3 Summary

In summary, the energy simulation of various archetype houses showed that the archetype house does not affect the ordering of energy consumption with different windows. This suggests that a representative archetype house may be used in the development of an ER to rank windows. However, comparing different cities shows that the far north location that was simulated (Yellowknife) has different trends than more southern Canadian cities (also seen in Section 7.3). This suggests it may be necessary to asses modifying the ER to provide a ranking system that is consistent in all climate zones.

7.5. Factors Directly Related to Windows

The following simulation cases were run with one variable changed to assess factors that are directly related to windows. The simulations use the single-storey archetype house with gas heating, existing construction and other parameters described in Section 7.3 and case A1 in Section 7.4.

- Window to wall ratio (vary between 5% and 30%, in 5% increments)
- Window orientation (north, south, east, west, north-south and east-west; total window area remains the same in each case, but percentage distribution is varied at each orientation)
- Shading (No shading, 0.5 m roof overhang [as in base case], 1 m overhang, 1.5 m overhang, 1 m overhang at south only, operable shades controlled to minimize cooling)

The following plots show the annual heating and cooling energy consumption simulated for each archetype house case in Vancouver, Toronto, Montreal, Winnipeg and Yellowknife.

7.5.1 Window to Wall Ratio

The archetype house was simulated with window to wall ratios (WWR) between 5% and 30%, adjusting the ratio in 5% increments. A maximum WWR of 30% was chosen since this was the upper range found in recent code development studies by Natural Resources Canada (NRCan), and is sufficient to view trends. WWRs above this range are also not common for single family dwellings.

Fig.7.44, Fig.7.45 and Fig.7.46 show the annual heating, cooling and total energy consumption for various WWRs in Vancouver. The heating plot shows an interesting trend where higher WWRs use more heating energy for lower ER windows and less heating energy for higher ER windows. There is a point where each of the WWRs simulated use about the same heating energy. In the Vancouver plot, this occurs at about W19 (U-0.9, SHGC-0.2, ER-32). However, the WWRs follow the same trend of increasing or decreasing heating energy, and therefore the same comparison between windows can be made for a given WWR. In other words, say for example, one is deciding between W08 and W09 for a particular house; W09 uses less energy than W08 for all WWRs, and therefore an ER comparison may be valid. For total energy, the crossing points occur at a higher ER value, though as with heating the lines follow the same trend of increasing or decreasing energy.

The cooling energy plot shows that higher WWRs result in greater variation in cooling energy, however, the pattern of increasing or decreasing energy consumption for different ERs does not change with WWR.

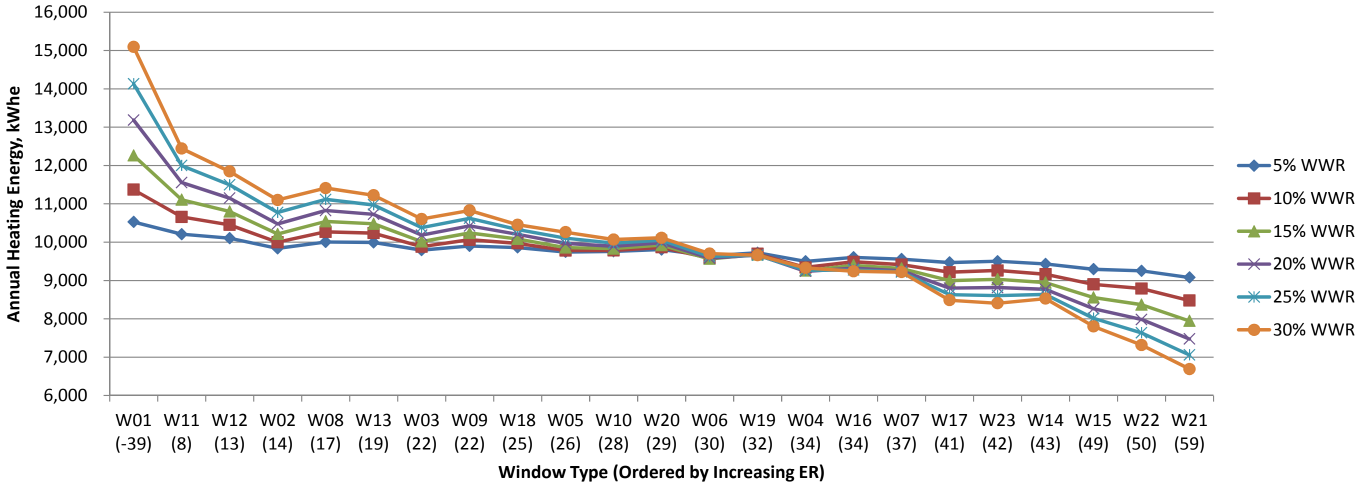


Fig.7.44 Annual heating energy consumption for window to wall ratios in Vancouver, kWh_e.

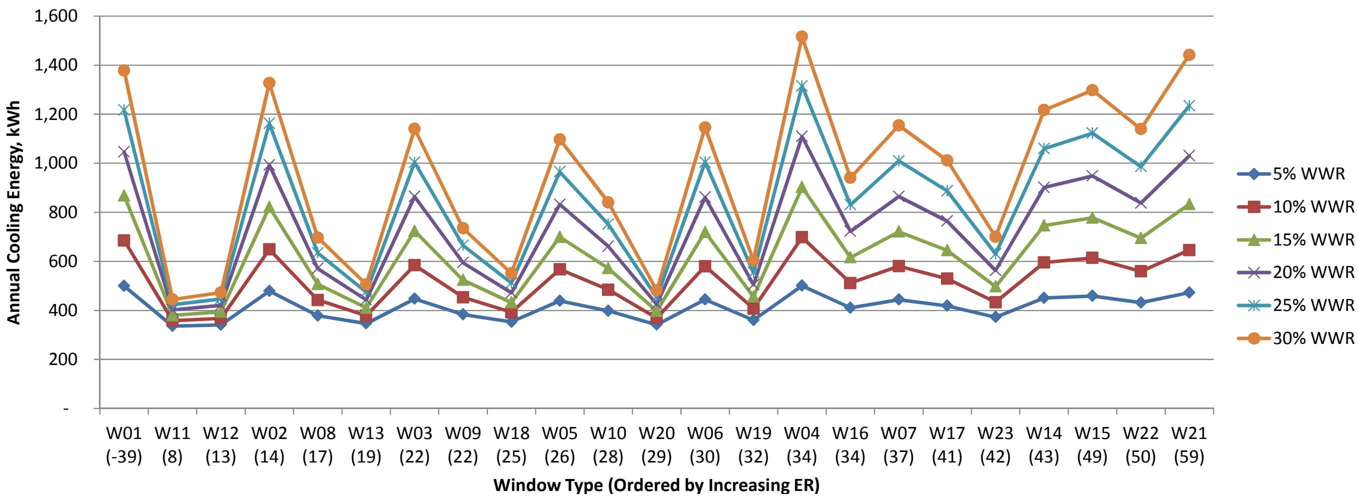


Fig.7.45 Annual cooling energy consumption for window to wall ratios in Vancouver, kWh.

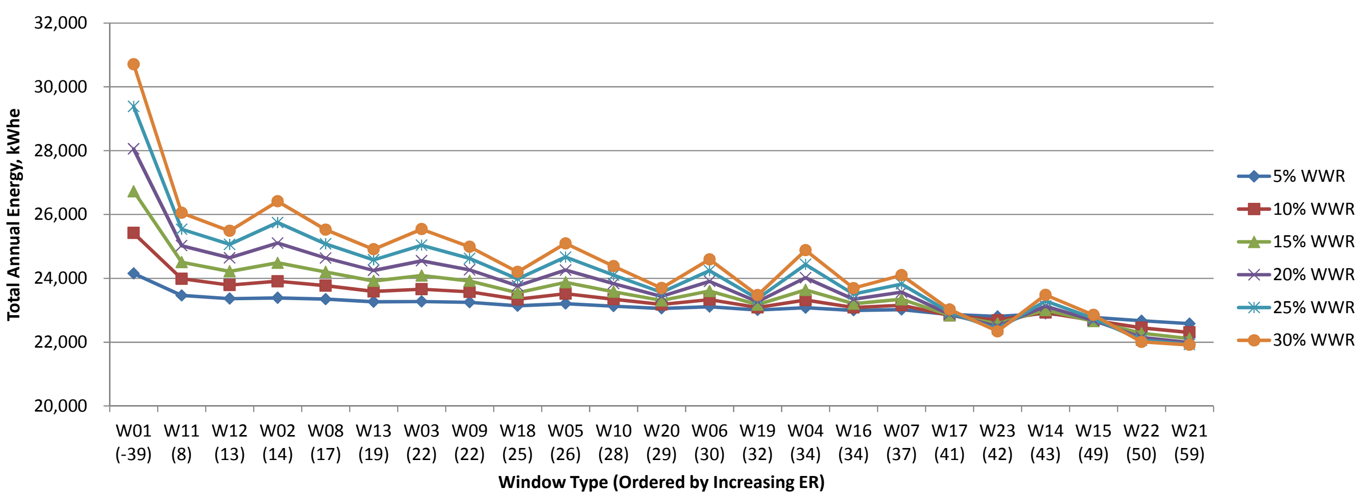


Fig.7.46 Total annual energy consumption for window to wall ratios in Vancouver, kWh_e.

Fig.7.47, Fig.7.48 and Fig.7.49 show the annual heating, cooling and total energy consumption for various WWRs in Toronto. Like Vancouver, the heating plot shows that higher WWRs use more heating energy for lower ER windows and less heating energy for higher ER windows. In the Toronto plot, W19, W04, W16 and W07 all use very close to the same annual heating energy. As with Vancouver, the WWRs follow the same trend of increasing or decreasing heating energy for different window types. For total energy, the crossing points occur at a higher ER value, though as with heating the lines follow the same trend of increasing or decreasing energy.

The cooling energy plot shows that higher WWRs result in greater variation in cooling energy, however, the pattern of increasing or decreasing energy consumption for different ERs does not change with WWR.

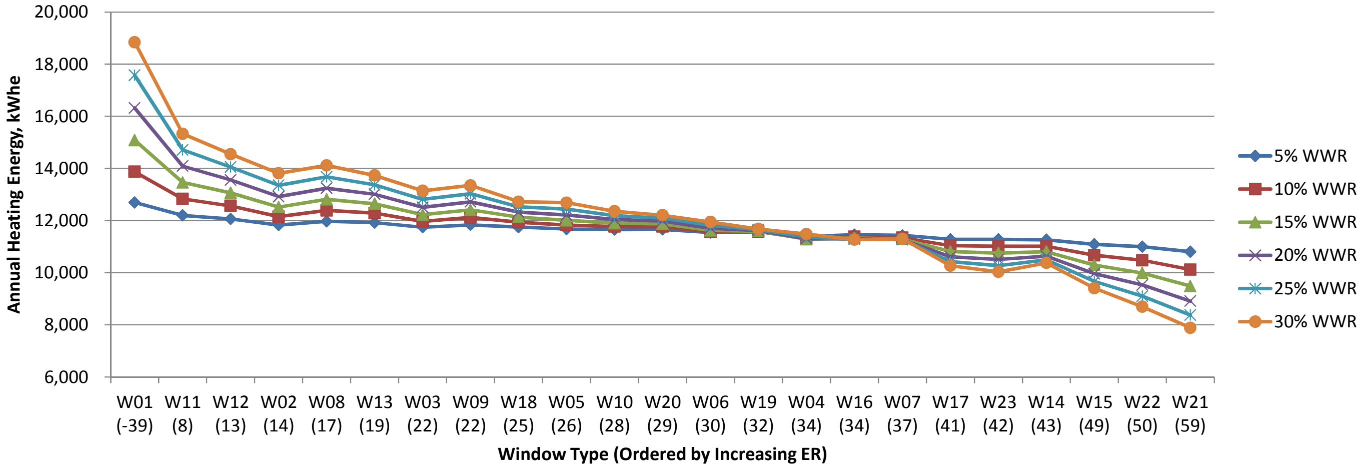


Fig.7.47 Annual heating energy consumption for window to wall ratios in Toronto, kWh_e.

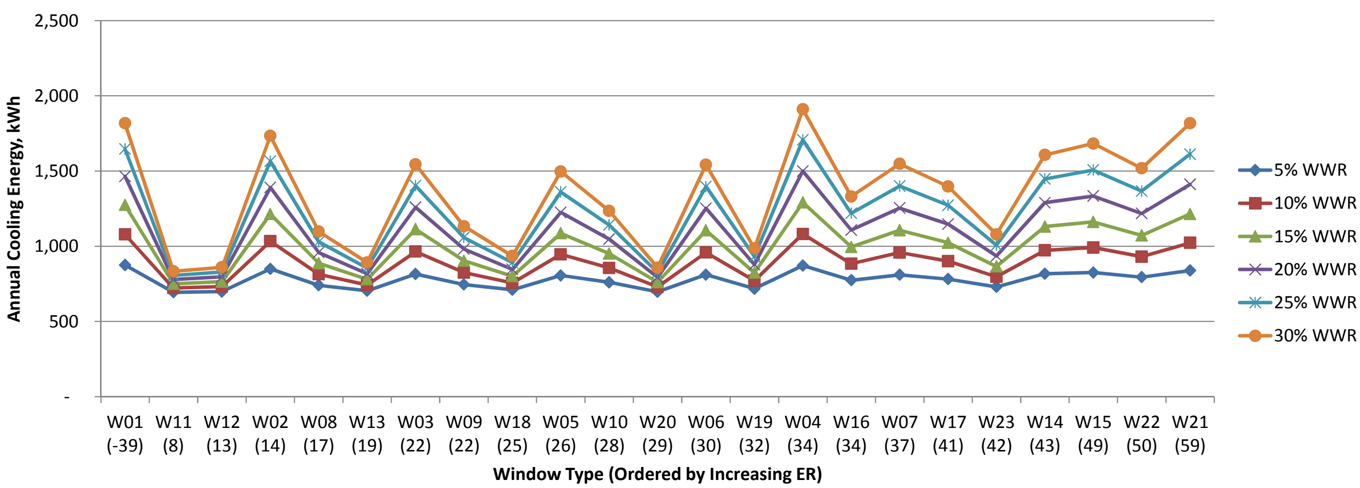


Fig.7.48 Annual cooling energy consumption for window to wall ratios in Toronto, kWh.

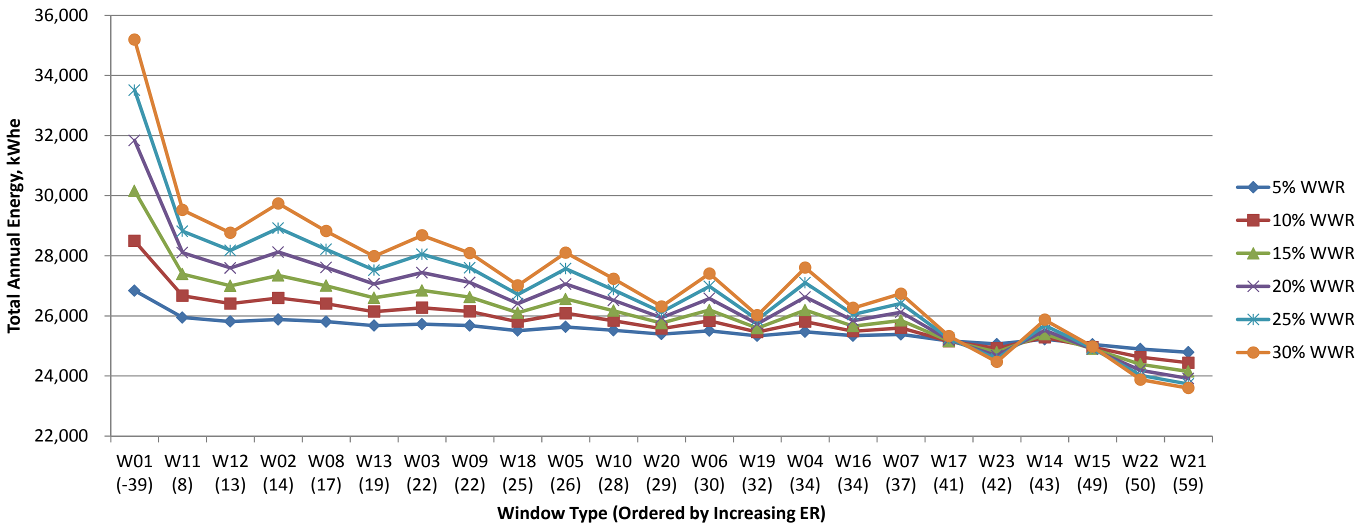


Fig.7.49 Total annual energy consumption for window to wall ratios in Toronto, kWh_e.

Fig.7.50, Fig.7.51 and Fig.7.52 show the annual heating, cooling and total energy consumption for various WWRs in Montreal. Like Vancouver and Toronto, the heating plot shows that higher WWRs use more heating energy for lower ER windows and less heating energy for higher ER windows. In the Montreal plot, W06 and W19 use very close to the same annual heating energy. As with Vancouver and Toronto, the WWRs follow the same trend of increasing or decreasing heating energy for different window types. For total energy, the crossing point occurs at a higher ER value, though as with heating the lines follow the same trend of increasing or decreasing energy.

The cooling energy plot shows that higher WWRs result in greater variation in cooling energy, however the pattern of increasing or decreasing energy consumption for different ERs does not change with WWR.

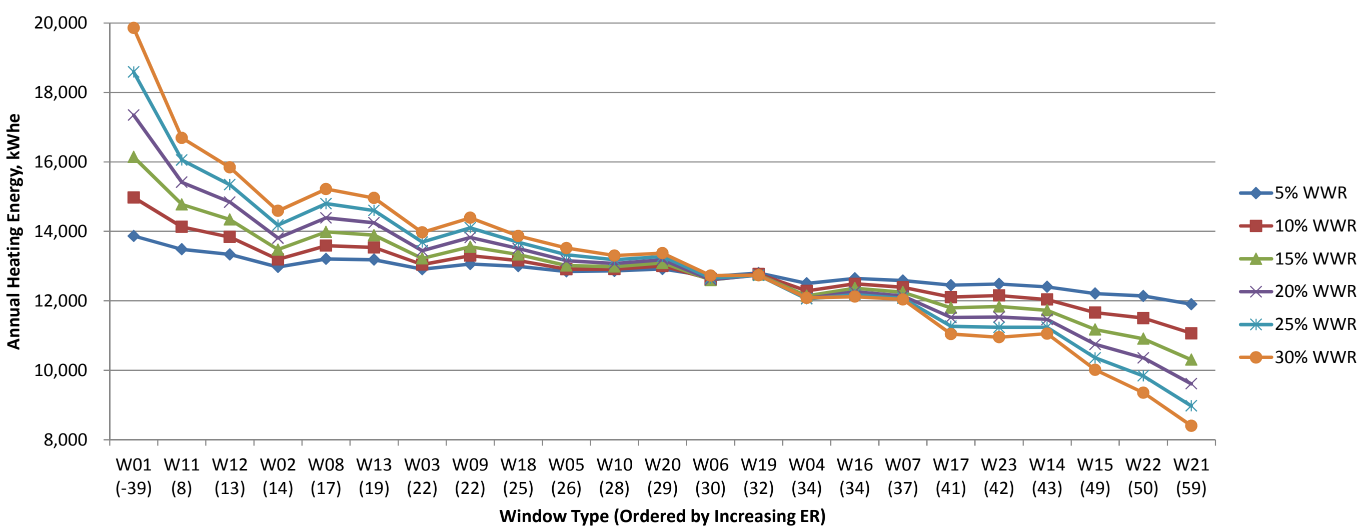


Fig.7.50 Annual heating energy consumption for window to wall ratios in Montreal, kWh_e.

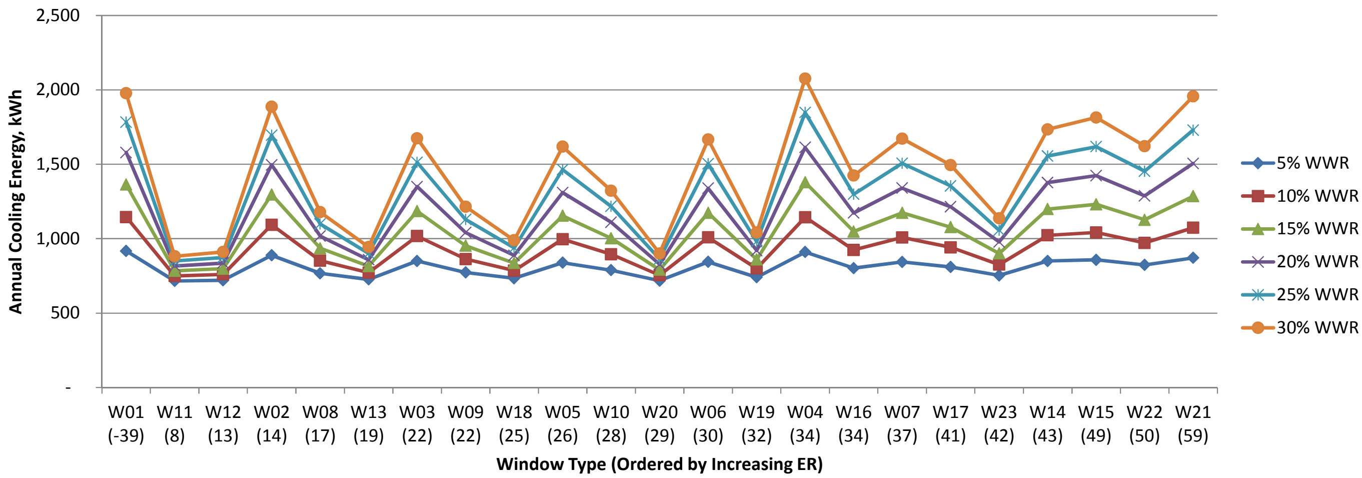


Fig.7.51 Annual cooling energy consumption for window to wall ratios in Montreal, kWh.

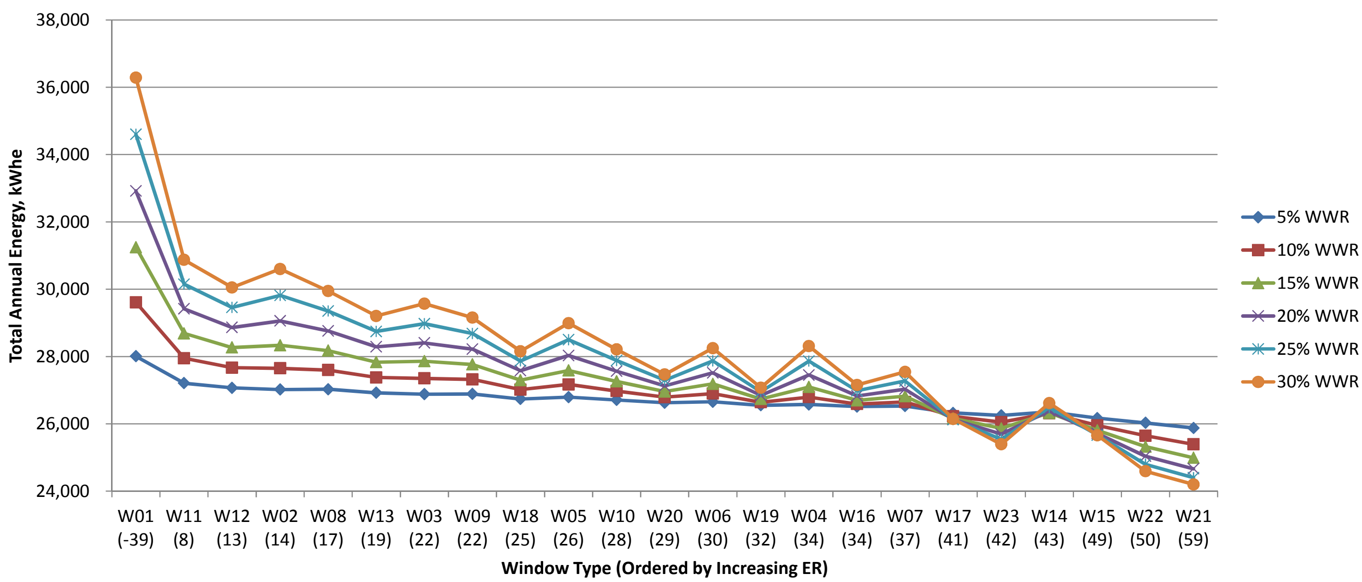


Fig.7.52 Total annual energy consumption for window to wall ratios in Montreal, kWh_e.

Fig.7.53, Fig.7.54 and Fig.7.55 show the annual heating, cooling and total energy consumption for various WWRs in Winnipeg. Like the previous cities, the heating plot shows that higher WWRs use more heating energy for lower ER windows and less heating energy for higher ER windows. In the Winnipeg plot, W16 and W07 consume similar annual heating energy. As with Vancouver, Toronto and Montreal, the WWRs follow the same trend of increasing or decreasing heating energy for different window types. For total energy, the crossing point occurs at a higher ER value, though as with heating the lines follow the same trend of increasing or decreasing energy.

The cooling energy plot shows that higher WWRs result in greater variation in cooling energy; however the pattern of increasing or decreasing energy consumption for different ERs does not change with WWR.

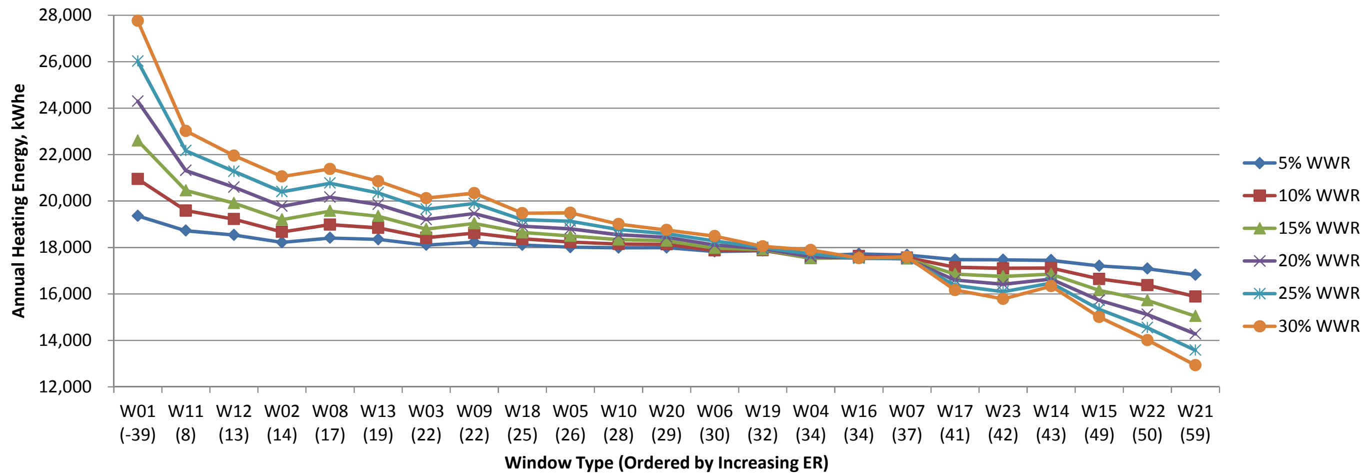


Fig.7.53 Annual heating energy consumption for window to wall ratios in Winnipeg, kWh_e.

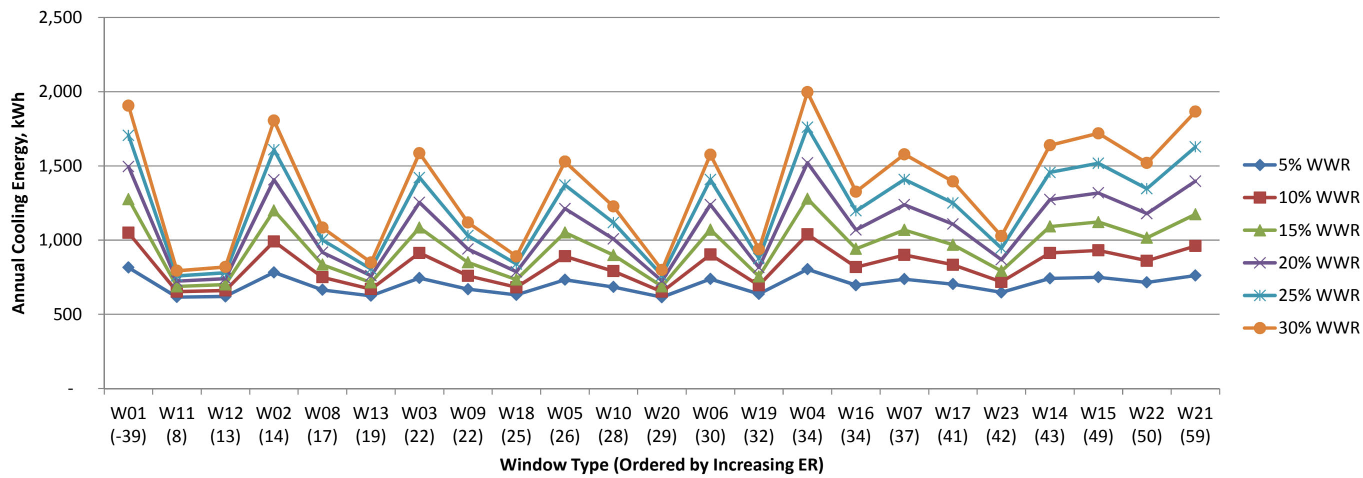


Fig.7.54 Annual cooling energy consumption for window to wall ratios in Winnipeg, kWh.

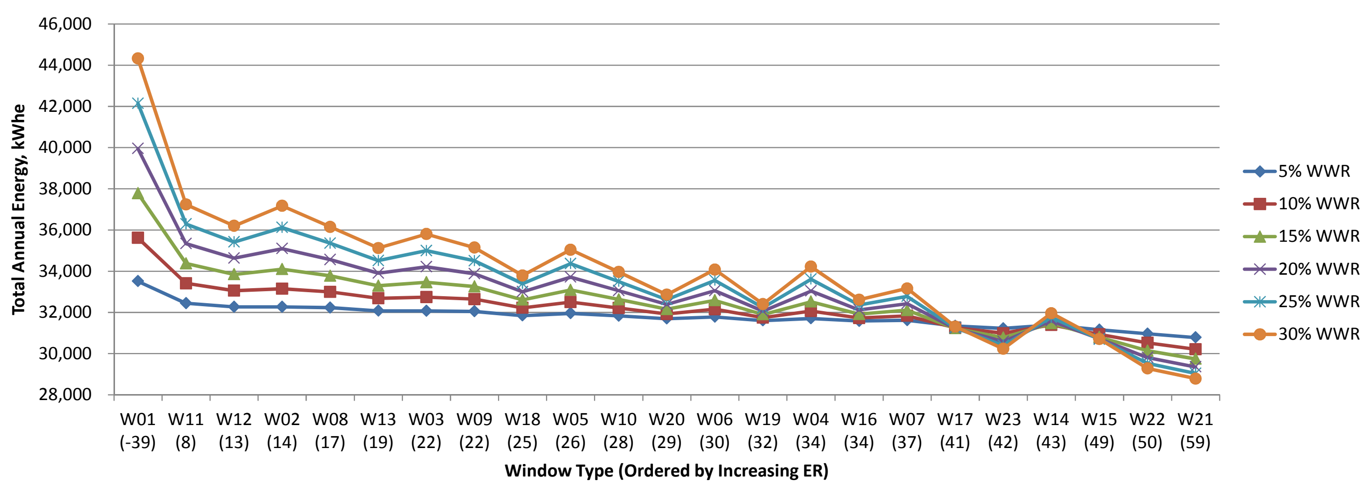


Fig.7.55 Total annual energy consumption for window to wall ratios in Winnipeg, kWh_e.

Fig.7.56, Fig.7.57 and Fig.7.58 show the annual heating, cooling and total energy consumption for various WWRs in Yellowknife. The results show that generally higher WWRs result in higher energy consumption. The few exceptions are W21, W22 and W23, the "advanced glazing" windows with U-0.45. Also, W15 and W17 have very close heating energy consumption for each WWR. As with the previous cities, the WWRs follow the same trend of increasing or decreasing energy for different window types.

The cooling energy plot shows that higher WWRs result in greater variation in cooling energy, however, the pattern of increasing or decreasing energy consumption for different ERs does not change with WWR.

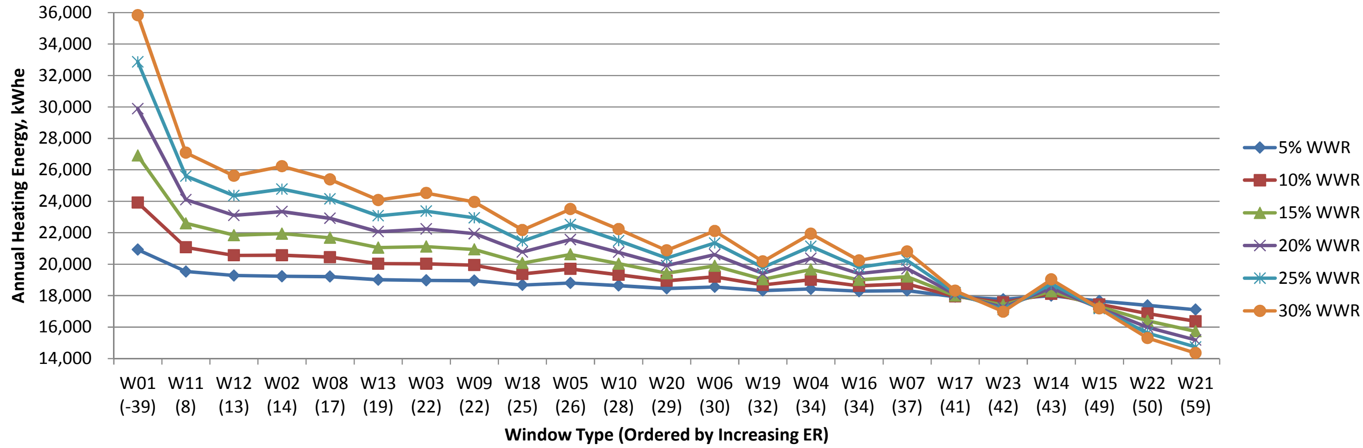


Fig.7.56 Annual heating energy consumption for window to wall ratios in Yellowknife, kWh_e.

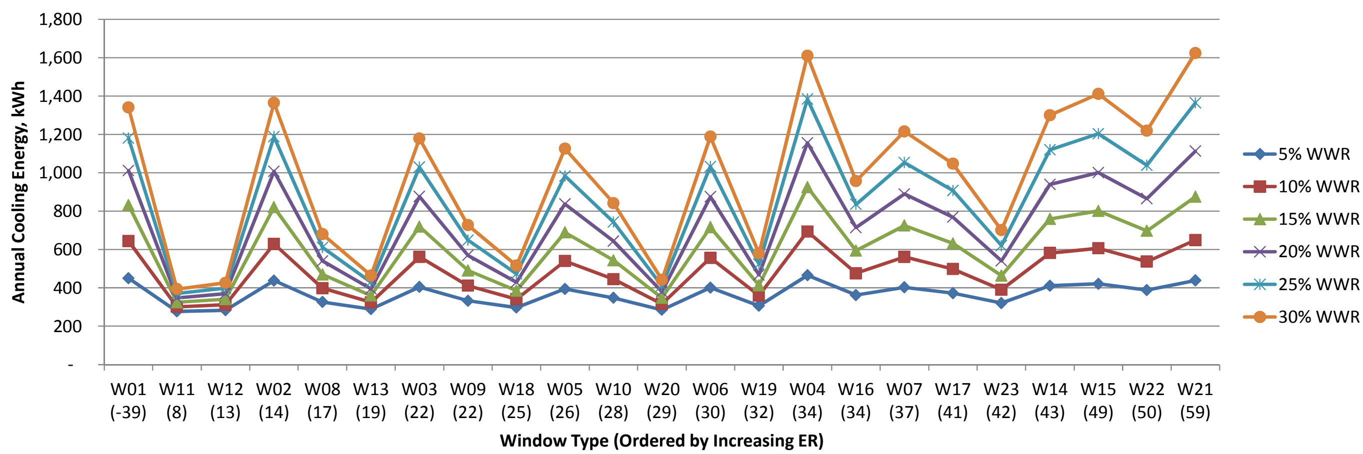


Fig.7.57 Annual cooling energy consumption for window to wall ratios in Yellowknife, kWh.

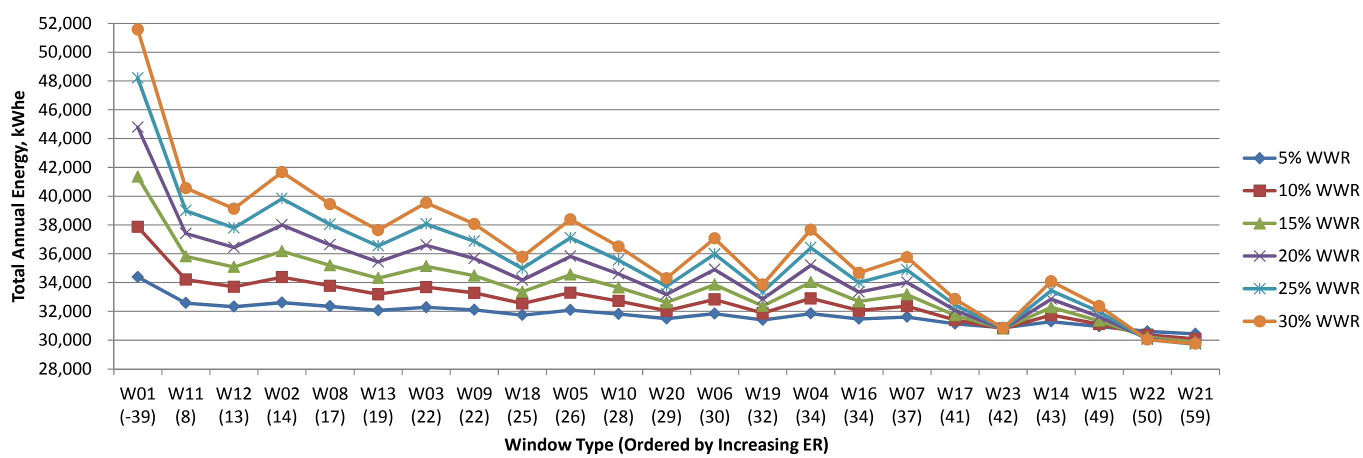


Fig.7.58 Total annual energy consumption for window to wall ratios in Yellowknife, kWh_e.

The simulations by WWR show the same general trend of increasing or decreasing energy consumption for both heating and cooling energy for different WWRs. For heating energy, higher WWRs result in higher heating energy for lower ERs and lower heating energy for higher ERs. In each plot there is a range where each WWR results in about the same heating energy, and this point generally occurs at higher window ERs for colder cities. However, the results show that each WWR follows the same general pattern of increasing or decreasing heating and cooling energy consumption, and therefore an ER may be used to appropriately rank windows for different WWRs.

7.5.2 Window Orientation

The window orientation scenarios were simulated with the following conditions: windows predominantly facing each of the four cardinal directions, windows facing predominantly north-south and east-west, and equal distribution on each elevation (as in the simulations presented previously). In each case the total window area remained the same, but the percent distribution was varied at each elevation. For scenarios with windows facing predominantly one direction, a 45% WWR was used in that direction versus 5% WWR in the other directions. For scenarios with windows facing predominantly two directions (north-south and east-west), a 25% WWR was used in the predominant directions and 5% WWR in the opposite directions.

Fig.7.59, Fig.7.60 and Fig.7.61 show the annual heating, cooling and total energy consumption for the single-storey archetype house in Vancouver with various window orientations. The heating energy plot shows that there are a number of cases where the trend is opposite for different orientations; that is, heating energy from one window to the next decreases for some orientations but increases for others.

The clearest example of this is the north windows, where there are a number of cases where energy increases for north windows but decreases for most other orientations. This occurs because north windows see very little solar heat gain, therefore a low U-value is more beneficial to north-facing windows than a high SHGC. In addition to the north case, there are some other small differences. For example, at W08 to W13 energy increases for south, is about the same for west, and decreases for the remaining orientation cases. Another example is W23 to W14, where energy increases for north and east but decreases for the other cases.

The cooling energy plot shows that the pattern of increasing or decreasing energy consumption is consistent for all window orientations. The total energy plot shows different trends than the heating energy plot for certain windows. This indicates that the addition of cooling energy to heating energy has a big enough impact to change the trend of increasing or decreasing energy for certain windows and orientations; only the north and south orientations keep the same pattern between heating and total energy.

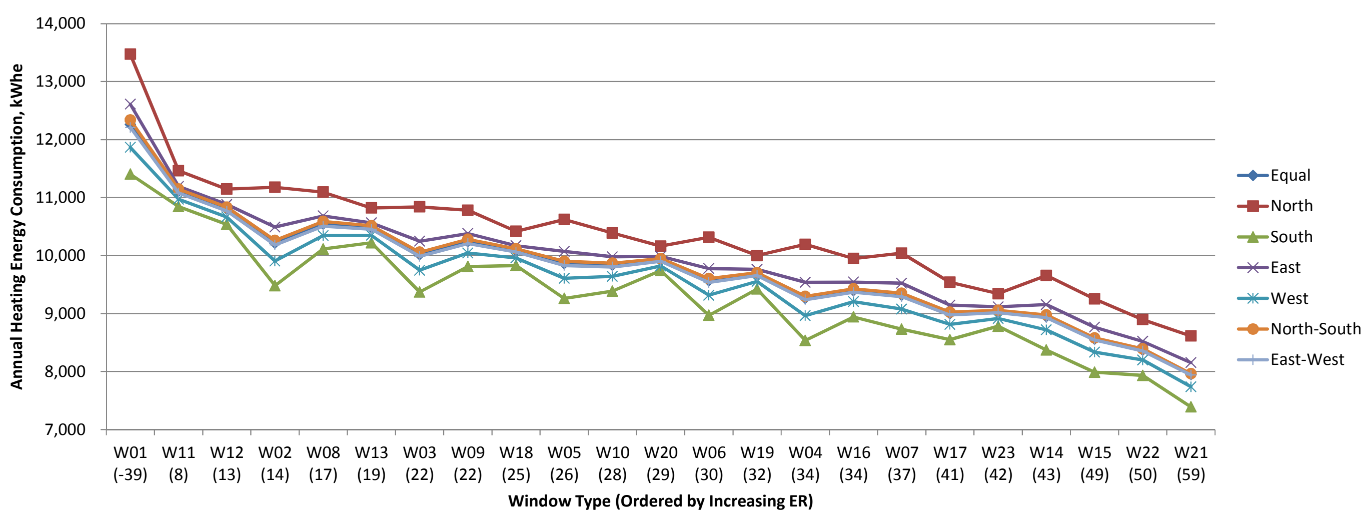


Fig.7.59 Annual heating energy consumption for window orientations in Vancouver, kWh_e.

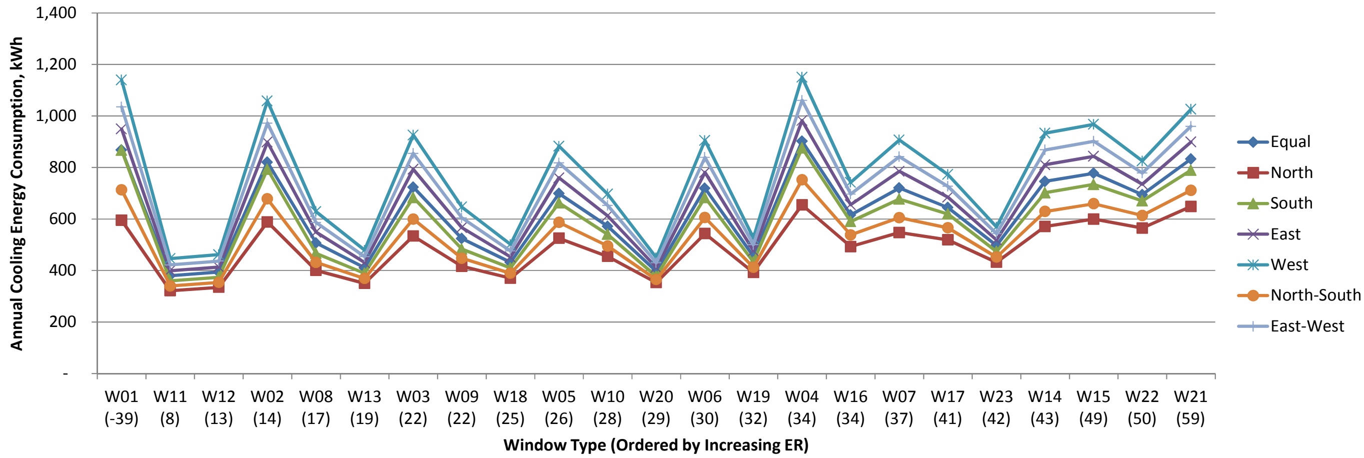


Fig.7.60 Annual cooling energy consumption for window orientations in Vancouver, kWh.

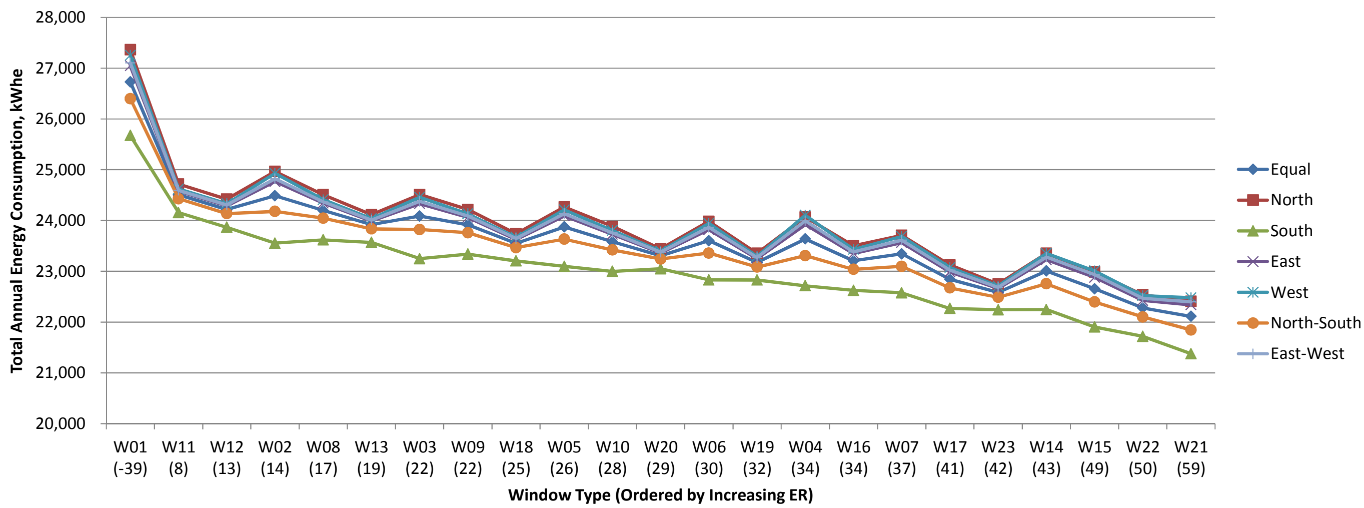


Fig.7.61 Total annual energy consumption for window orientations in Vancouver, kWh_e.

Fig.7.62, Fig.7.63 and Fig.7.64 show the annual heating, cooling and total energy consumption for the single-storey archetype house in Toronto with different window orientations. Similar to Vancouver, the heating energy plot shows a very different trend of increasing or decreasing energy for north windows, as well as some smaller differences between the other orientations. The south windows experience greater variations in energy consumption between different window types than the east, west, east-west and north-south cases. The cooling energy plot shows the same pattern for all orientations. The total energy plot shows different trends than the heating energy plot for certain windows.

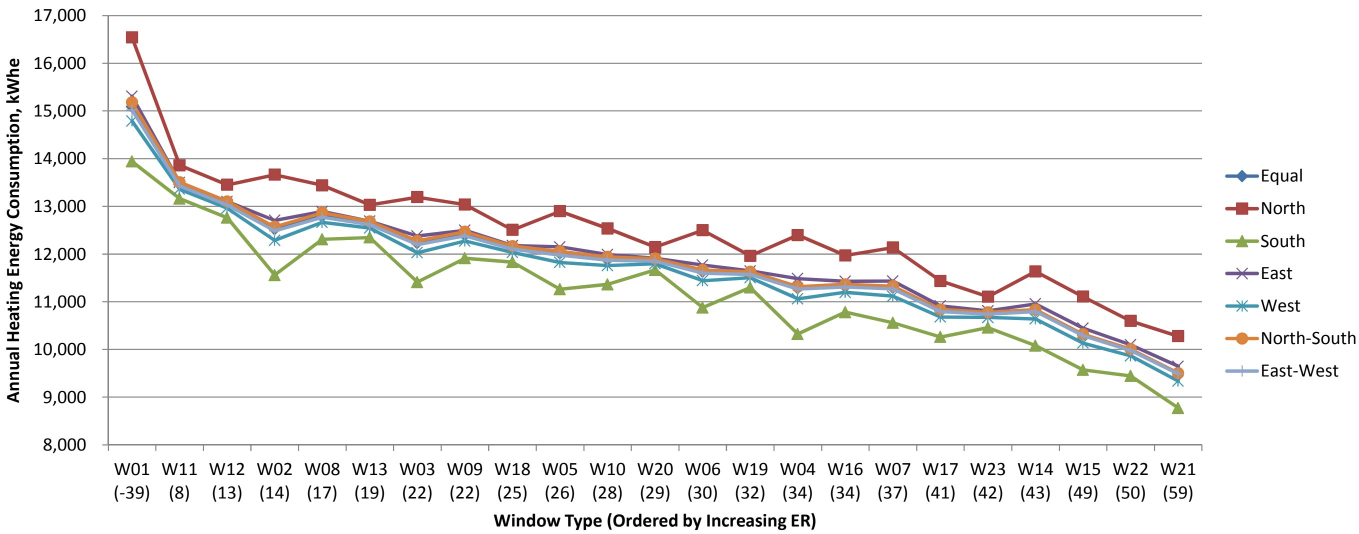


Fig.7.62 Annual heating energy consumption for window orientations in Toronto, kWh_e.

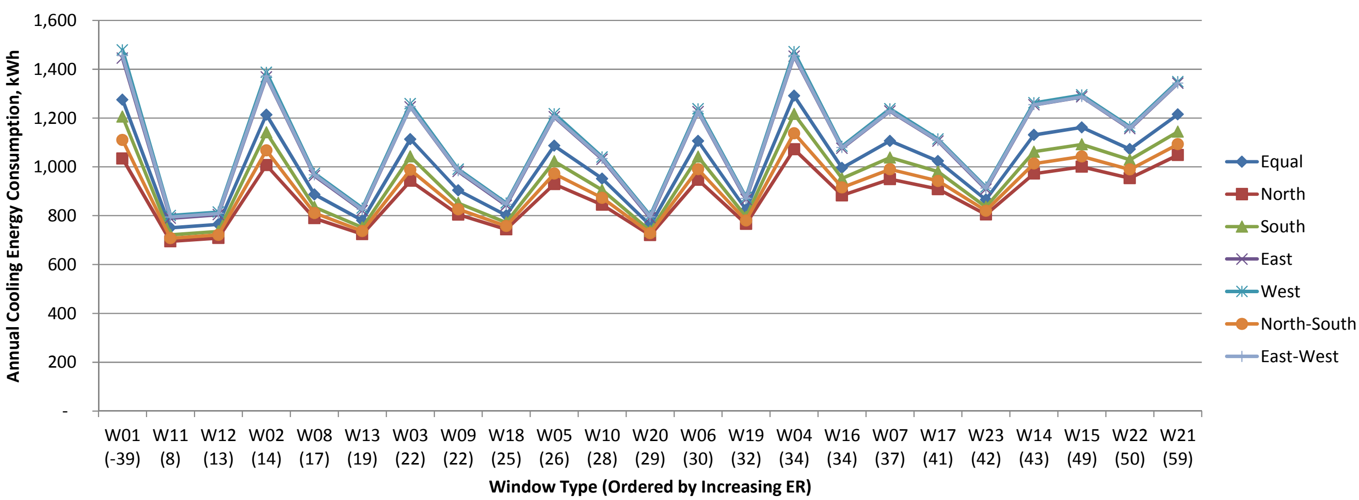


Fig.7.63 Annual cooling energy consumption for window orientations in Toronto, kWh.

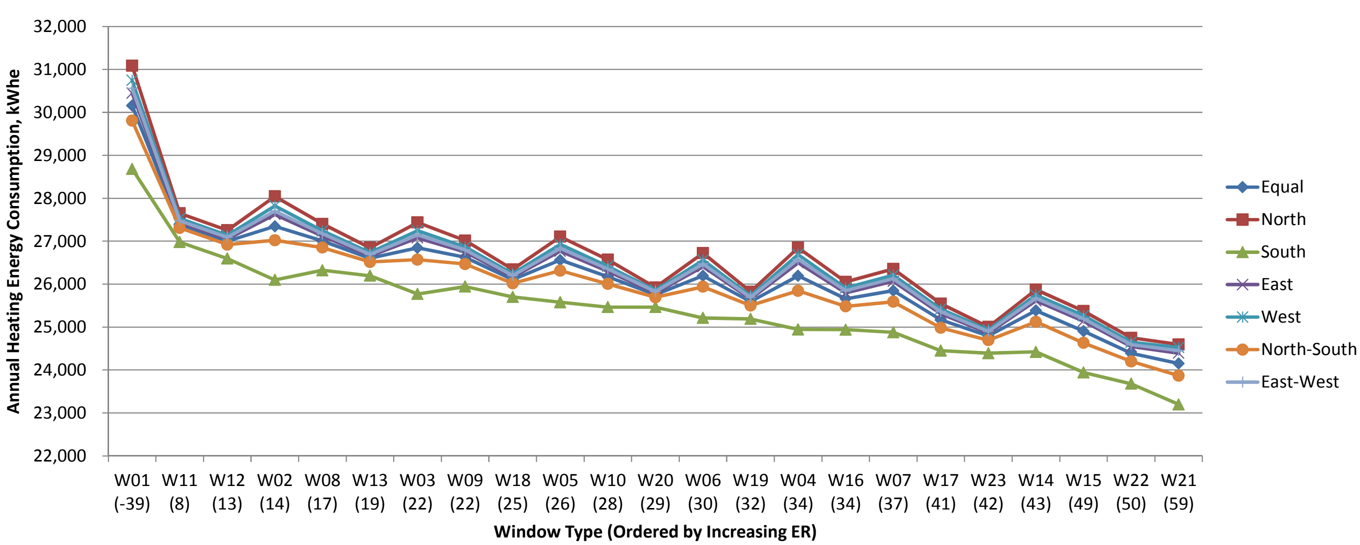


Fig.7.64 Total annual energy consumption for window orientations in Toronto, kWh_e.

Fig.7.65, Fig.7.66 and Fig.7.67 show the annual heating, cooling and total energy consumption for the single-storey archetype house in Montreal with different window orientations. Similar to Vancouver and Toronto, the heating energy plot shows that the trend of increasing or decreasing energy for north windows is unlike the other scenarios, and that there are some smaller differences between the other orientations. As with Toronto, the south windows show greater swings in heating energy than the east and west orientations. The cooling energy plot shows the same pattern for all orientations. The total energy plot shows different trends than the heating energy plot for certain windows.

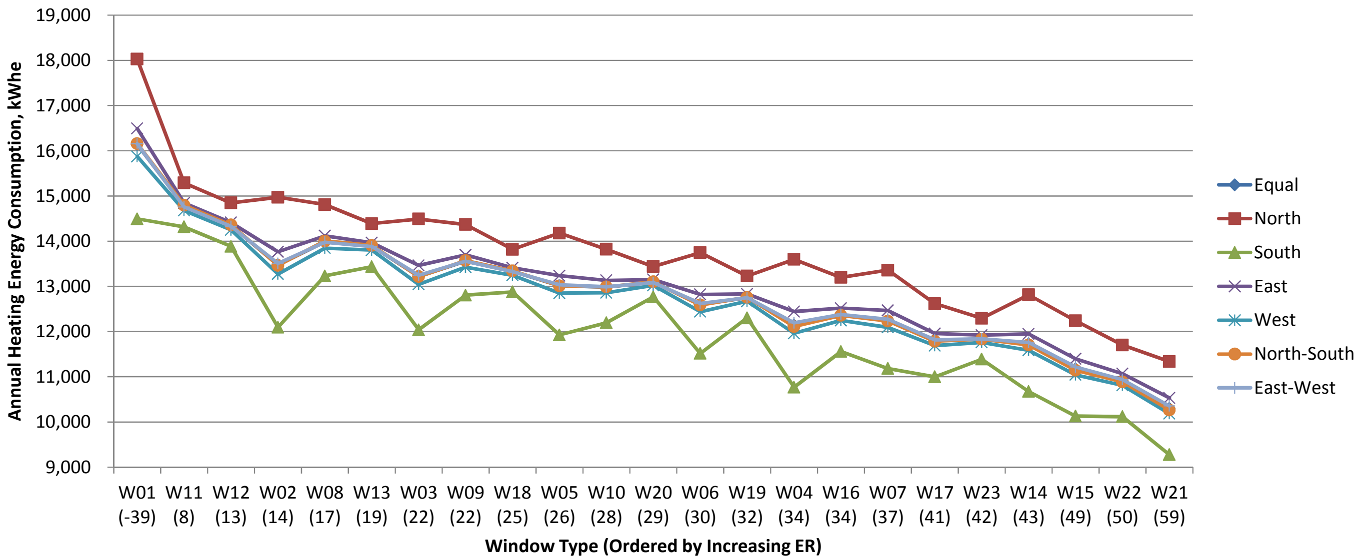


Fig.7.65 Annual heating energy consumption for window orientations in Montreal, kWh_e.

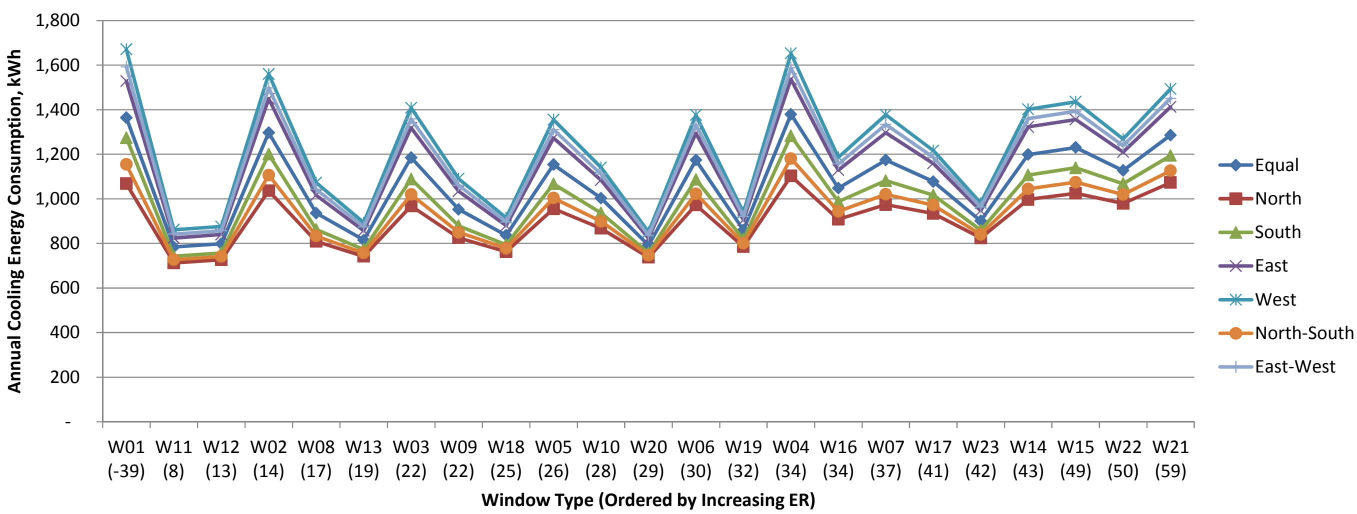


Fig.7.66 Annual cooling energy consumption for window orientations in Montreal, kWh.

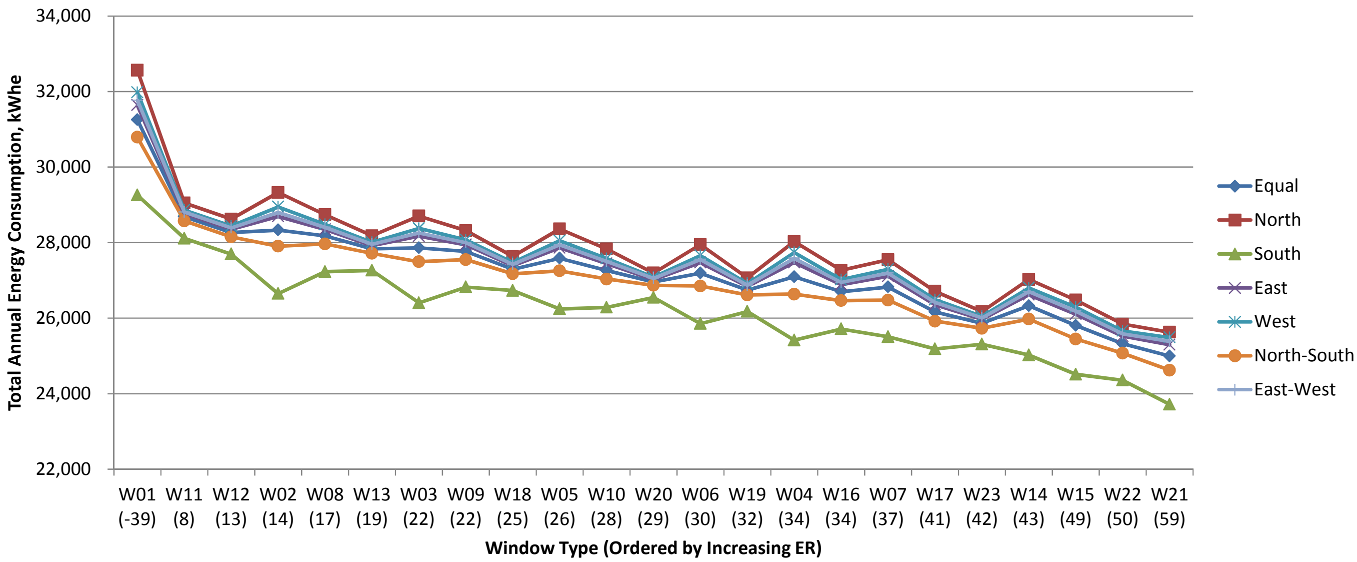


Fig.7.67 Total annual energy consumption for window orientations in Montreal, kWh_e.

Fig.7.68, Fig.7.69 and Fig.7.70 show the annual heating, cooling and total energy consumption for the single-storey archetype house in Winnipeg with different window orientations. Similar to Vancouver, Toronto and Montreal, the heating energy plot shows that the trend of increasing or decreasing energy for north windows is unlike the other scenarios, and that there are some smaller differences between the other orientations. In this location the south windows show much greater changes in energy consumption than the east, west, east-west and north-south windows, with a number of cases where the south trend is opposite to the other orientations. The cooling energy plot shows the same pattern for all orientations. The total energy plot shows different trends than the heating energy plot for certain windows.

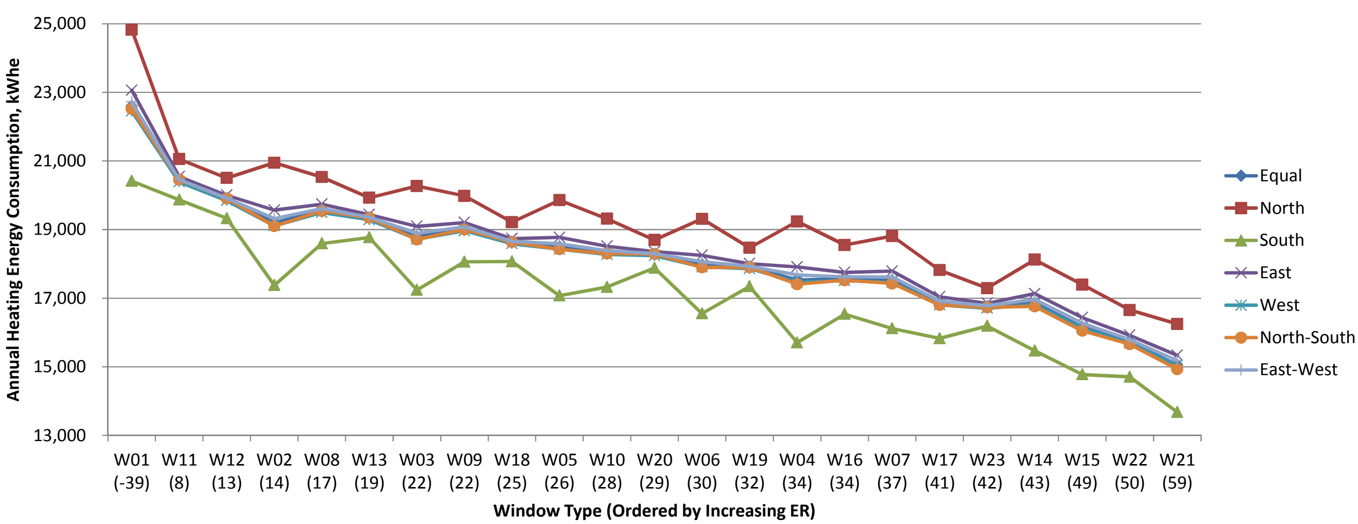


Fig.7.68 Annual heating energy consumption for window orientations in Winnipeg, kWh_e.

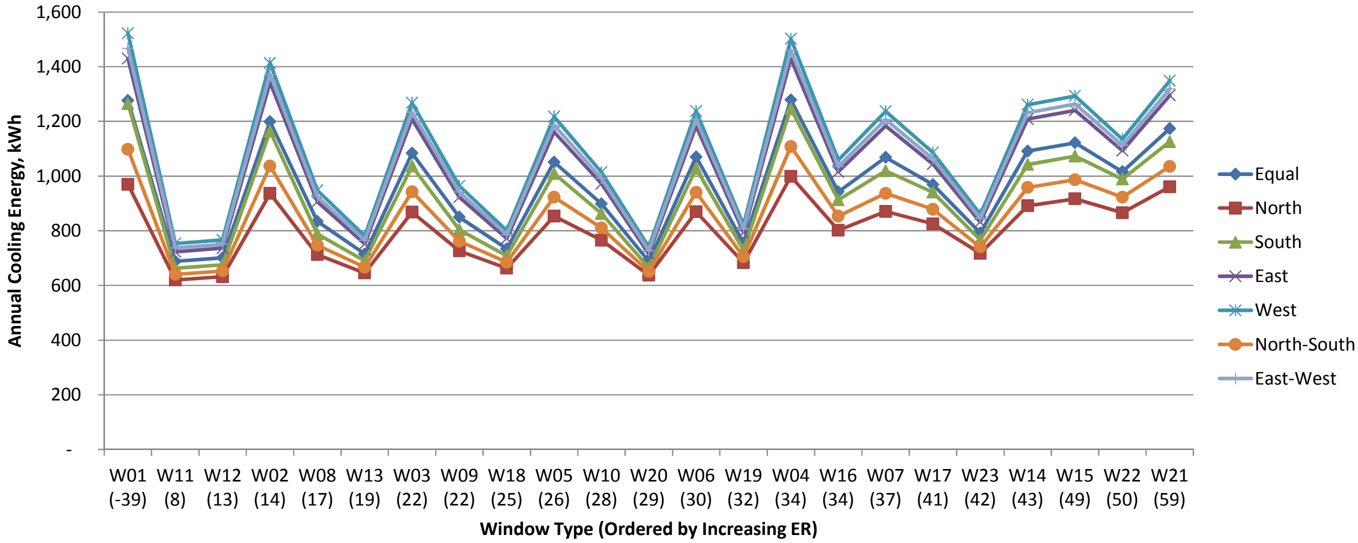


Fig.7.69 Annual cooling energy consumption for window orientations in Winnipeg, kWh.

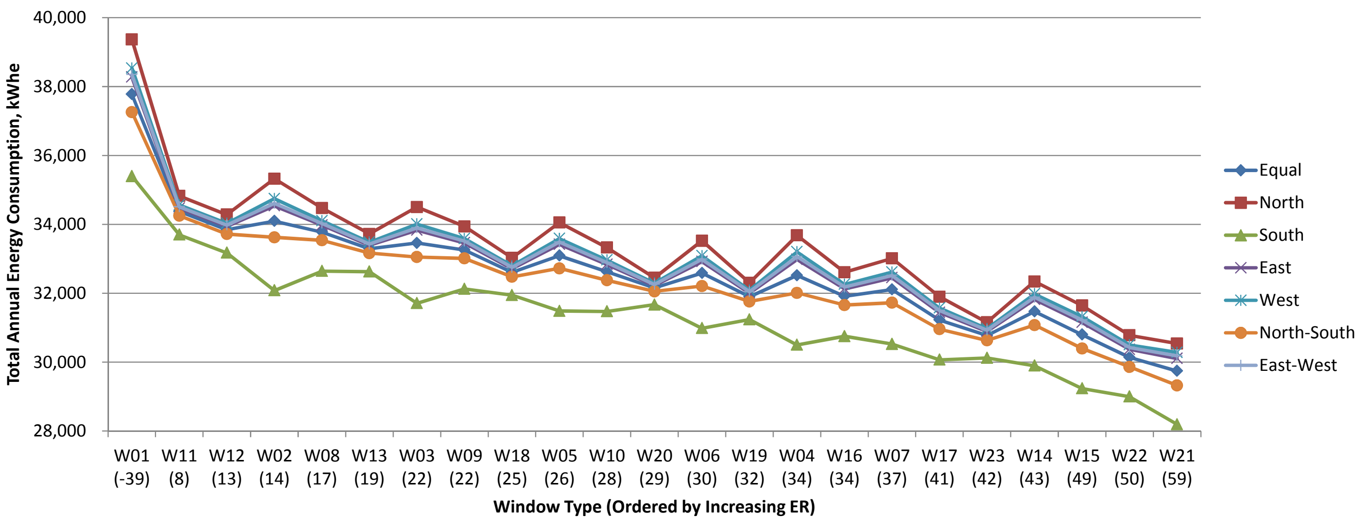


Fig.7.70 Total annual energy consumption for window orientations in Winnipeg, kWh.

Fig.7.71, Fig.7.72 and Fig.7.73 show the annual heating, cooling and total energy consumption for the single-storey archetype house in Yellowknife with different window orientations. The heating energy plot shows that the north and south orientations have opposite trends in a number of areas, with the remaining cases generally following the same trend as the north windows (though smaller differences). This is opposite to the previous locations examined where the orientations generally followed the trend of the south facing windows. This likely occurs because in the far northern climate there is less solar heat gain, particularly at the east and west elevations due to limited sun in the winter months. As with the previous locations, the cooling energy plot shows the same pattern for all orientations. For total energy, unlike the previous locations, the total energy plot follows the same pattern as the heating energy plot. In this location cooling energy is not high enough to change the trend.

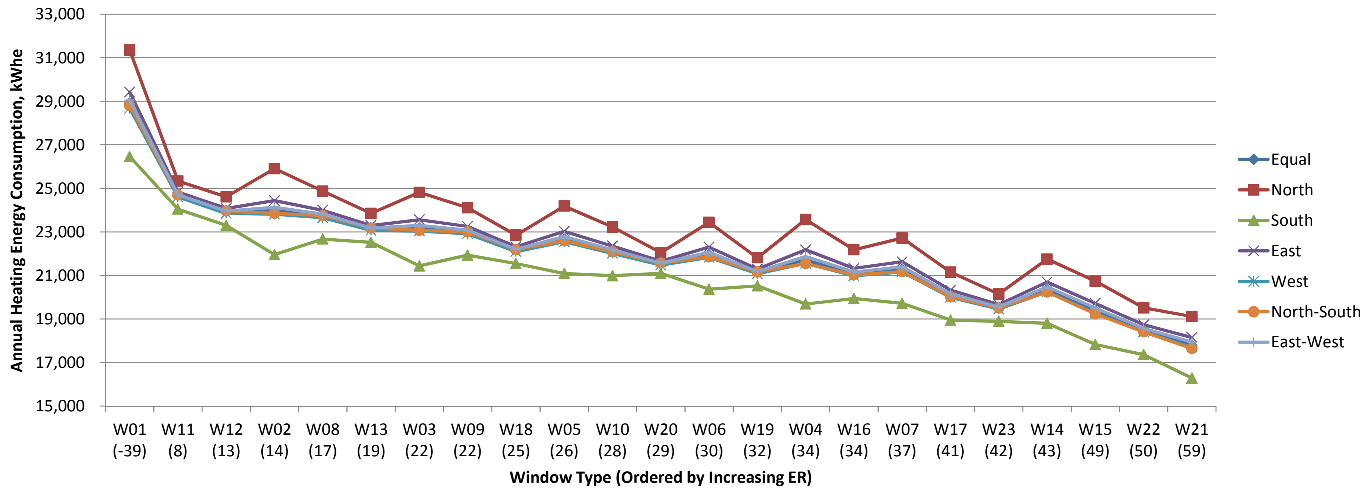


Fig.7.71 Annual heating energy consumption for window orientations in Yellowknife, kWh_e.

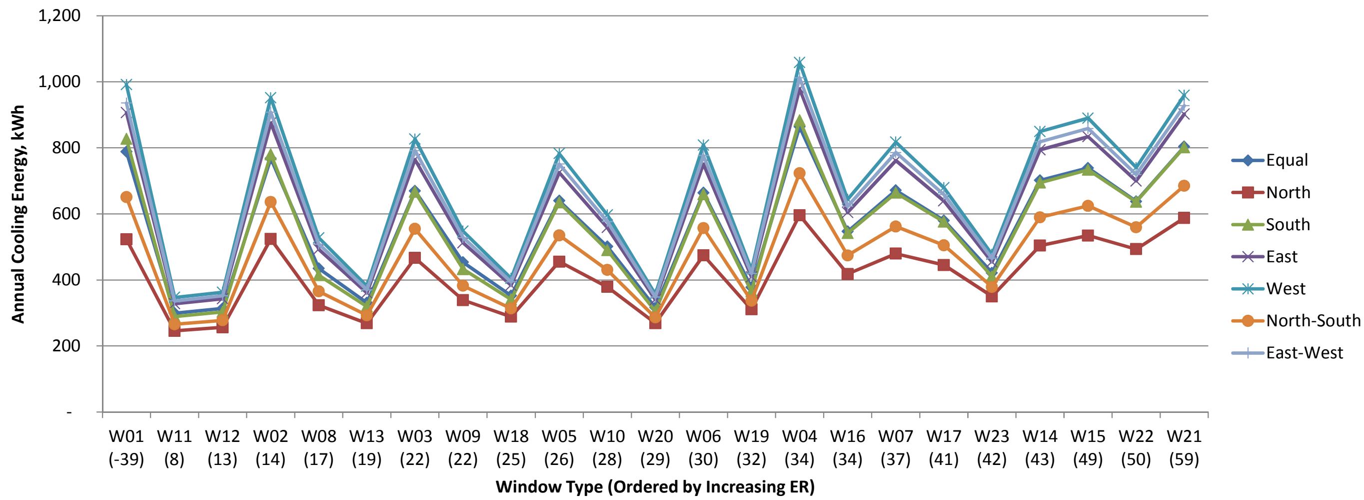


Fig.7.72 Annual cooling energy consumption for window orientations in Yellowknife, kWh.

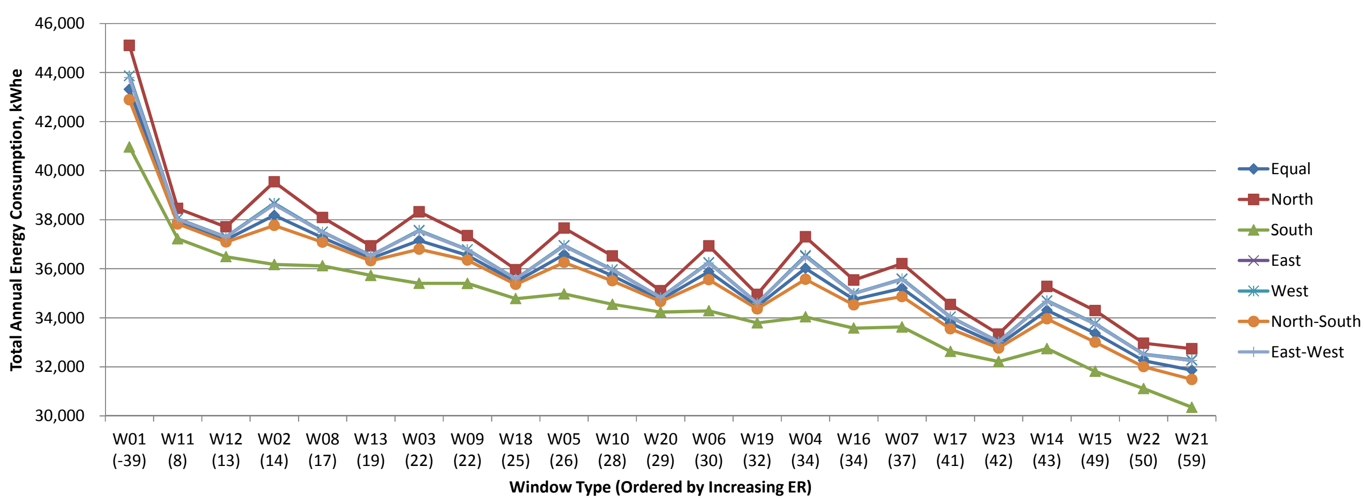


Fig.7.73 Total annual energy consumption for window orientations in Yellowknife, kWh_e.

The window orientation simulations show different trends of increasing and decreasing heating energy consumption for different orientations, particularly the north and south facing windows. This suggests that rating windows with a single ER number may not correctly indicate lower energy for houses with windows oriented predominantly in certain directions.

7.5.3 Window Orientation with Electric Baseboard Heating

To view the impact of zoned temperature control combined with different window orientations, the orientation simulations were run for the single-storey archetype house with electric baseboard heating in Vancouver and Toronto. Note that the air conditioning system did not change for these simulations (still central air conditioning with a central thermostat). Fig.7.74 shows the heating energy results for Vancouver, and Fig.7.75 shows the results for Toronto.

Like the gas heating system, the electric baseboard Vancouver plot shows different trends for the north and south facing windows. The east, west, north-south and east-west cases are closer together for the electric baseboard case than for the gas furnace case, suggesting that the zoned temperature control takes away some of the orientation variation. However, this archetype still results in different trends of increasing or decreasing heating energy for different orientations. This is also the case for the Toronto results.

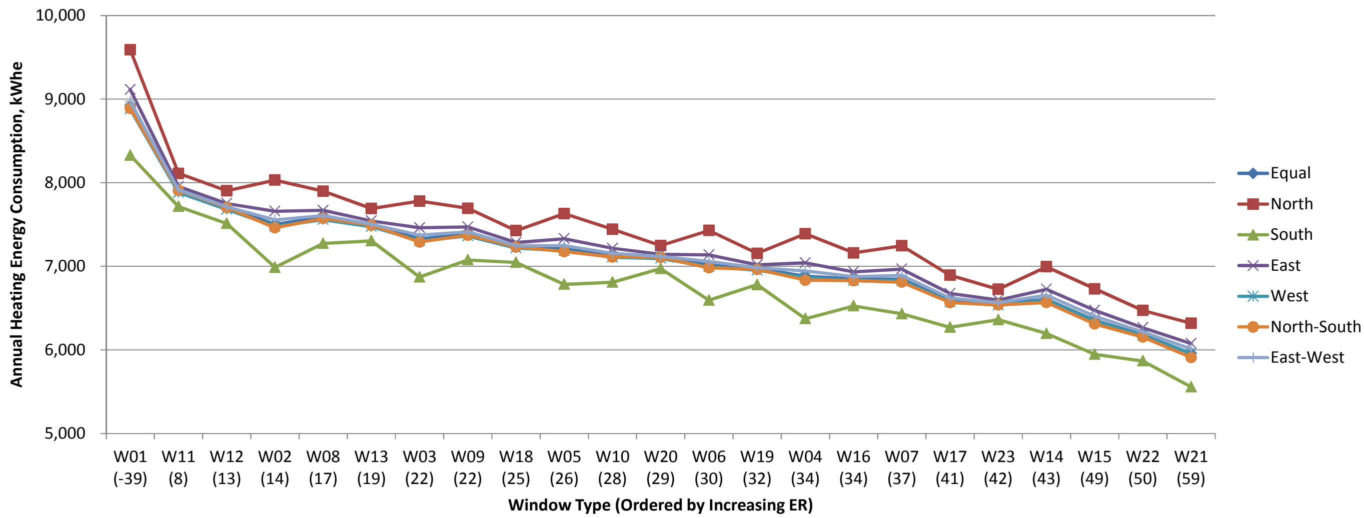


Fig.7.74 Annual heating energy consumption for window orientations in Vancouver with electric baseboard heating, kWh_e.

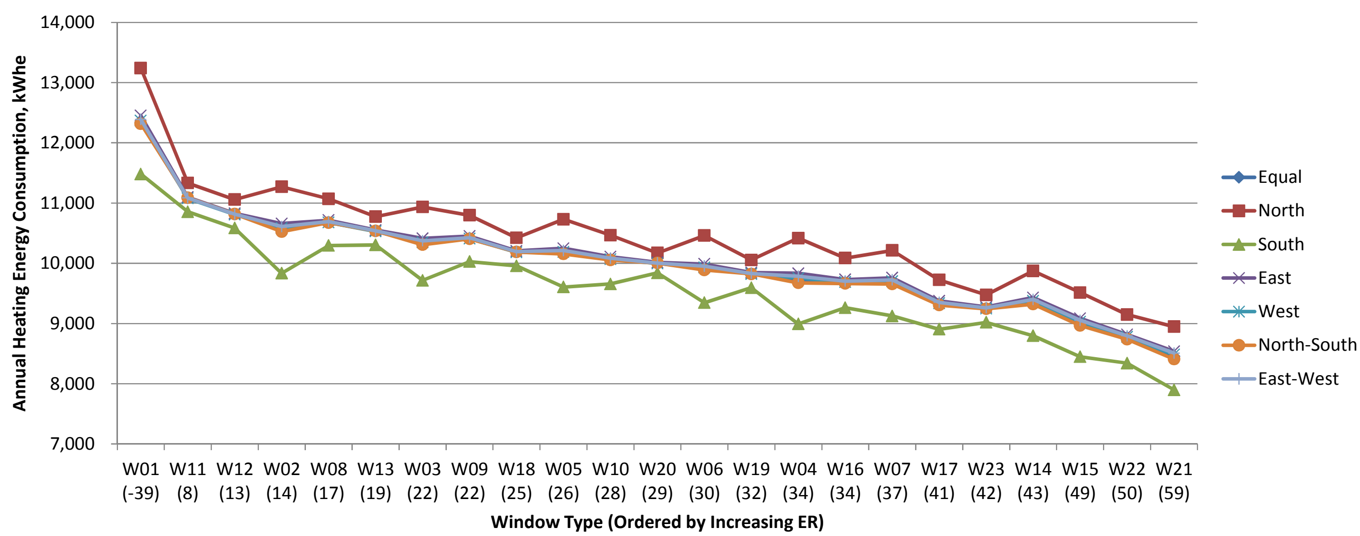


Fig.7.75 Annual heating energy consumption for window orientations in Toronto with electric baseboard heating, kWh_e.

7.5.4 Shading

The window shading scenarios were simulated with various shading strategies:

- No shading
- Small roof overhang, 0.5 m (baseline archetype case)
- 1 m overhang directly above windows, all elevations
- 1.5 m overhang directly above windows, all elevations
- 1 m overhang directly above windows, at south elevation only
- Operable shading optimized for cooling (all windows shaded if cooling needed during previous hour)

Fig.7.76, Fig.7.77 and Fig.7.78 show the heating, cooling and total energy for the various shading strategies in Vancouver, with windows ordered by lowest to highest ER. In the heating plot, the pattern of increasing or decreasing heating energy has some differences for the various shading conditions. The cases with no shading, 0.5 m roof overhang and 1m south shading follow the same trend. The 1.5m and 1m overhang cases follow the same trend for most windows, but are opposite to the low shading scenarios for a number of windows. For example, see window W19 (U-0.9, SHGC-0.2, ER-32) to W04 (U-2.0, SHGC-0.65, ER-34): heating energy increases for the 1m and 1.5m overhang cases and decreases for no shading and 0.5m roof overhang. When windows are shaded, windows with a lower U-value will use less heating energy than windows with a high SHGC.

The cooling energy results show that all shading conditions follow the same general trend of increasing or decreasing energy consumption, with the exception of the operable shades. As expected, windows with less or no shading use more cooling energy, and result in greater differences between windows with higher and lower SHGCs. The operable shading line is nearly linear, indicating that operable shades optimized for cooling minimize cooling energy consumption, and essentially remove the solar heat gain contribution to the cooling load of the house.

The total energy plot shows that unlike the heating plot, each shading scenario follows the same general trend of increasing or decreasing energy consumption, except for the case with operable shades.

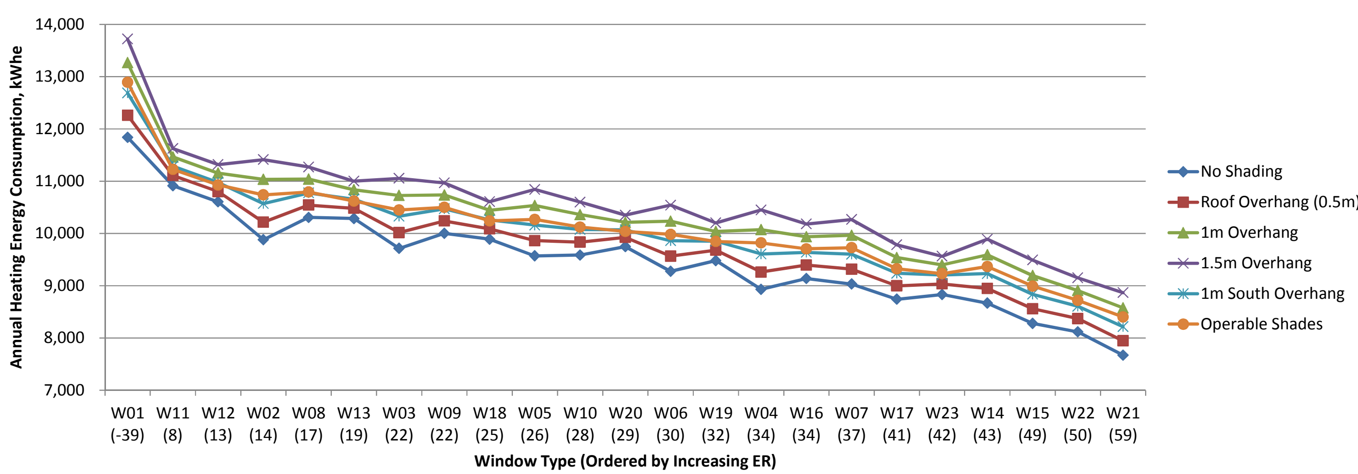


Fig.7.76 Annual heating energy consumption for window shading scenarios in Vancouver, kWh_e.

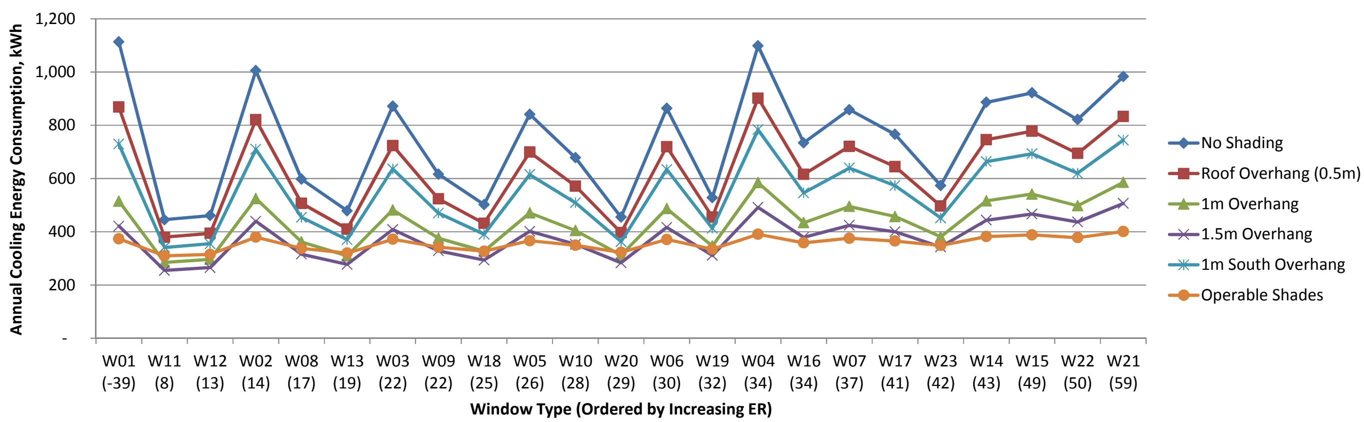


Fig.7.77 Annual cooling energy consumption for window shading scenarios in Vancouver, kWh.

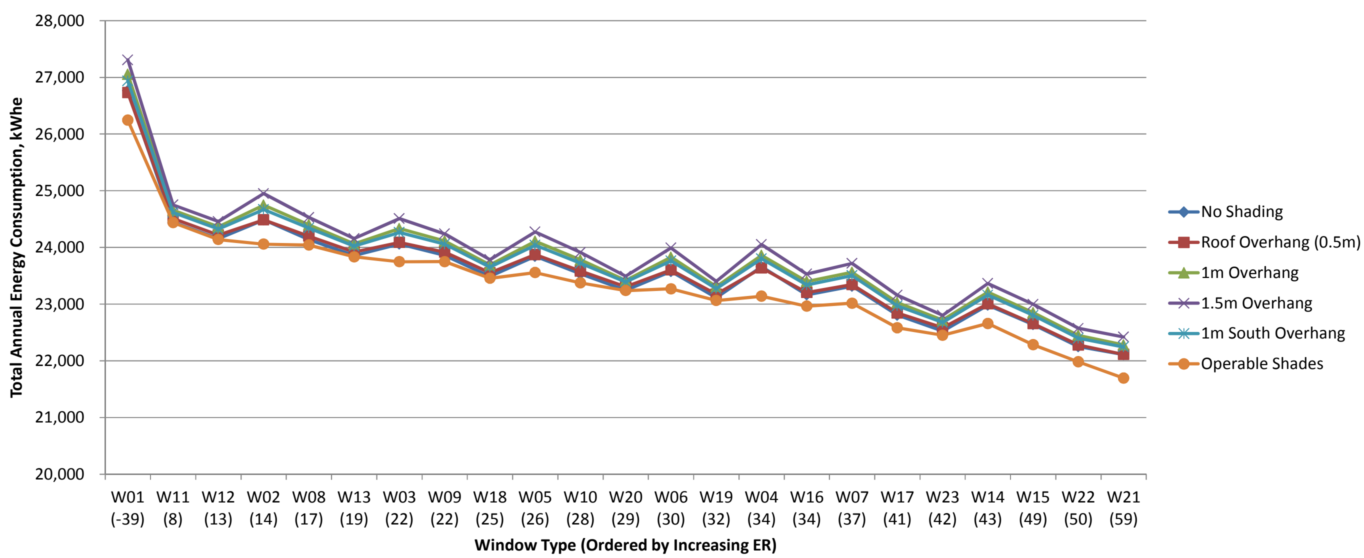


Fig.7.78 Total annual energy consumption for window shading scenarios in Vancouver, kWh_e.

Fig.7.79, Fig.7.80 and Fig.7.81 show the heating, cooling and total energy for the various shading strategies in Toronto, with windows ordered by lowest to highest ER. Like Vancouver, the cases with no shading, 0.5 m roof overhang and 1m south shading follow the same trend; the case with operable shading also follows this pattern fairly closely. The 1.5m and 1m overhang cases follow the same trend for most windows, but are opposite to the low shading scenarios for a number of windows. For example, see window W19 (U-0.9, SHGC-0.2, ER-32) to W04 (U-2.0, SHGC-0.65, ER-34): heating energy increases for the 1m and 1.5m overhang cases and decreases for no shading and 0.5m roof overhang.

As with Vancouver, the cooling energy results show that all shading conditions follow the same general trend of increasing or decreasing energy consumption with the exception of the operable shades. The operable shading case shows very little change in cooling energy for different window types.

The total energy plot shows that unlike the heating plot, each shading scenario follows the same general trend of increasing or decreasing energy consumption, except for the case with operable shades.

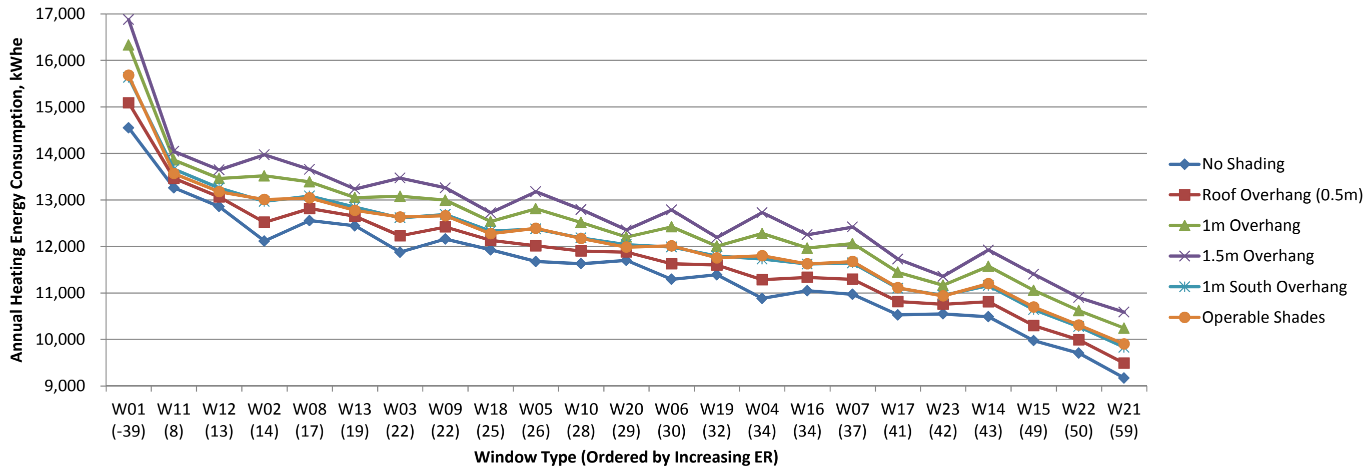


Fig.7.79 Annual heating energy consumption for window shading scenarios in Toronto, kWh_e.

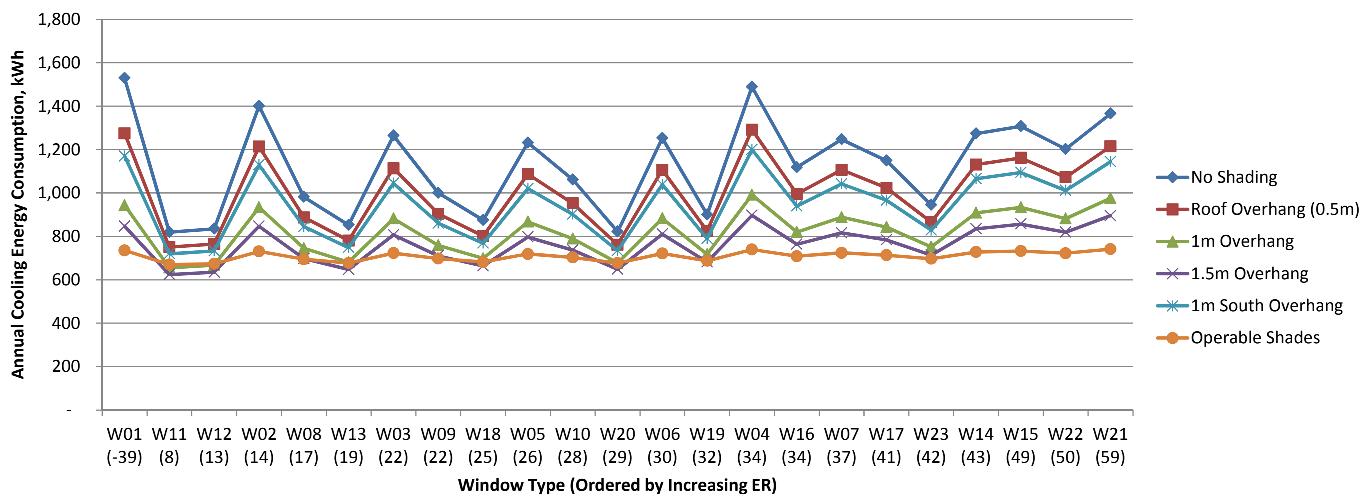


Fig.7.80 Annual cooling energy consumption for window shading scenarios in Toronto, kWh.

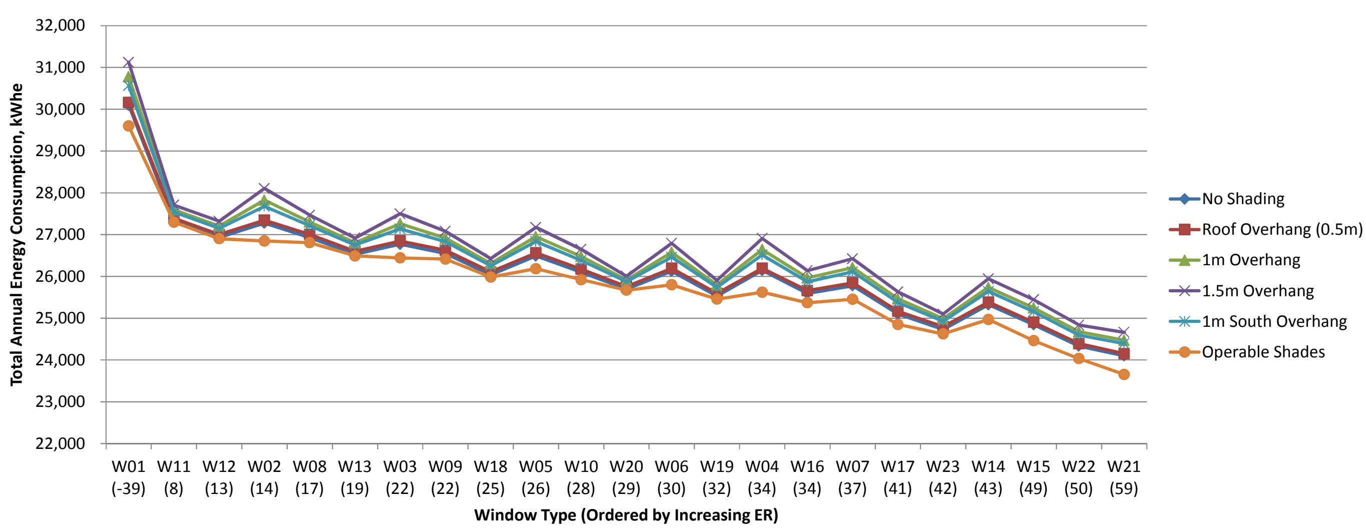


Fig.7.81 Total annual energy consumption for window shading scenarios in Toronto, kWh_e.

Fig.7.82, Fig.7.83 and Fig.7.84 show the heating, cooling and total energy for the various shading strategies in Montreal, with windows ordered by lowest to highest ER. The heating plot shows that the cases with no shading, 0.5 m roof overhang, 1 m south overhang, and operable shades follow the same general trend for most windows. The 1 m overhang and 1.5 m overhang have different patterns of increasing or decreasing heating energy in a number of cases.

The cooling energy results for Montreal are similar to Toronto and Vancouver, with all shading conditions following the same general trend of increasing or decreasing energy consumption with the exception of the operable shades. The operable shading case shows very little change in cooling energy for different window types.

The total energy plot shows that unlike the heating plot, each shading scenario follows the same general trend of increasing or decreasing energy consumption, except for the case with operable shades.

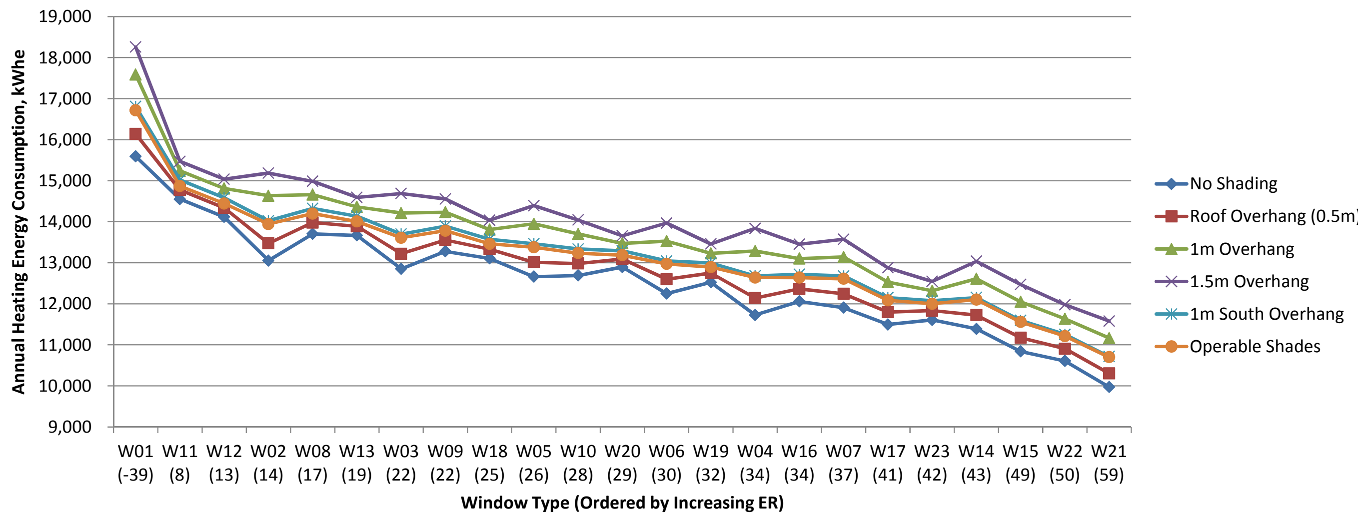


Fig.7.82 Annual heating energy consumption for window shading scenarios in Montreal, kWh_e.

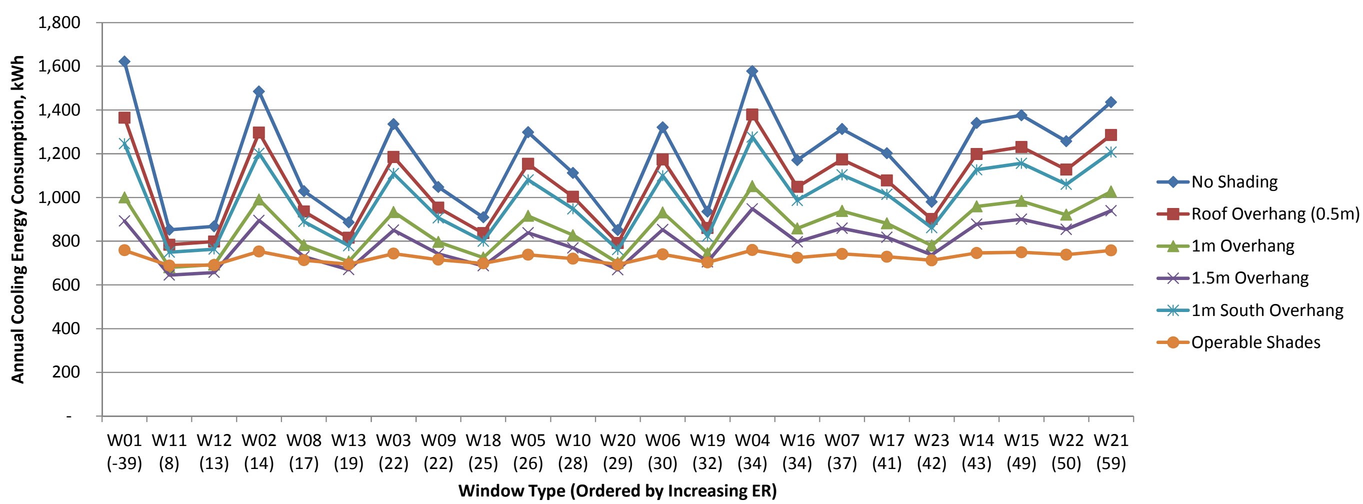


Fig.7.83 Annual cooling energy consumption for window shading scenarios in Montreal, kWh.

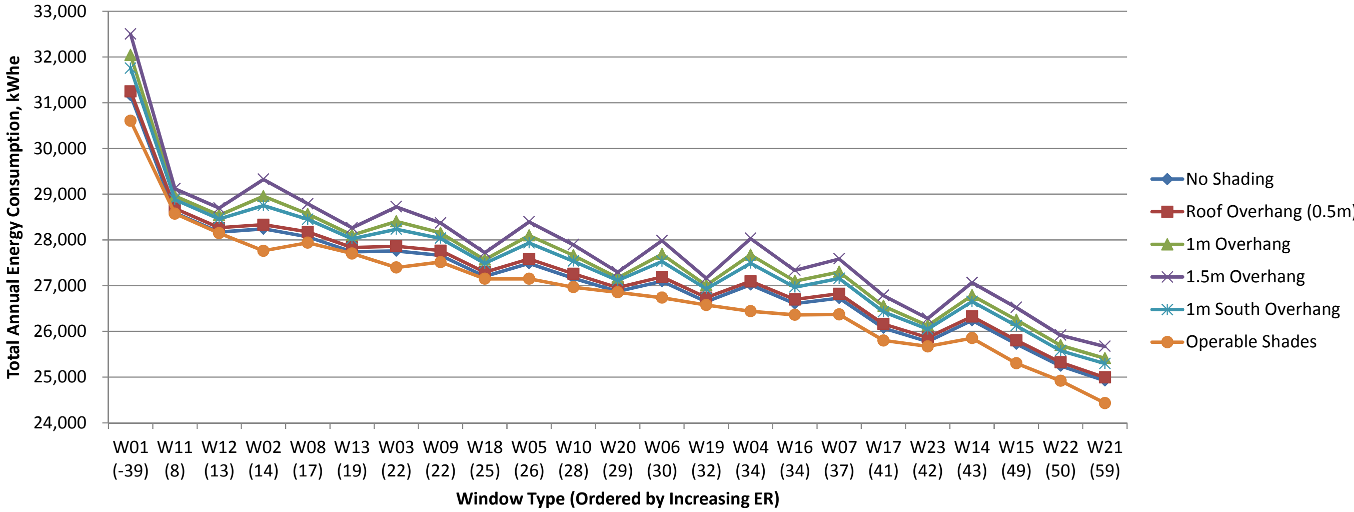


Fig.7.84 Total annual energy consumption for window shading scenarios in Montreal, kWh_e.

Fig.7.85, Fig.7.86 and Fig.7.87 show the heating, cooling and total energy for the various shading strategies in Winnipeg, with windows ordered by lowest to highest ER. The heating plot shows that the different shading strategies have different trends of increasing or decreasing heating energy consumption. The cooling energy results for Winnipeg are similar to Montreal, Toronto and Vancouver, with all shading conditions following the same general trend of increasing or decreasing energy consumption with the exception of the operable shades. The operable shading case shows very little change in cooling energy for different window types. The total energy plot shows that unlike the heating plot, each shading scenario follows the same general trend of increasing or decreasing energy consumption, except for the case with operable shades.

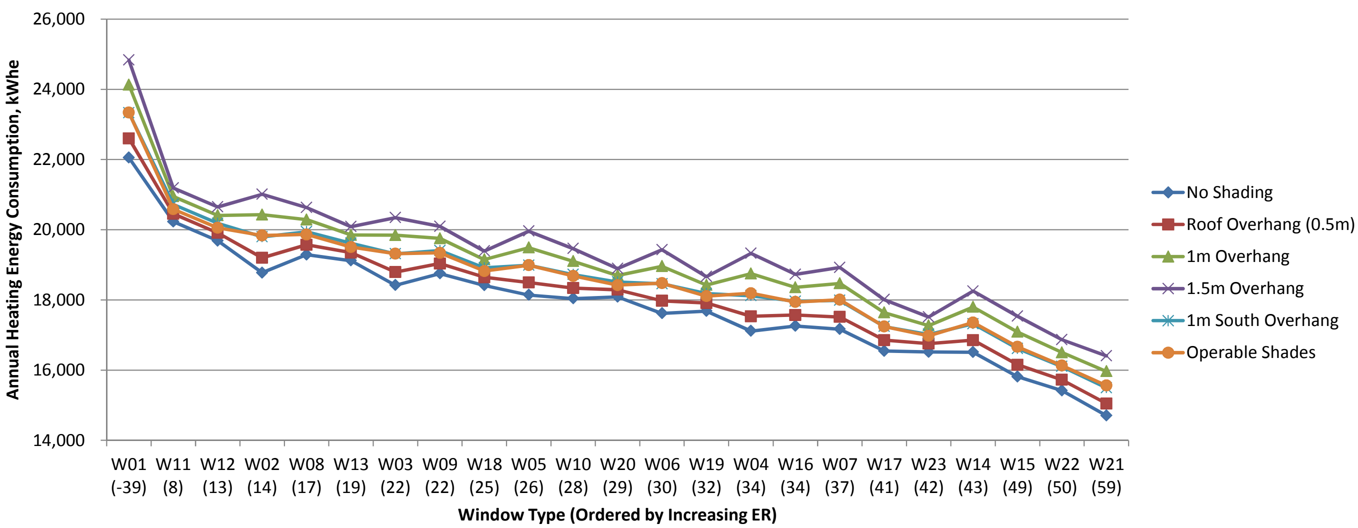


Fig.7.85 Annual heating energy consumption for window shading scenarios in Winnipeg, kWh_e.

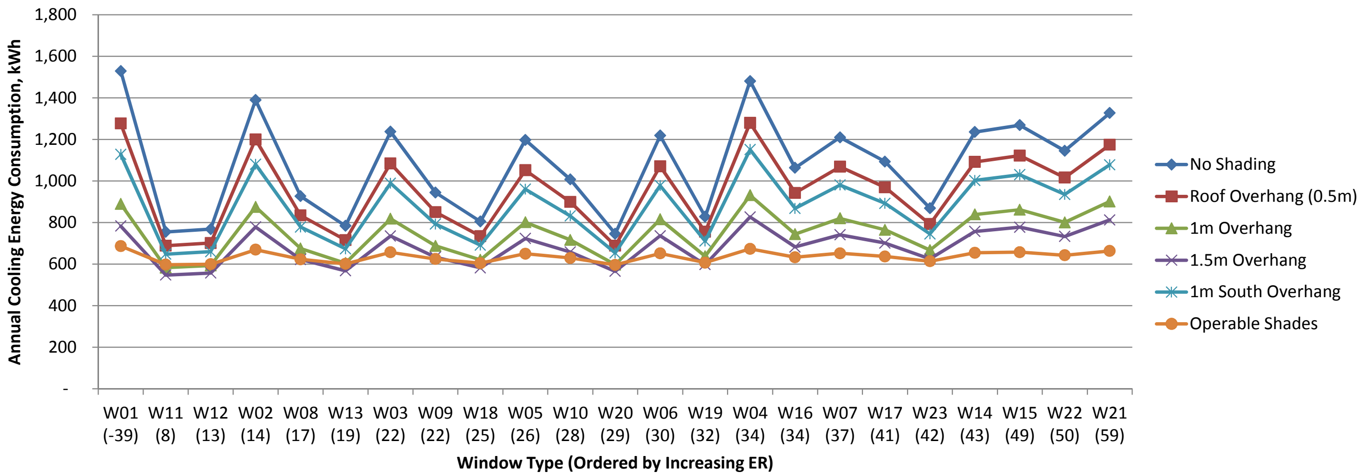


Fig.7.86 Annual cooling energy consumption for window shading scenarios in Winnipeg, kWh.

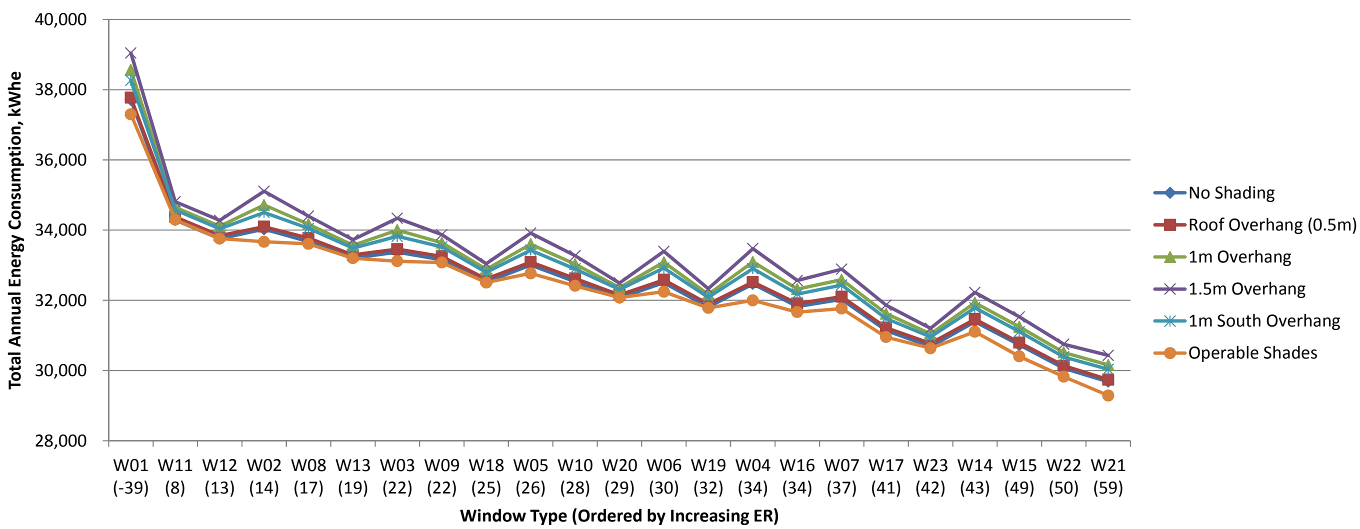


Fig.7.87 Total annual energy consumption for window shading scenarios in Winnipeg, kWh_e.

Fig.7.88, Fig.7.89 and Fig.7.90 show the heating, cooling and energy for the various shading strategies in Yellowknife, with windows ordered by lowest to highest ER. The heating plot shows that the different shading strategies follow the same general trend of increasing and decreasing energy consumption in most cases, with only a few exceptions. This suggests that shading does not impact the ordering of window energy consumption very much in far north locations. This is likely due to the lower amount of solar radiation in the winter in the far north. For cooling, all shading conditions following the same general trend of increasing or decreasing energy consumption with the exception of the operable shades, as with the other locations. The operable shading case shows very little change in cooling energy for different window types. The total energy plot shows that unlike the heating plot, each shading scenario follows the same general trend of increasing or decreasing energy consumption (including the case with operable shades).

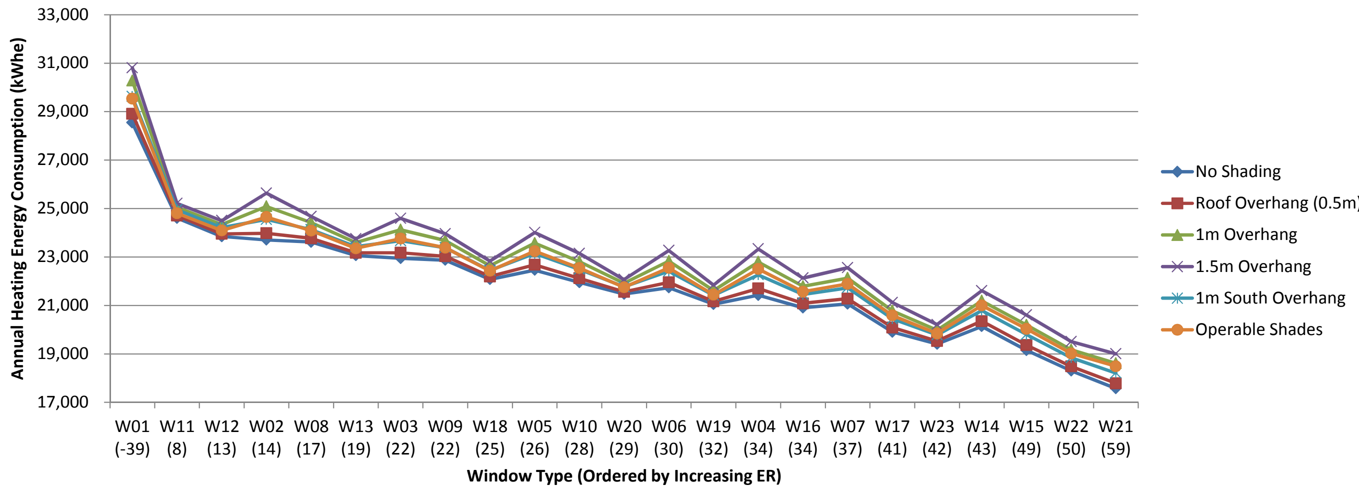


Fig.7.88 Annual heating energy consumption for window shading scenarios in Yellowknife, kWh_e.

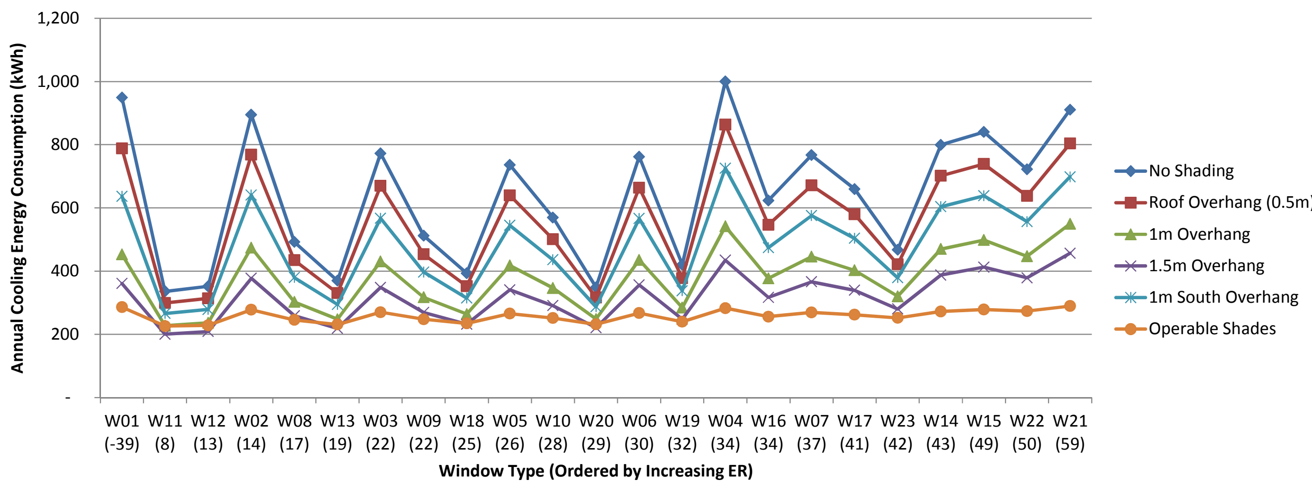


Fig.7.89 Annual cooling energy consumption for window shading scenarios in Yellowknife, kWh.

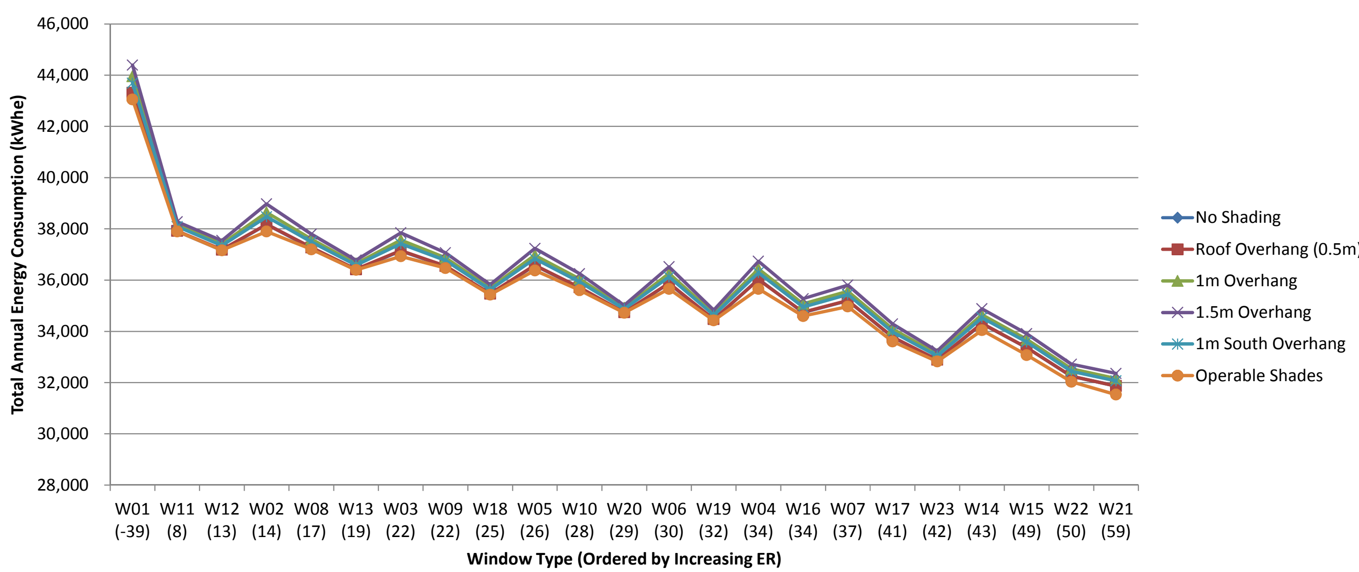


Fig.7.90 Total annual energy consumption for window shading scenarios in Yellowknife, kWh_e.

The window shading simulations show different trends of increasing and decreasing heating energy consumption for different shading scenarios. This suggests that rating windows with a single ER number may not correctly indicate lower energy consumption for houses where some windows are shaded.

7.6. Additional Scenarios

Several questions regarding certain archetype house parameters were raised through comments received during the work. Based on the previous analysis, it is anticipated that these parameters will not impact the ordering of heating or cooling energy consumption by window ER. It is also important to recognize that this report is used to analyze the ER approach, and not to develop new equations or parameters. However, for completeness, several simulations were run for these parameters to confirm this hypothesis. The following parameters were investigated:

- Furnace efficiency: A comment was raised that furnace efficiencies in older homes may be lower than the 78% used in the previous simulations. An efficiency of 70% was suggested. A higher efficiency was chosen in Section 4 since older furnaces will need to be replaced, if they haven't been already, and are likely to be replaced with a higher efficiency unit. Simulations were run for Toronto to compare a furnace efficiency of 70% and 78%.
- Airtightness: A comment was raised that many older homes have air leakage rates much higher than the 7, 4 and 3 ACH @ 50 Pa used in these simulations. Simulations were run for Toronto to compare an airtightness rate of 4 ACH_{50} (used in the previous simulations), 10 ACH_{50}, 20 ACH_{50}, and 40 ACH_{50}.

Fig.7.91 and Fig.7.92 show the heating and cooling energy consumption of the additional simulation cases. The results show that, like the other archetype house parameters not directly related to windows, these scenarios do not change the pattern of increasing or decreasing energy consumption for different window types.

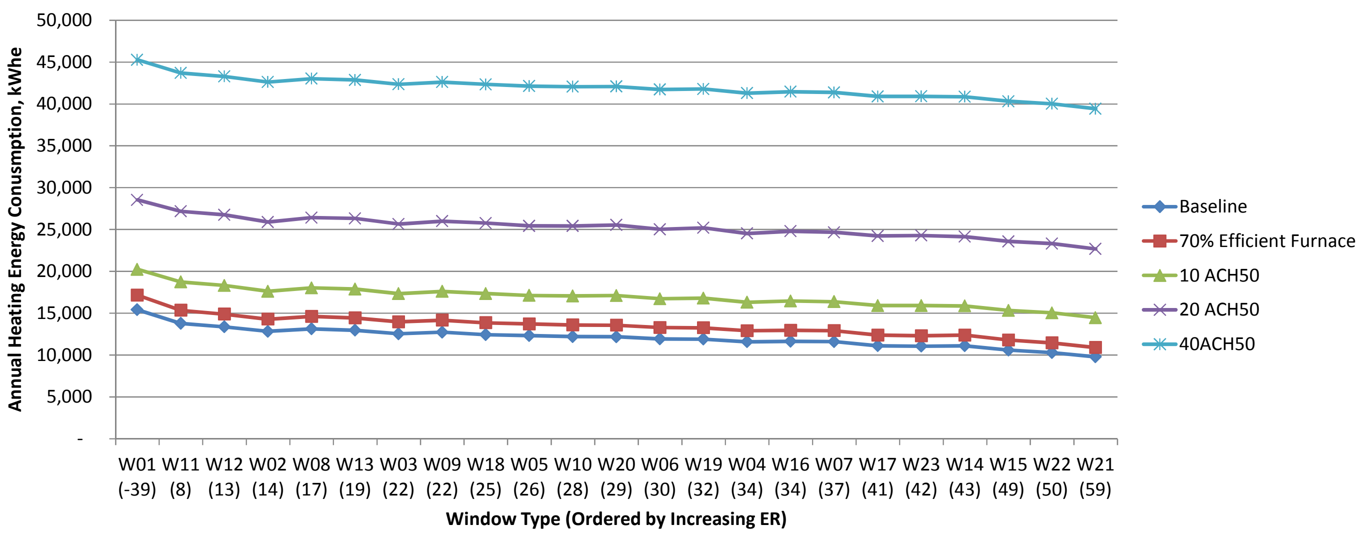


Fig.7.91 Annual heating energy consumption in Toronto, kWh_e.

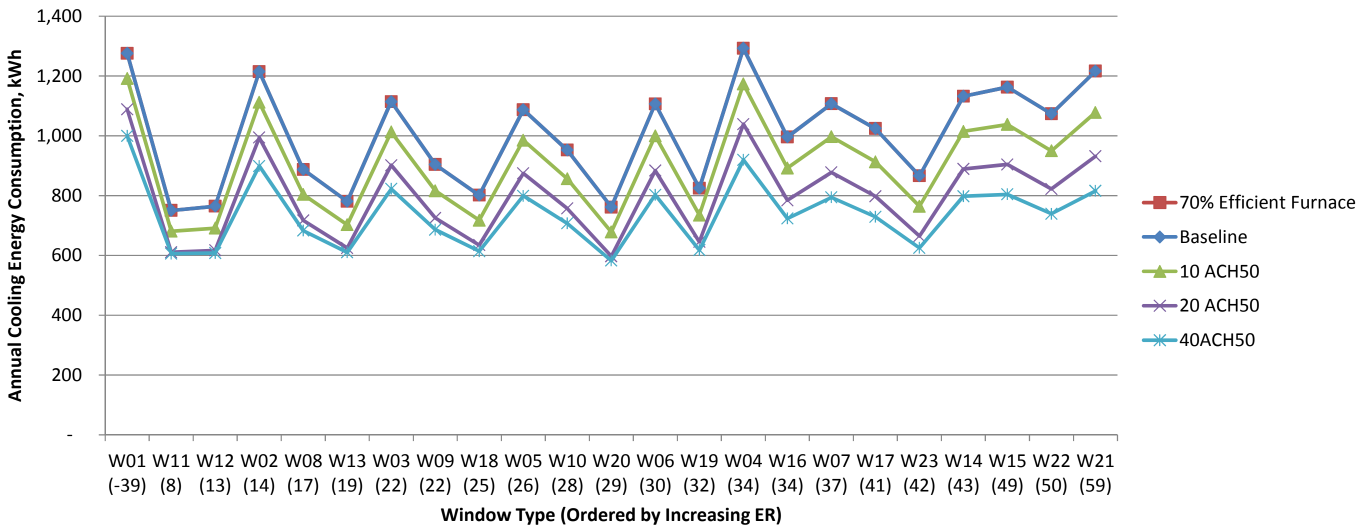


Fig.7.92 Annual cooling energy consumption in Toronto, kWh.

7.7. Summary

The goal of this section was to simulate a wide range of archetype house variables to assess how the ER ranks window energy consumption for different types of windows and in different climates. Over 5,400 simulations were completed, and some general conclusions can be developed based on the simulation results.

In general, windows with a higher ER use less heating energy. However, there are a number of windows simulated where the ER values are close, where a higher ER results in higher heating energy consumption. Though the ER does not rank cooling energy appropriately (as expected), cooling energy consumption is very low compared to heating energy in all Canadian locations under worst-case cooling conditions. Therefore, when looking at energy consumption alone, heating energy outweighs cooling. Note that thermal comfort is studied in Section 9 of this report, which will examine the impact of overheating.

The same trends of increasing or decreasing heating and cooling energy consumption are seen for the majority of the geographic locations simulated. The exception to this was Yellowknife, where significant differences were seen compared to the other locations. It is thought that this is due to the low amount of sunlight that Yellowknife receives in the winter.

The same trends of increasing or decreasing heating and cooling energy consumption are seen for all of the archetype house parameters that were simulated (variables not directly related to the windows). These parameters included natural ventilation to reduce cooling energy, electric baseboard heating with zoned thermostat control, high internal gains, no basement, new enclosure thermal performance, high thermal mass, walkout basement with fenestration, and house size. This suggests that a representative archetype house may be used in the development of an ER to rank windows.

For the window to wall ratio (WWR) simulations, high and low ER windows performed differently at different WWRs. However, the general pattern of increasing or decreasing heating and cooling energy consumption was consistent across the various window types. Therefore, when comparing windows for a given WWR, the ER can still be used to consistently rank or compare windows.

The simulations of different window orientations and shading strategies showed varying patterns of increasing or decreasing heating energy. This suggests that rating windows with a single ER number may not correctly indicate lower energy consumption for houses with different window orientations and shading.

8. Greenhouse Gas Emissions

8.1. GHG Emissions Factors

Greenhouse Gas (GHG) emissions factors used in this report were obtained from Environment Canada, 2008 data (Table 8.1). The emissions factors for electricity vary significantly by province, depending on the province's primary source of electricity. The electricity factors by province range from a low of 0.002 $kgCO_2e/kWh$ in Quebec, where the majority of electric power is hydroelectric, to a high of 0.88 $kgCO_2e/kWh$ in Alberta where the majority of power is fossil-fuel based. In some provinces, the emission factor for electricity is lower than that of natural gas, while in other provinces the natural gas factor is lower.

The natural gas emissions factors depend primarily on fuel properties, including carbon content, density, and heating value. The slight variation in natural gas emissions factors by province is a result of regional variations in the properties of the natural gas. These factors were developed based on a chemical analysis of natural gas samples from each province. Refer to *Environment Canada's National Inventory Report*, 1990 – 2009, for additional information on natural gas emissions factors.

GHG emissions conversion factors vary by location, depending on how electricity is generated and how far natural gas travels. Conversion factors also vary hourly depending on the mix of fuels and, in some locations, renewable energy generation.

Generally, higher energy consumption will result in higher GHG emissions. However, the ER may impact GHG results differently than energy consumption results due to the different emissions factors, depending on the fuel source. Specifically, cooling uses electrical energy, while heating is primarily by electricity or natural gas. Provinces with higher electrical emissions factors result in cooling energy having an increased importance compared to heating by natural gas. The provinces where the electricity emissions factor is higher than the natural gas emissions factor include Nova Scotia, New Brunswick, Saskatchewan, and Alberta.

Heating oil, common in the Maritimes and Territories, is not given by province, however, Environment Canada reports "Heavy Fuel Oil" (including residential use) has an emissions factor of 3.124 $kgCO_2/L$. The fuel oil emissions factor is used in this report to calculate emissions for a house located in Halifax, where fuel oil heating is common.

Table 8.1 GHG Emissions Factors

	Electricity, $kgCO_2e/kWh$ [14]	Natural Gas, $kgCO_2/m^3$ [15]	Heating Oil, $kgCO_2/L$ [15]
Newfoundland and Labrador	0.020	1.891	
Prince Edward Island	Not Available	Not Available	
Nova Scotia	0.790	1.891	
New Brunswick	0.460	1.891	
Quebec	0.002	1.878	
Ontario	0.170	1.879	
Manitoba	0.010	1.877	
Saskatchewan	0.710	1.820	
Alberta	0.880	1.918	
British Columbia	0.020	1.916	
Yukon	0.060	Not Available	
Northwest Territories	0.060	2.454	
Canada	0.200	Not Available	0.29

[14] Environment Canada, 2008, http://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=EAF0E96A-1#section11
[15] Environment Canada, http://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=AC2B7641-1#section2

8.2. GHGs and the ER

For houses that are heated and cooled using electricity, the ability of the ER to rank GHG emissions will not be different from the energy ranking (Section 7), since a single emissions factor would be applied to all electricity consumption. However, houses that are heated by gas and cooled by electricity may be affected since a different emission factor is applied to each fuel source. The following analysis is therefore based on the energy simulation results from Section 7 using the single-storey house heated by natural gas, or oil in the Maritime Provinces.

In locations where the electricity emission factor is much lower than the gas emission factor, it is expected that the overall ability of the ER to rank GHG emissions would not be affected since the cooling energy is much lower than heating energy to begin with, and the impact of cooling would be further reduced by a low emissions factor. However, in locations where the electricity emission factor is higher than the gas emission factor, the importance of cooling to GHG emissions will be greater, and this could impact the ability of the ER to rank GHG emissions.

Fig.8.1 to Fig.8.7 show the heating, cooling and total heating and cooling GHG emissions for the single-storey archetype house in various Canadian cities. As expected, in Vancouver, Winnipeg, Montreal and Yellowknife (all gas-heated), GHG emissions are so low that the total heating and cooling emissions is very close to the heating emissions. In Toronto, the GHG emissions from cooling are greater, however, the trend of increasing or decreasing total emissions is very close to the trend for heating only. There are only a few cases where the trend lines go in different directions, and the difference is small.

In Edmonton (gas heated) and Halifax (heating oil) the GHG emissions from cooling energy are more significant. The total heating and cooling emissions in these two cities follow different trends of increasing and decreasing emissions than the heating only plot. Particularly in Edmonton, the total emissions correlation is not as good as the correlation for heating emissions. This indicates that for houses that have cooling in locations with high electrical emissions factors, the ER rating may not be a good indicator of lower GHG emissions. Otherwise, the ER appears to rate GHG emissions similarly to energy consumption.

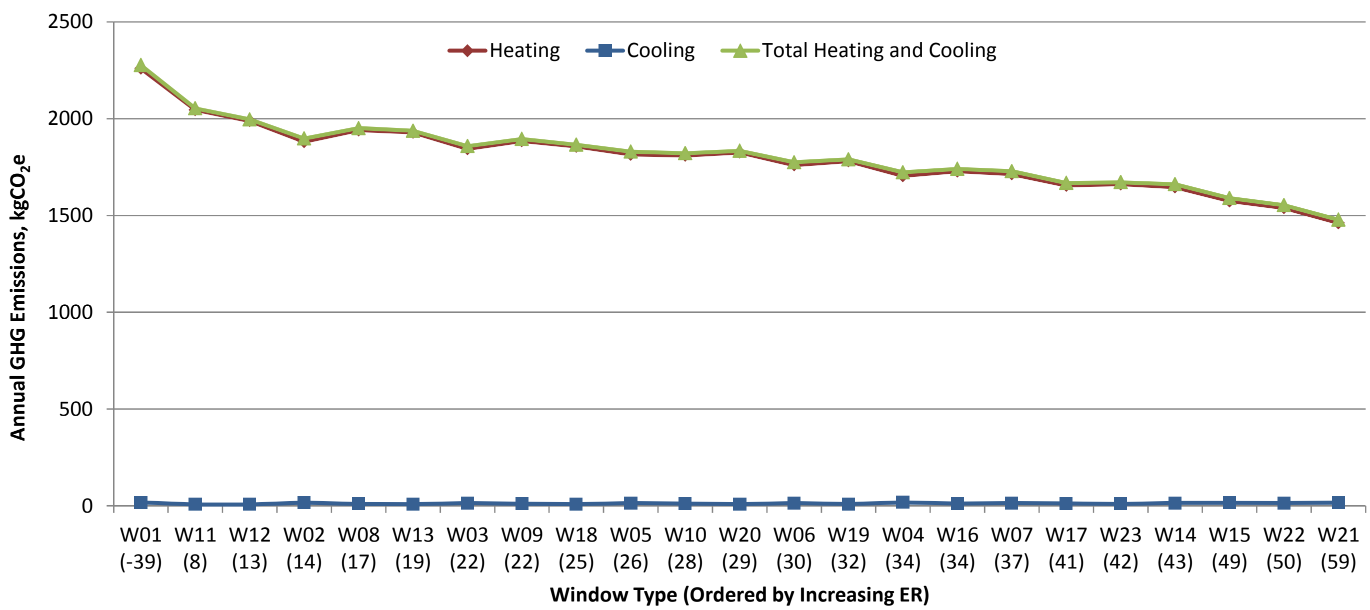


Fig.8.1 Annual GHG emissions for Vancouver, gas-heated, $kgCO_2e$.

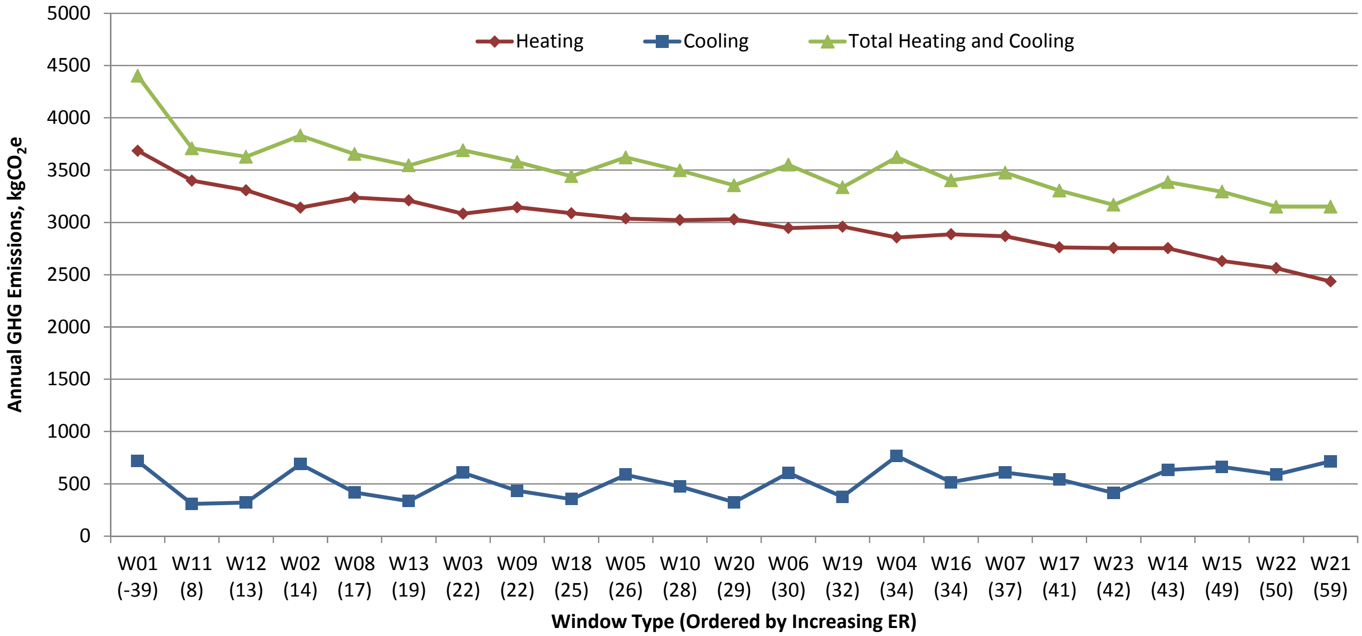


Fig.8.2 Annual GHG emissions for Edmonton, gas-heated, $kgCO_2e$.

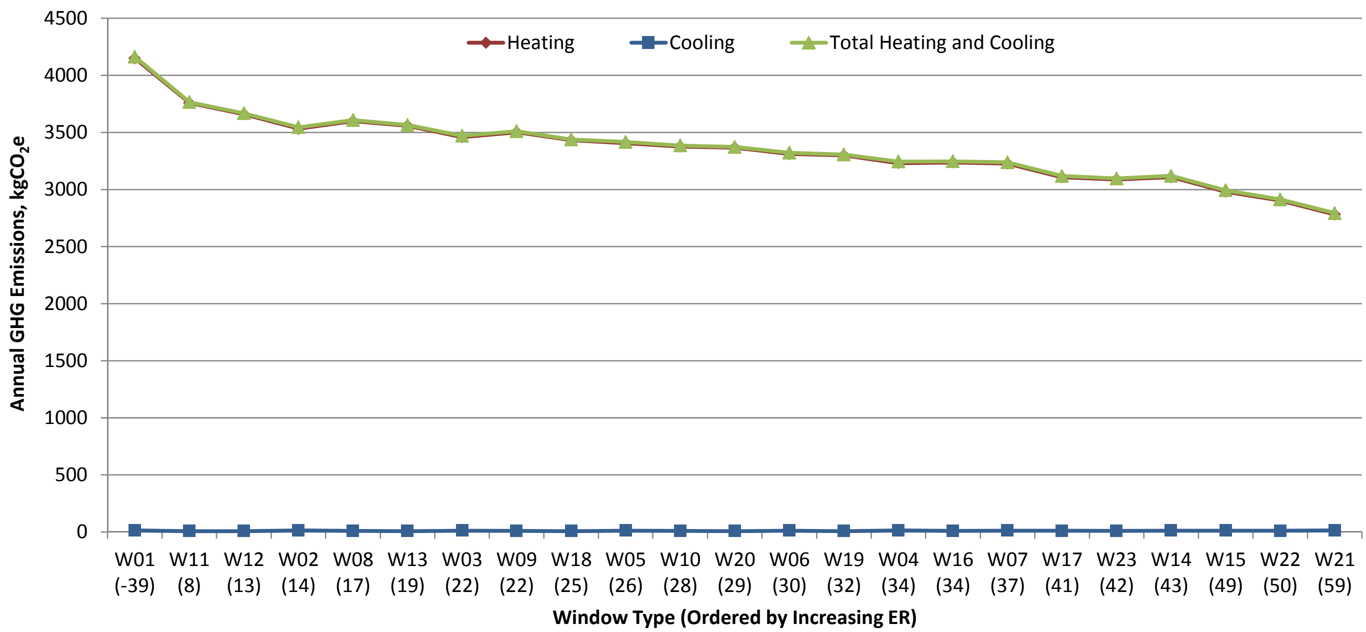


Fig.8.3 Annual GHG emissions for Winnipeg, gas-heated, $kgCO_2e$.

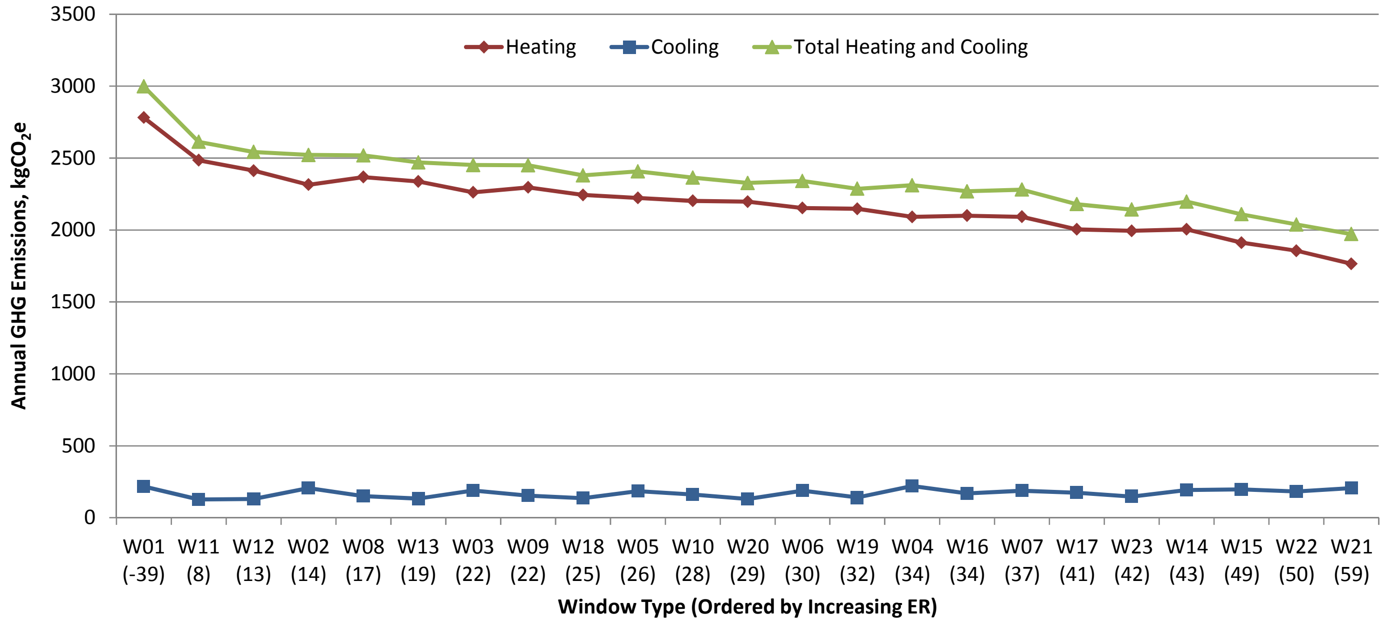


Fig.8.4 Annual GHG emissions for Toronto, gas-heated, $kgCO_2e$.

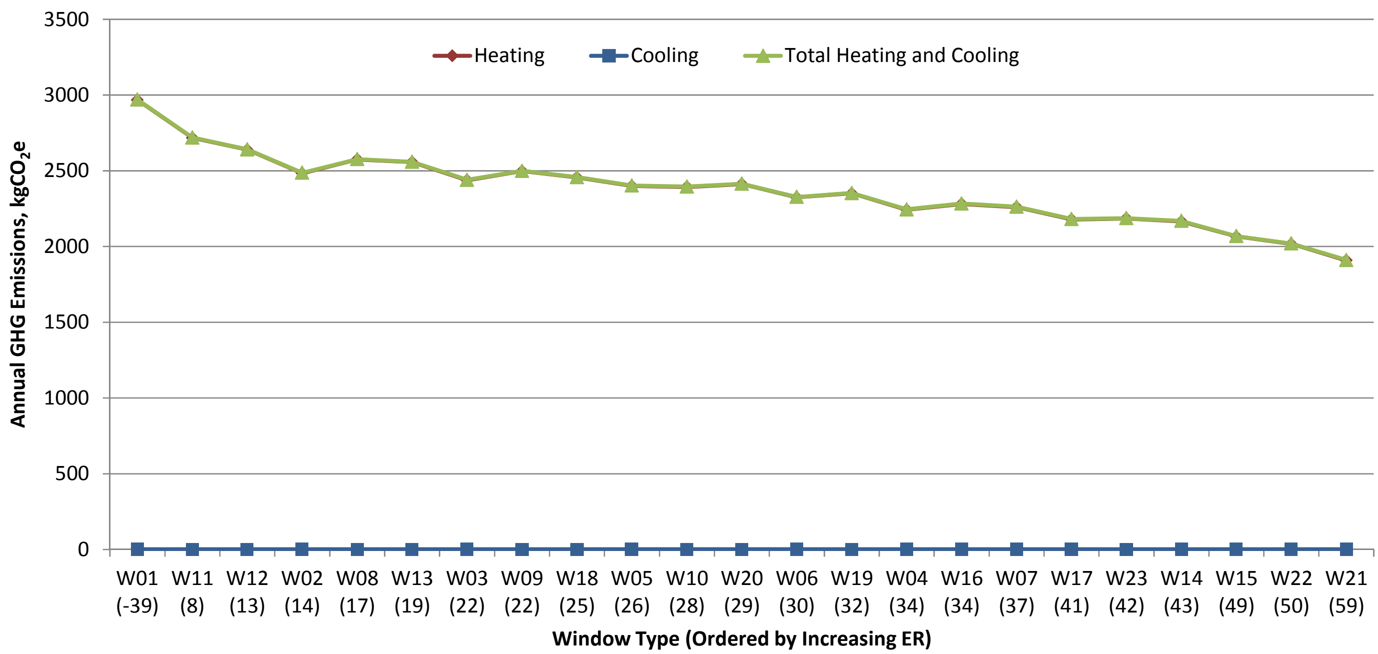


Fig.8.5 Annual GHG emissions for Montreal, gas-heated, $kgCO_2e$.

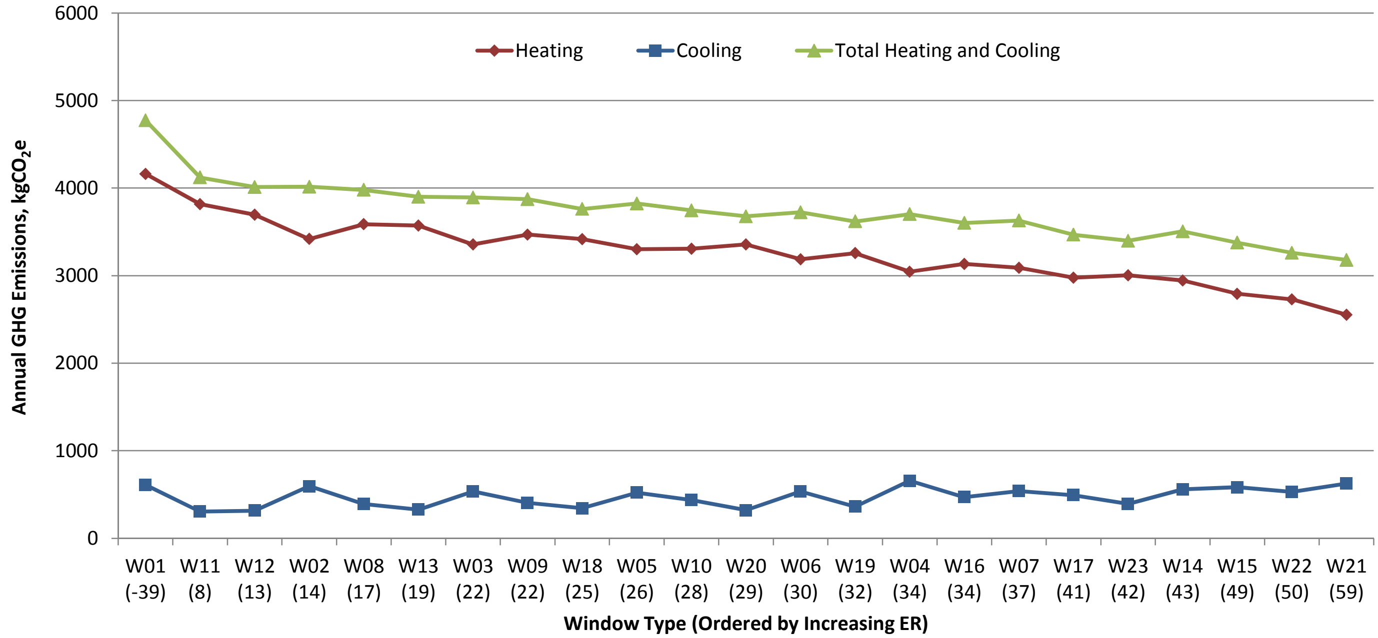


Fig.8.6 Annual GHG emissions for Halifax, heating oil, $kgCO_2e$.

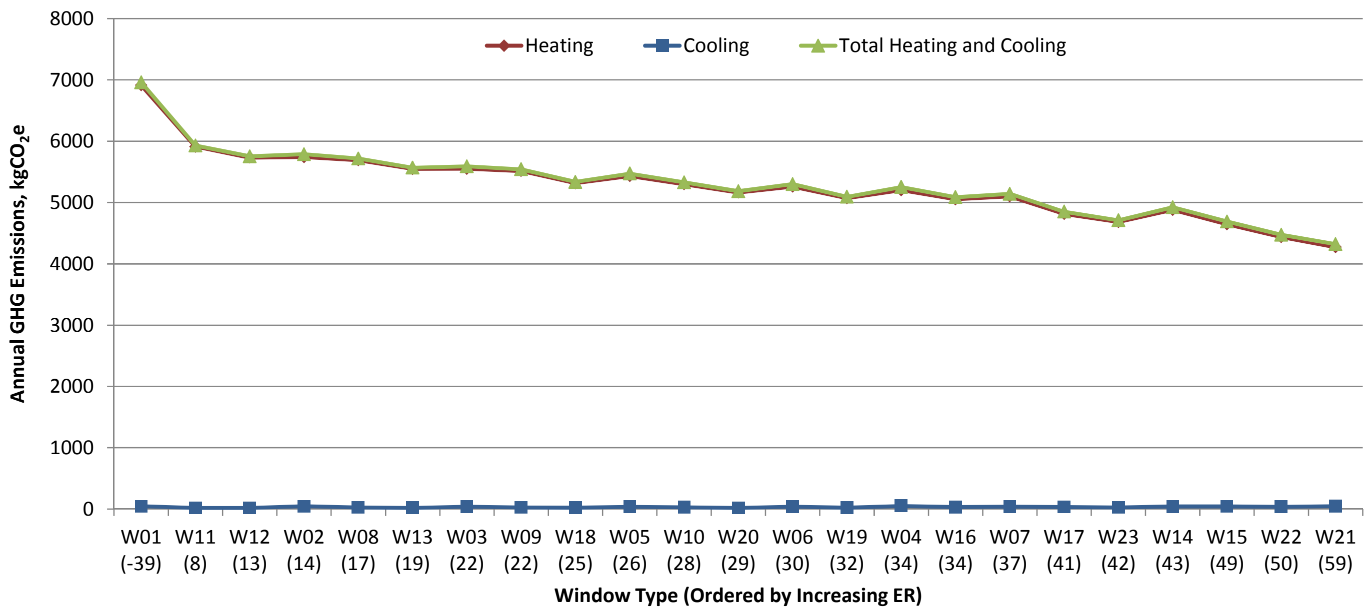


Fig.8.7 Annual GHG emissions for Yellowknife, gas-heated, $kgCO_2e$.

9. Thermal Comfort

9.1. Objectives

The thermal comfort portion of the Energy Rating (ER) for fenestration study was undertaken to evaluate if the energy efficient objectives of the ER system are consistent with thermal comfort objectives. Through annual energy simulations, several design parameters were studied to understand whether they related to thermal comfort and, by association, the ER. These included: natural ventilation, electric baseboard heating, thermal mass, building orientation, and a second storey.

Quantifying thermal comfort in order to allow comparison between the design parameters was a challenge as it is a subjective parameter that can vary based on a number of characteristics. ASHRAE 55[16], an internationally-recognized standard for determining thermal comfort parameters, recognizes six primary factors contributing to thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and air humidity. As some of these parameters are out of the range of mechanical system control, certain quantifiable conditions were chosen to represent a general level of thermal comfort, based on standard mechanical design practice.

Energy simulations for each of the design parameters were performed, and the resulting indoor thermal conditions were analyzed by extracting hourly operative temperature and window surface temperature data for each window type, with the windows ordered from lowest to highest ER. If the ER objectives are aligned with those of thermal comfort performance, then a higher ER should represent a lower number of thermal discomfort hours. By plotting multiple cases on one chart, it can be seen whether the trends for each window ER are the same across different variables.

9.2. Definitions

Several terminologies used in this report are described in further detail below, some of which are industry standard and others that were adopted directly for this study.

Standard Terms

Air (Dry-Bulb) Temperature	The average air temperature within a space.
Radiant Temperature	There are three primary types of heat transfer: conduction, convection and radiation. The magnitude of radiant heat transfer depends on the emissivity of the object radiating and the object absorbing the radiation; a common example is the sensation that a person (absorber) experiences when moving from a shady spot into the direct sunlight (radiator). The radiant temperature that a person feels within a room depends on the temperature of the surrounding surfaces, including: walls, windows, ceiling, floor and internal objects, as well as any heat sources (e.g. lights) or sinks (e.g. cold windows). For the purposes of this study, the DesignBuilder software records the mean radiant temperature as "the average Mean Radiant Temperature (MRT) of the zone, calculated assuming that the person is in the centre of the zone, with no weighting for any particular surface."
Operative Temperature	The DesignBuilder software records the operative temperature as the mean of the internal air and radiant temperatures.

[16] **"**ASHRAE Standard 55-2010 Thermal Environmental Conditions for Human Occupancy**"**, *American Society of Heating Refrigeration and Air-Conditioning Engineers*, 2010

Thermal comfort	*ASHRAE Standard 55-2010 Thermal Environmental Conditions for Human Occupancy*, the industry standard for determining human comfort conditions, describes thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation." Thermal comfort is a subjective parameter that varies between individuals and varies for an individual over time.
Human comfort perception	People perceive temperature with relation to the three types of heat transfer previously described: conduction, convection and radiation. Conduction is primarily influenced by the air temperature surrounding to a person, convection by the air speed across a person, and radiation by the adjacency of thermal radiators or absorbers. Radiation is generally accepted to be the dominant factor that humans feel, influencing about 40-50% of a person's overall perception.
Radiant symmetry and asymmetry	Since radiant heat transfer is the predominant effect felt by humans, the temperature of surrounding objects (and their ability to radiate or absorb heat) can be an important factor in determining a person's level of thermal comfort. A person will be most comfortable when radiant symmetry is achieved, that is, when surrounding objects are within a certain range of the person's comfortable temperature so that significant heat transfer (gains or losses) are not occurring. The range varies on a number of parameters, such as the size and location of surrounding objects, their proximity to the person, and the rate of emittance or absorption of each object. Radiant symmetry is not an output captured in the DesignBuilder software, therefore, in order to account for it the surface temperatures of the windows are recorded since they will vary the most based on outdoor conditions. Radiant asymmetry is a commonly used industry term referring to lack of radiant symmetry, and is considered a parameter that causes thermal discomfort.

Study-Specific Terms

Window surface temperature	For the purposes of this study, the window surface temperature was recorded as the average temperature of the internal surface of the window across its entire area.
Thermal comfort zone	For the purposes of this study, a thermal comfort zone has been defined for operative temperatures and window surface temperatures, described in Table 9.3.5. Any temperature outside of this zone is considered to cause thermal discomfort.
Cool hours	For the purposes of this study, any temperature (operative or window surface) that is lower than the minimum limit of the thermal comfort zone is considered "cool." This terminology was chosen rather than a term such as "under-heated" because thermal comfort is subjective so not all occupants would be dissatisfied with this temperature, and to avoid any implication that the mechanical system was under-performing, since it would in fact be working as designed.
Warm hours	For the purposes of this study, any temperature (operative or window surface) that is higher than the maximum limit of the thermal comfort zone is considered "warm." This terminology was chosen rather than a term such as "over-heated" because thermal comfort is subjective so not all occupants would be dissatisfied with this temperature, and to avoid any implication that the mechanical system was under-performing, since it would in fact be working as designed.

9.3. Methodology

The research presented in this report was completed using the following methodology.

- Parameters to analyze through energy simulation were identified in Sections 4, 5 and 6 of the study, and analyzed in Section 7 of the study. These variables were re-visited for the thermal comfort analysis, and several were selected for analysis because they were considered to have potential impact on comfort. These variables are listed in Section 9.3.2.
- The number of window types run was reduced to five, which represented the range of low to high performance encompassed by the original 23 representative windows.
- The energy analysis software, DesignBuilder, was selected to perform the analysis for this work as it was also used for the previous energy analysis. The software is a front-end for the EnergyPlus software, which is provided by the US Department of Energy and is a recognized tool for annual building energy analysis.
- For consistency with previous sections, the energy model files were copied and updated to include separate rooms on the main level, and the upper level in the two-storey scenarios. These interior partitions would have impact on thermal comfort, due to effects such as radiant symmetry, which were not applicable in the previous analyses. Further descriptions of the floor plans for the archetypes are provided in Section 9.3.1.
- The single-storey archetype simulation was run for the five window types. The results are shown in graphic and tabular format, and initial observations regarding the use of the ER to rank thermal comfort are noted for one specific location (Vancouver). The results from this analysis are shown in Section 9.4.1.
- The same archetype was then run for all locations, which are compared in Section 9.4.2.
- All iterations representing the variable parameters were then simulated, and are presented in comparison with one another in Section 9.4.3, and individually in Section 9.5.
- Summary and conclusions from the thermal comfort findings are presented in Section 9.6.

9.3.1 Archetypical Houses

The basis for the room sizes and locations in the single and two-storey houses were two archetypical Canadian house floor plans, determined from another project. The attic and basement were maintained as per the previous work, with no windows to the basement.

The modeling inputs remained the same as Section 7, as described below:

- Mechanical System
    - Heating (natural gas furnace): Same as Section 7
    - Heating (electric baseboard): Same system as Section 7, however, a baseboard heater was added to every space, sized to meet the peak heating load for that room
    - Cooling: Same as Section 7
- Lighting (load, schedule): Same as Section 7, assumed constant across all rooms
- Occupancy (load, schedule): Same as Section 7, assumed constant across all rooms
- Equipment (load, schedule): Same as Section 7, assumed constant across all rooms
- Window to wall Ratio: Same as Section 7 (15% on all sides)

Single-Storey

The single-storey house used in Section 7 was used for the thermal comfort simulations, with all of the same input parameters except that the main floor was divided into four separate zones: the kitchen, living room, bathroom and bedroom. All rooms were separated by a closed door, with the exception of the kitchen and living room that were open to one another.

Fig. 9.3.1 shows the main floor plan with the room breakdowns. Fig. 9.3.2 displays an isometric floor plan, on which the study windows are highlighted; these are explained more in Section 9.3.3, but briefly, represent one window on each façade for which surface temperature data was extracted after each simulation. The north arrow is also included in each image, and is consistent for all simulations except D5, when the impact of rotating the building is examined.

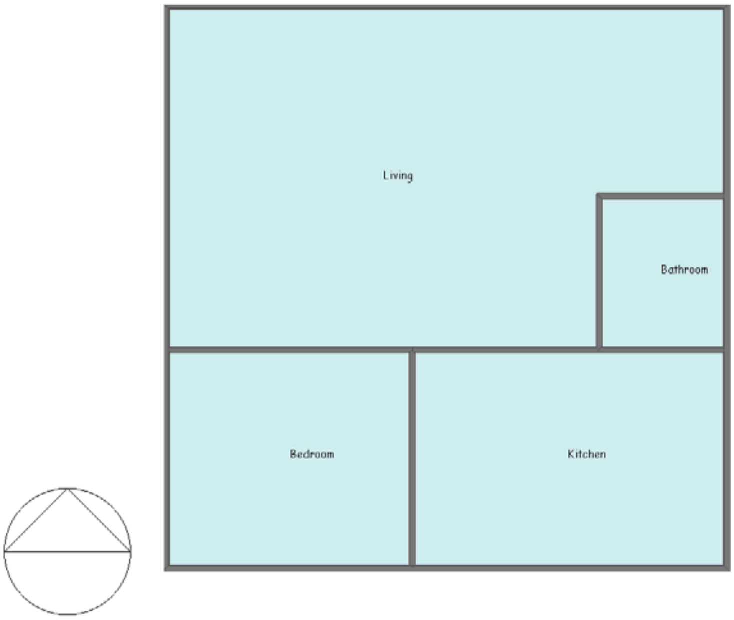


Fig. 9.3.1 Main floor plan view

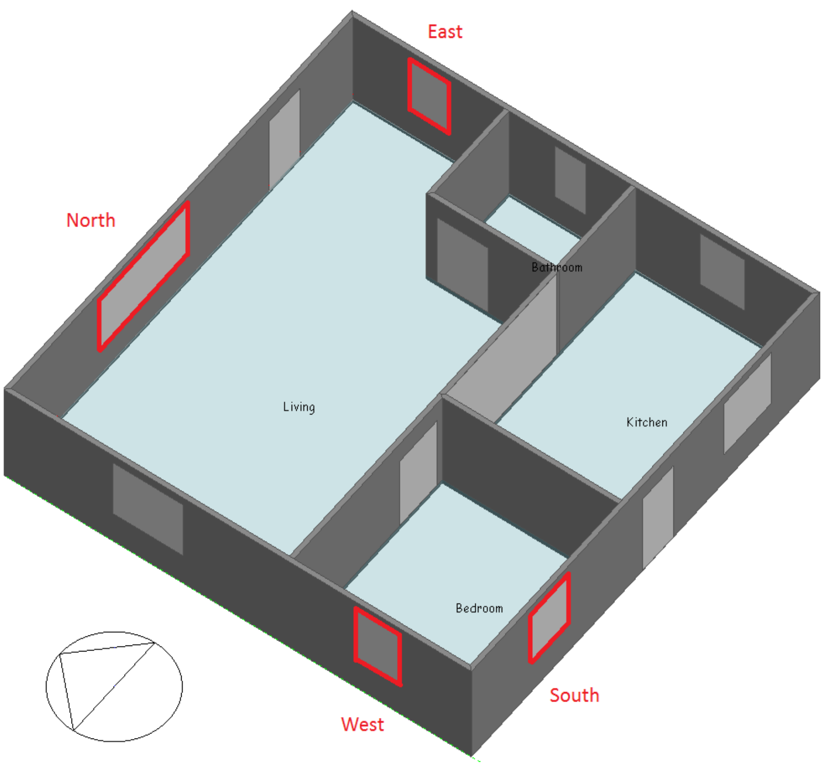


Fig. 9.3.2 Windows used for Surface Temperature Analysis

Two-Storey

Similar to the single-storey house, the two-storey house was also copied from Section 7 and was updated by sub-dividing the main and upper levels into a total of 12 rooms, as follows:

- Main floor was divided into: kitchen, living/dining, den, bathroom, hallway
- Upper floor was divided into: 3 bedrooms, 2 bathrooms, hallway

As in the single-storey house, the rooms are all separated by closed doors, except for two openings connecting the lower hallway with the den and the living/dining room. In addition, the upper and lower hallways are connected by an opening, to simulate the stairwell. This opening is visible on the upper level floor plan. Fig. 9.3.3, and Fig. 9.3.4 show the floor plans, and targeted windows for the thermal comfort simulations.

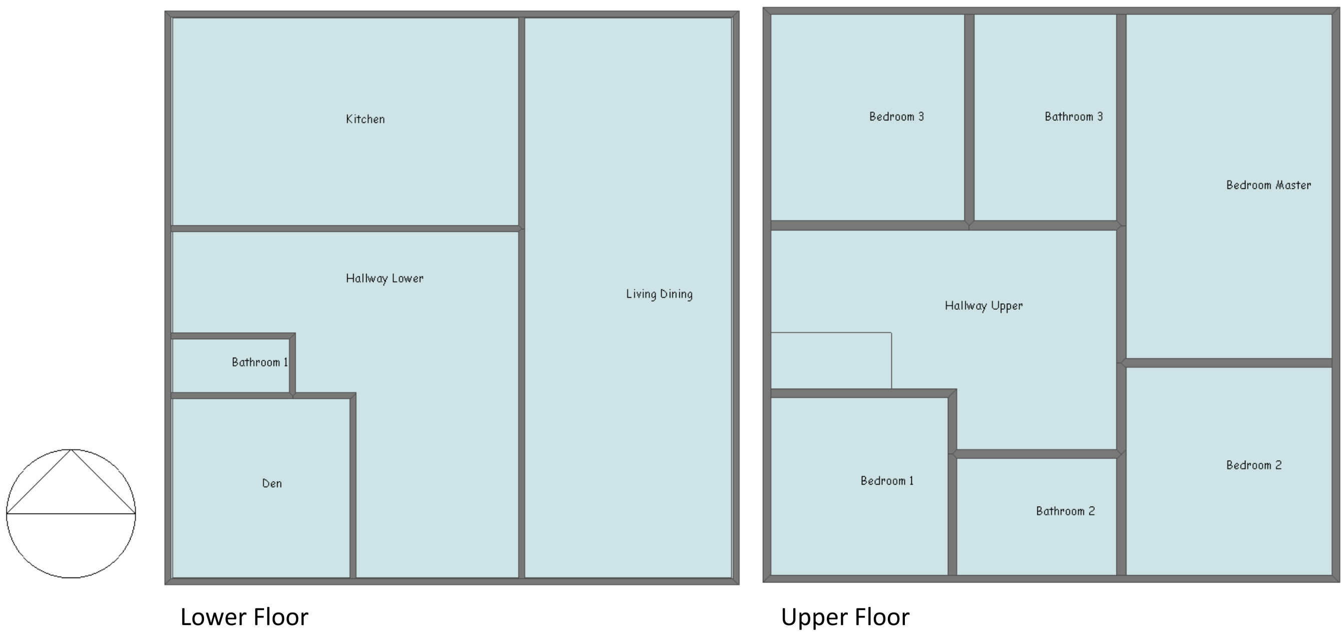
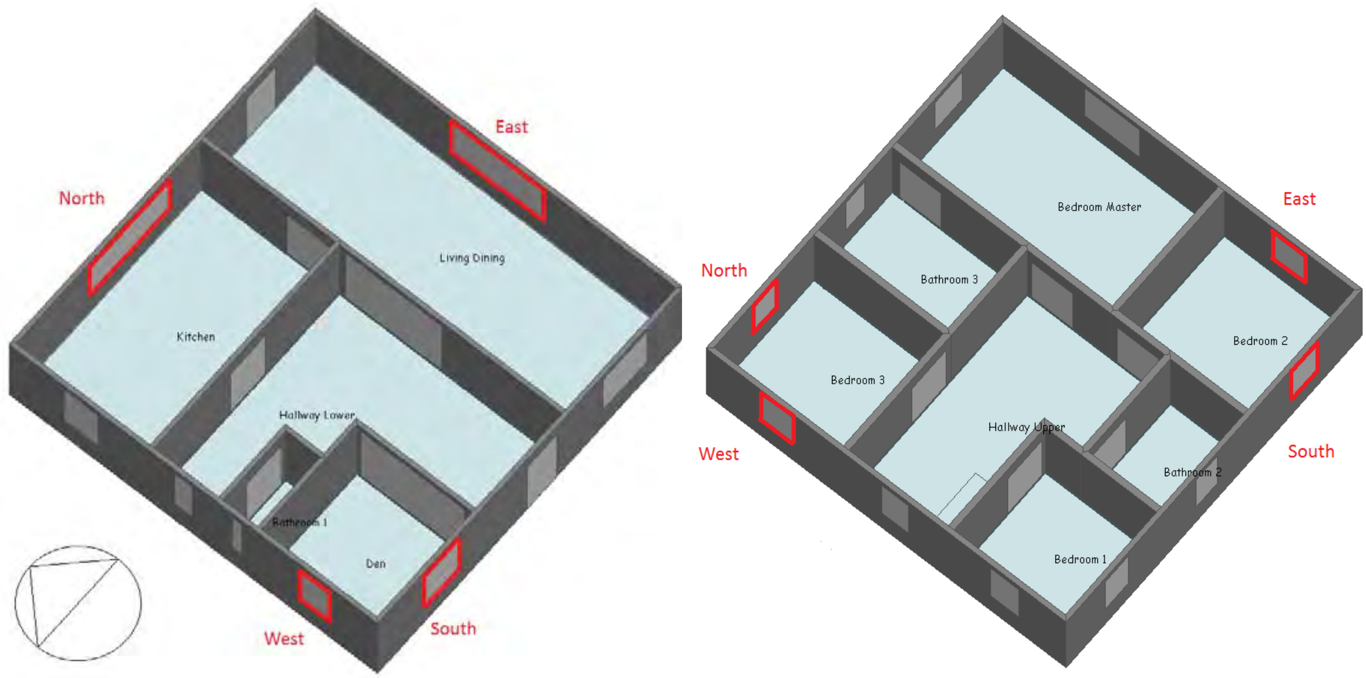


Fig. 9.3.3 Main floor plan view



Lower Floor Upper Floor

Fig. 9.3.4 Lower & Upper Floor Windows used for Surface Temperature Analysis

9.3.2 Energy Models

The energy modeling process used was similar to that of Section 7; however, different data were extracted from the results of each simulation in order to quantify the level of thermal comfort. These are discussed in further detail in Section 9.3.3.

Sections 4 through 6 established the parameters for the energy simulations. The non-window related variables that were included are shown for reference in Table 9.3.1.

Table 9.3.1 Archetype house variables simulated

Variable	Parameters
Size of house	Single-storey, two-storey
Mechanical System	Gas furnace (central thermostat control), electric baseboards (zoned thermostat control), central air conditioning
Natural Ventilation	With natural ventilation to offset cooling energy
Thermal Mass	Normal (wood framing) and high thermal mass (exposed to interior)
Orientation	Rotating the building through the cardinal axes (0°, 90°, 180° and 270° of rotation)

The window parameters chosen for thermal comfort analysis were selected to represent a wide range of products with different frame and glazing configurations. Table 9.3.2 describes the windows selected for energy simulation with the number and type of each window found in the ENERGY STAR® database. This list was compiled to further examine the relationship between window parameters (U-value and SHGC) and operator type. As previously discussed, in order to reduce simulation time, fewer windows were analysed in this portion of the study than in the Section 7 energy simulations.

Table 9.3.2 Window types simulated

Window	Representative Window	U-value, W/m^2-K ($Btu/h\text{-}ft^2$-F)	SHGC	ER	ENERGY STAR® Zones, U-Value Path	ENERGY STAR® Zones, ER Path
W2	Double glazed, clear, air fill, wood or vinyl frame (existing house in cold climate)	2.83 (0.50)	0.64	14	None	None
W5	Double glazed, high U, high SHGC	2.00 (0.35)	0.50	26	None	AB
W11	Double glazed, high U, low SHGC	2.00 (0.35)	0.20	8	None	None
W15	Triple glazed, low U, high SHGC	0.9 (0.16)	0.50	49	ABCD	ABCD
W19	Triple glazed, low U, low SHGC	0.9 (0.16)	0.20	32	ABCD	ABC

Table 9.3.3 summarizes the iterations that were simulated for the thermal comfort analysis into seven main groups: D1 to D5 and E1 to E2. A description of the variables that were simulated within each group is also included.

Table 9.3.3 Thermal comfort energy model iterations

Iteration	Description	Iteration	Description
D1	Storeys = 1 Heating = Natural Gas Cooling = Mechanical Construction = Wood-frame Cities = Vancouver, Kelowna, Toronto, Montreal, Halifax, Prince Rupert, St John's, Quebec, Edmonton, Timmins, Winnipeg, Yellowknife Overhangs = 0.5 m roof overhang	E1	Same as D1, except: Storeys = 2 Cities = Vancouver, Toronto, Montreal, Winnipeg, Yellowknife Overhangs = 0.5 m roof overhang (no overhang above first floor windows)
D2	Same as D1, except: Cooling = Natural Ventilation Cities = Vancouver, Toronto, Montreal, Winnipeg, Yellowknife	E2	Same as D2, except: Storeys = 2 No overhang above 1st floor windows
D3	Same as D1, except: Heating = Electric Baseboard Cities = Vancouver, Toronto, Montreal, Winnipeg, Yellowknife	-	-
D4	Same as D1, except: Construction = Thermal Mass Cities = Vancouver, Toronto, Montreal, Winnipeg, Yellowknife	-	-
D5	Same as D1, except: Rotated 90, 180 and 270 degrees from north Cities = Vancouver, Toronto, Montreal, Winnipeg, Yellowknife	-	-

9.3.3 Results Analysis

As previously discussed, ASHRAE Standard 55 outlines six factors that impact occupant thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and air humidity. Metabolic rate and the level of clothing insulation can't be controlled by the building/mechanical system design, and are therefore not areas of focus for this study; the contribution of the other four parameters to human comfort perception is listed in Fig. 9.3.4. Standard ASHRAE metabolic rates and clothing levels for residential occupancy were used in the simulations.

Table 9.3.4 Human comfort perception

Factor	Contribution to Thermal Comfort
Air Temperature	6 %
Mean Radiant Temperature	50 %
Air Speed	26 %
Air Humidity	18 %

Air speed and humidity are important factors for determining thermal comfort. However, they are not related to windows and are therefore not a focus of this study. Air temperature, though the smallest contributor, is affected by windows and is included in the thermal comfort analyses. Mean radiant temperature, summarizing the impact of surface temperatures, has the most significant contribution. Surface temperature will also impact whether an occupant experiences radiant symmetry or not.

Aligning these parameters with the available DesignBuilder outputs, two parameters were used for quantifying thermal comfort: operative temperature, which combines mean radiant temperature and air temperature, and window surface temperature, used to evaluate radiant symmetry. Both temperatures, along with the dry-bulb temperature, were recorded for each room within the model on an hourly basis over the course of the year (8760 hours).

For each parameter, a "comfortable" temperature range was determined, based on the ASHRAE 55 and standard design, which typically heats rooms to 21°C in the winter and cools to 24°C in the summer. These limits are summarized below in Table 9.3.5.

Table 9.3.5 Minimum and maximum temperature limits for thermal comfort

	Minimum Temperature for Comfort	Maximum Temperature for Comfort
Operative Temperature	19°C	25°C
Window Surface Temperature	15°C	30°C

The operative temperature "comfort" range was based on the acceptable operative temperature range outlined in ASHRAE 55-2010, displayed on the psychrometric chart in Fig. 9.3.5. A few notes on interpreting the chart:

- The x-axis represents a scale of operative temperatures.
- The two comfort zones, denoted "1.0 clo" and "0.5 clo" loosely represent "winter" and "summer" clothing values, respectively. Since Canada is a heating-dominant climate, the comfort temperatures used in the analysis align more with the winter than the summer operative temperatures.

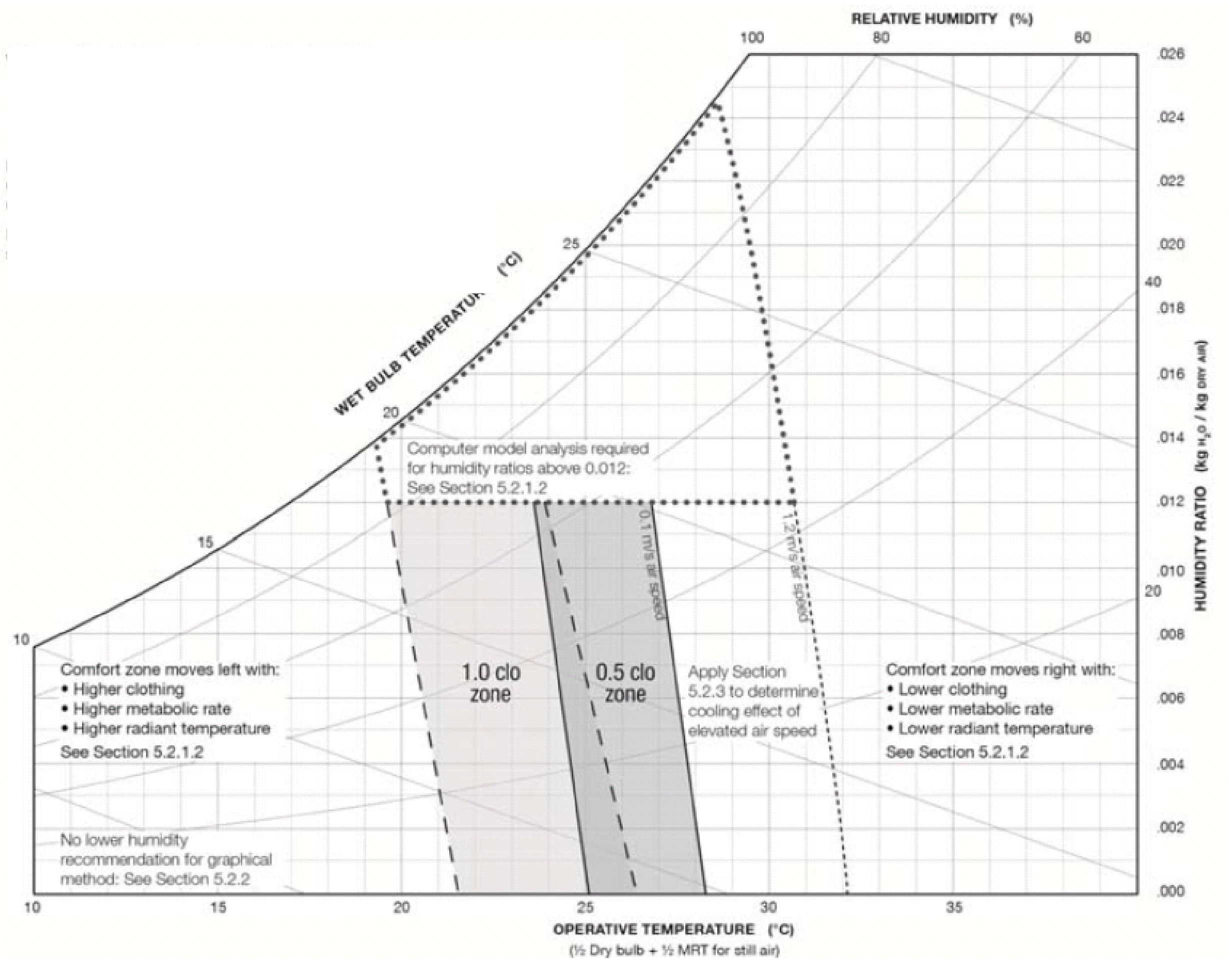


Fig. 9.3.5 ASHRAE Standard 55-2010 (Fig 5.2.1.1), thermal comfort limits.

The window surface temperature limits were based on ASHRAE 55-2010 comfort parameters defined for radiant symmetry. Fig. 9.3.6 and Table 9.3.6 outline temperatures for various surfaces and the subsequent number of people who would be dissatisfied with those conditions; window would be akin to a cool or warm wall. For this study, an average room temperature of 22.5°C was assumed, based on the mid-point of the previously discussed mechanical setpoints of 21°C and 24°C. Therefore, in order to minimize discomfort due to asymmetry, the window temperatures should remain within approximately ±7.5°C (this is the point where the curves intersect the x-axis) of 22.5°C, which equates to the limits of 15°C and 30°C.

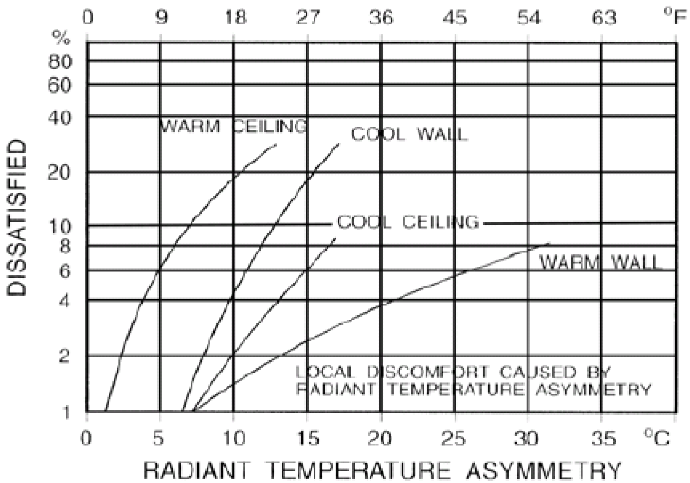


Fig. 9.3.6 ASHRAE Standard 55-2010 (Fig 5.2.4.1), Allowable radiant asymmetry

TABLE 5.2.4.1
Allowable Radiant Temperature Asymmetry

Radiant Temperature Asymmetry °C (°F)			
Warm Ceiling	Cool Wall	Cool Ceiling	Warm Wall
<5 (9.0)	<10 (18.0)	<14 (25.2)	<23 (41.4)

Table 9.3.6 ASHRAE Standard 55-2010 (Table 5.2.4.1), Allowable radiant asymmetry

For both operative and window surface temperature analysis, the time for which the space would be considered cool (below minimum temperature) or warm (above maximum temperature) was recorded for each room. The data is presented as a total number of discomfort hours for the entire house; for the single-storey house, this is summed over four rooms, so represents a total of 4 x 8760 = 35,040 hours. As the two-storey house has 12 rooms, the total comes to 105,120 hours. In a side-by-side comparison this would skew the results. Therefore, when results from different archetypes are compared, they are divided by the number of rooms to generate a comparable value: average number of discomfort hours per room.

In each simulation the air temperature was also extracted and reviewed, to ensure that the results were staying within the mechanical setpoint temperatures of: above 21°C at all times and less than 24°C in the summer time (for all models except D2 and E2 that did not contain mechanical cooling). These design temperatures are summarized in Table 9.3.7 along with the months to which they apply. In some cases, “cool” temperature conditions occurred during months that predominantly require cooling (late spring, summer and early fall), or “warm” temperature conditions occurred during predominantly heating months (late fall, winter and early spring), defined in Table 9.3.7 below. As these conditions can improve thermal comfort, in some of the analyses these hours have been isolated so that they don’t contribute to the tally of hours outside the comfort range.

Table 9.3.7 Predominantly heating/cooling months

	Months	**Heating Setpoint**	**Cooling Setpoint**
Heating Months	October to March	21°C	none
Cooling Months	April to September	21°C	24°C (none in D2 or E2- Natural Ventilation)

Another factor that can impact thermal comfort level is time of day; for example, an east-facing window that has heated up in the morning may cause less discomfort than a west-facing window at the same surface temperature in the afternoon when the outside air temperature is higher. In addition, direct solar gains on a person can cause significant levels of discomfort. However, due to the complexity of the analysis associated with these factors, which vary through every hour of the year based on the intensity and angle of the sun, they were not considered in the analysis.

9.4. Findings

This section presents the results of the analysis described in Section 9.3. Throughout the section, five windows types are regularly referenced. For ease of interpretation, the parameters of these windows have been summarized in a table on the bottom left of each page within this section.

9.4.1 Baseline Comfort Results (D1)

This section reviews the results for a single location (Vancouver), with occasional references to a colder climate (Yellowknife) to develop an in-depth understanding of the method used to determine thermal comfort, and show its consistency across the mildest and coldest climates. Therefore, no reference is made to trends with respect to the ER, since multiple situations are not examined.

The single-storey archetype house described under iteration D1 in Table 9.3.3 was simulated with five of the 23 windows established in Section 6. Simulations were performed for this archetype for the 13 cities identified in Section 5. It should be noted that the same archetype was simulated for Yellowknife even though houses in the far north typically do not have basements. This was done so that Yellowknife energy consumption results could be compared to the other cities.

The results presented here are from iteration D1, representing an existing wood-framed single-storey house, with double-glazed windows (type W2), a natural gas furnace and air conditioning in the summer, located in Vancouver. Similar results for other iterations are included in Appendix D.

In Fig. 9.4.1, the outdoor air temperature for Vancouver can be seen to vary from approximately -8°C to 26°C over the 8760 hours of the year, extracted from the appropriate Canadian Weather for Energy Calculations (CWEC) file that was used for each location. The dry-bulb air temperatures for each room remain above the 21°C heating setpoint throughout the year; in the summer season, when the cooling system is activated, the air temperature also remains below the setpoint temperature of 24°C. In the winter time the air temperature is allowed to exceed the 24°C setpoint (by turning off the mechanical cooling), since this would not adversely affect energy or thermal comfort. These results are as expected, since the mechanical system is designed to condition the room to dry-bulb temperatures.

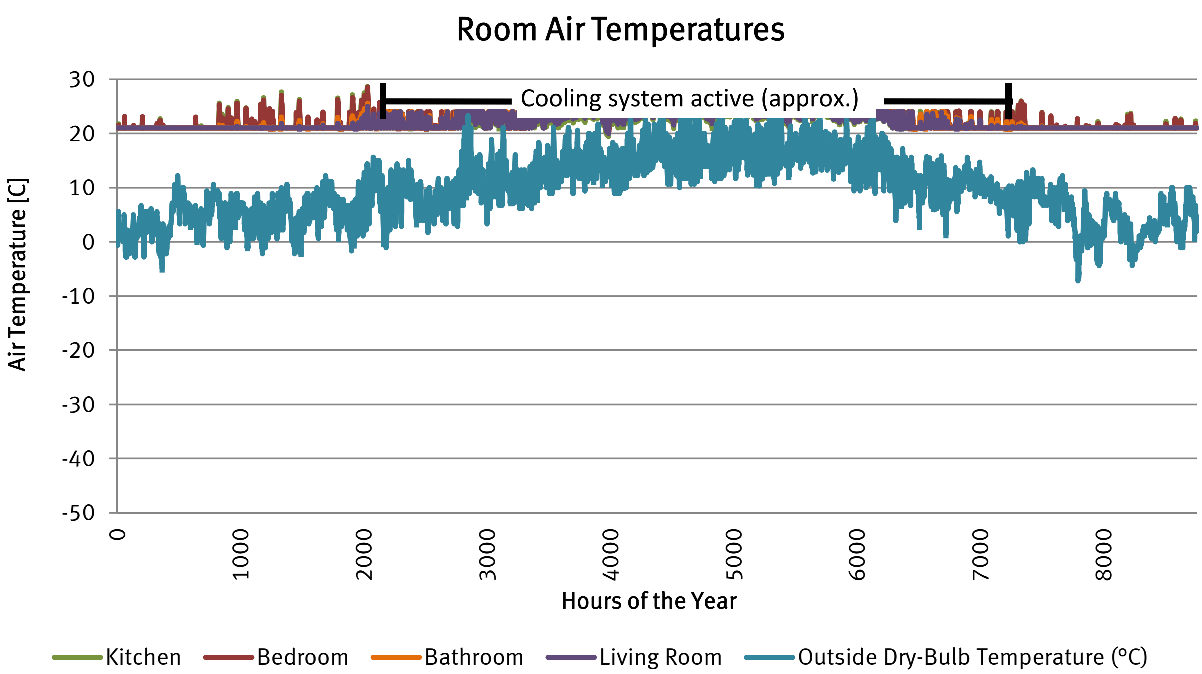


Fig. 9.4.1 D1 Vancouver, Room air temperatures

Similarly in Yellowknife, although the outdoor air temperature varies over a significantly wider range than in Vancouver, the room air temperatures remain within the same setpoints, as shown in Fig. 9.4.2. This is expected because the dry-bulb temperature should be governed by the mechanical system inputs, which remain constant between the two simulations.

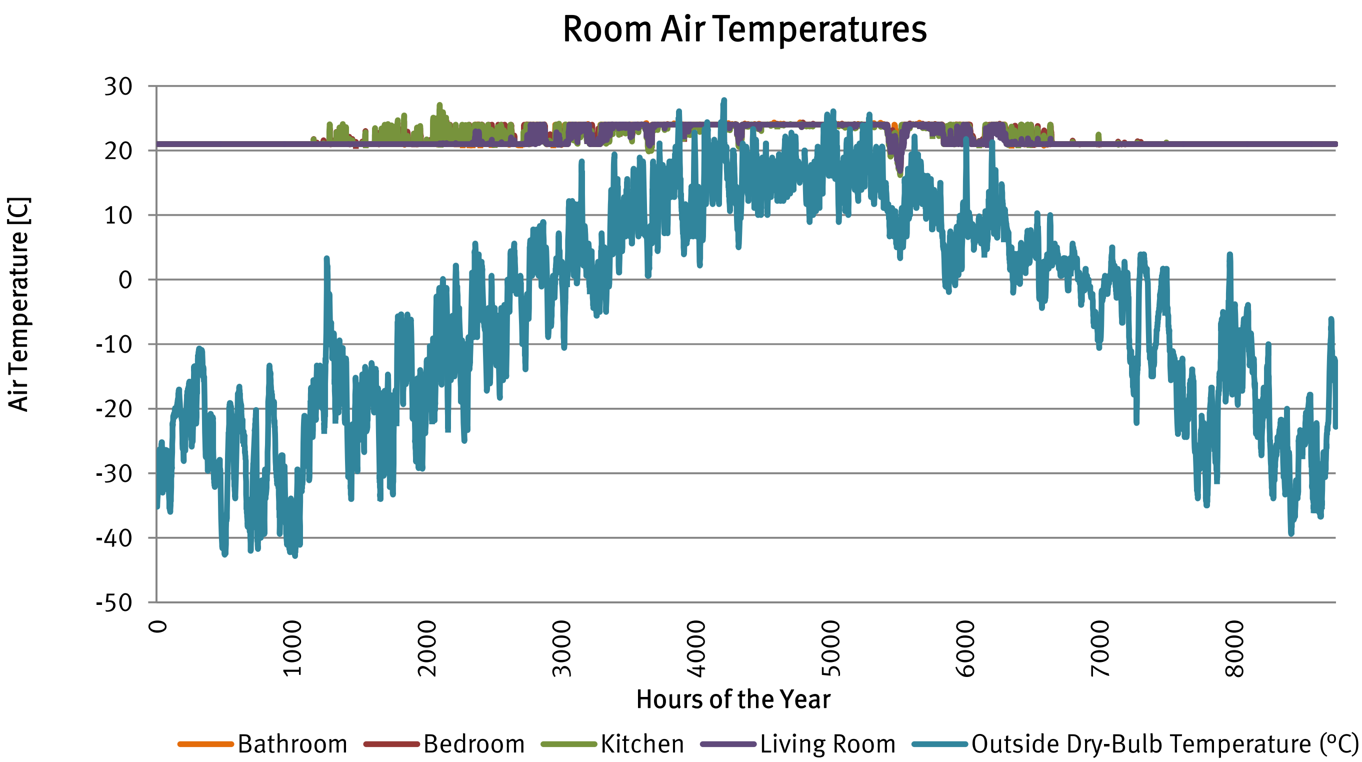


Fig. 9.4.2 D1 Yellowknife, Room air temperatures

The hourly room operative temperatures over the course of the year for the same simulation are shown in Fig. 9.4.3. The temperatures vary within a larger range than the air temperatures, from below 20°C throughout the year to above 25°C in the summer months. This is expected because the operative temperature reflects the radiant temperatures of objects within the space as well as dry-bulb temperatures. Since the mechanical system only considers conditions based on dry-bulb temperatures, the radiant temperatures will fluctuate more with the outdoor conditions, thereby causing the operative temperature to vary accordingly. Again, the outdoor dry-bulb temperature is included for information.

In Vancouver, the minimum operative temperature of 19.3°C occurs in the kitchen, as does the maximum of 28.8°C.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

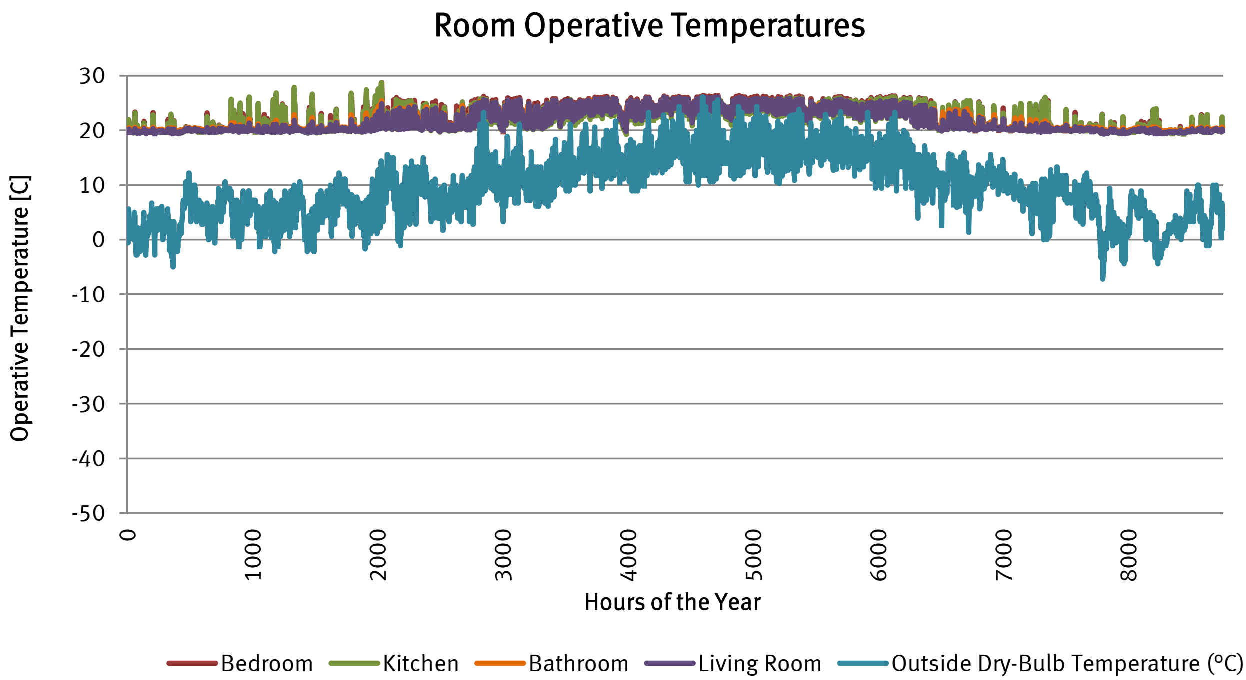


Fig. 9.4.3 D1 Vancouver, Room operative temperatures

The operative temperature range for Yellowknife also increases when compared to Vancouver, as the minimum temperature in Fig. 9.4.4 is 16.0°C, while the maximum is 27.1°C, both of which again occur in the kitchen.

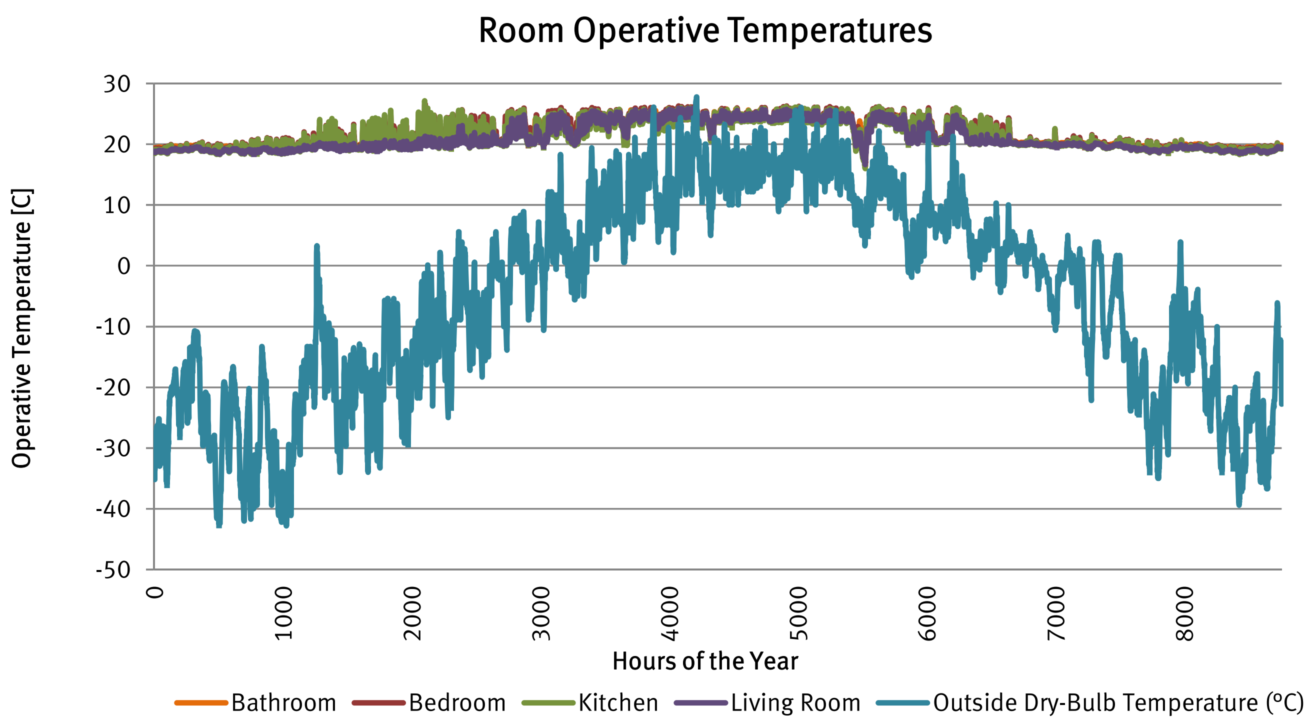


Fig. 9.4.4 D1 Yellowknife, Room operative temperatures

As previously discussed, in order to evaluate radiant symmetry the surface temperatures of the four windows (one on each façade) identified in Section 9.3.1 are examined. The windows will typically vary most drastically in temperature over the course

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

of the year, when compared to other elements within the building enclosure, as they lose the most heat in the winter and admit the most solar gains in the summer. They therefore have the most potential to impact comfort by achieving radiant symmetry.

The four cardinal windows' internal surface temperatures are plotted for each hour of the year on Fig. 9.4.5. These temperatures vary over a greater range than both air and operative temperatures, from below 10°C to nearly 35°C for this particular simulation. These surface temperatures would have significant impact on the thermal comfort of individuals within the space, by affecting their radiant symmetry.

Unlike the air temperature results, window surface temperatures are not noticeably impacted by air conditioning in the summer time, as there is no perceptible drop in temperature for any of the rooms (between the ~2000 and ~7000 hour time periods).

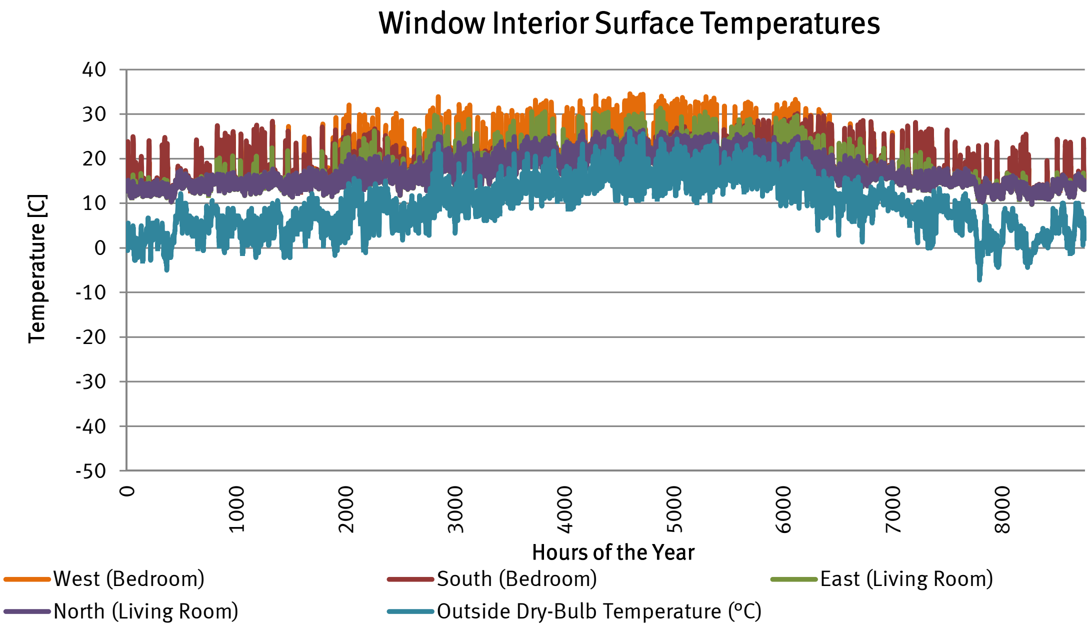
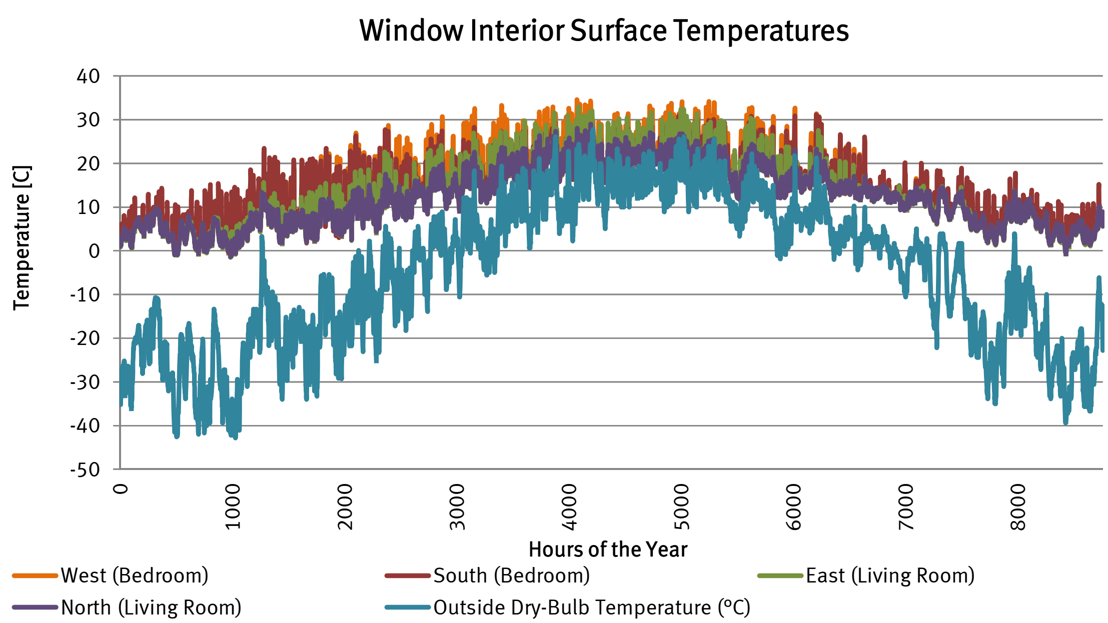


Fig. 9.4.5 D1 Vancouver, Window surface temperatures



	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Fig. 9.4.6 D1 Yellowknife, Window surface temperatures

This data can also be sorted into bins on a histogram, as shown in Fig. 9.4.7. For the majority of the year, the operative temperature is between either 19-21°C (approximately 45% of the year) or 23-25°C (approximately 25% of the year). This is a seasonal effect, with winter months falling into the colder range and summer months into the higher range.

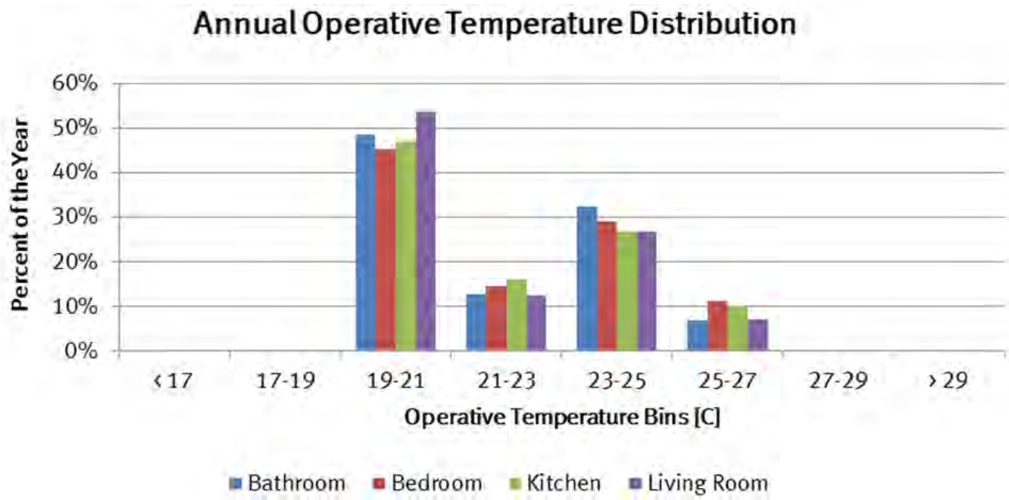


Fig. 9.4.7 D1 Vancouver, Operative temperature distribution

There is some disparity between the rooms, which is primarily due to their location within the house and the direction that they face, outlined in Table 9.4.1. The living room, for example, is north-facing and experiences the least amount of solar gain over the course of the year. It therefore has the highest number of hours between 19-21°C and the fewest between 25-27°C. Conversely, the bedroom on the south-west wall, experiences the most heat gains, particularly in the latter half of the day when outdoor air temperatures are higher, and has the opposite trend to the living room.

Table 9.4.1 Single-storey, Directions faced by each room

Room	Direction (Primary noted with *)
Bathroom	East*
Bedroom	South, West
Kitchen	South*, East
Living Room	North*, East, West

The window surface temperatures can be examined in the same way, as shown in Fig. 9.4.8, further demonstrating the wider temperature range experienced by the window surfaces than operative temperatures. Because of this wider temperature range, the bins into which the data have been sorted are larger than the operative temperature analysis (5°C instead of 2°C). In addition, it corroborates the findings that rooms (and windows) with south and west exposures will experience the most solar gains and, therefore, the lowest number of cool hours and the highest number of warm hours.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

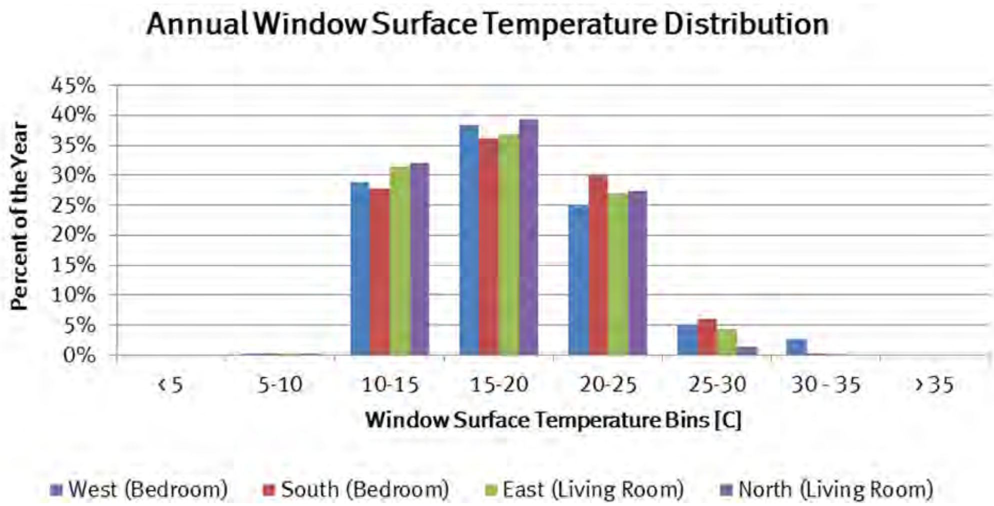


Fig. 9.4.8 D1 Vancouver, Window surface temperature distribution

Colder climates, such as Yellowknife, naturally experience colder temperatures, causing operative and window surface temperatures to occur in the lower temperature bins, as demonstrated in Fig. 9.4.9 and Fig. 9.4.10. As expected, in both cases, but particularly the window surface temperatures, far more hours fall into the lower temperature bins than the Vancouver simulations.

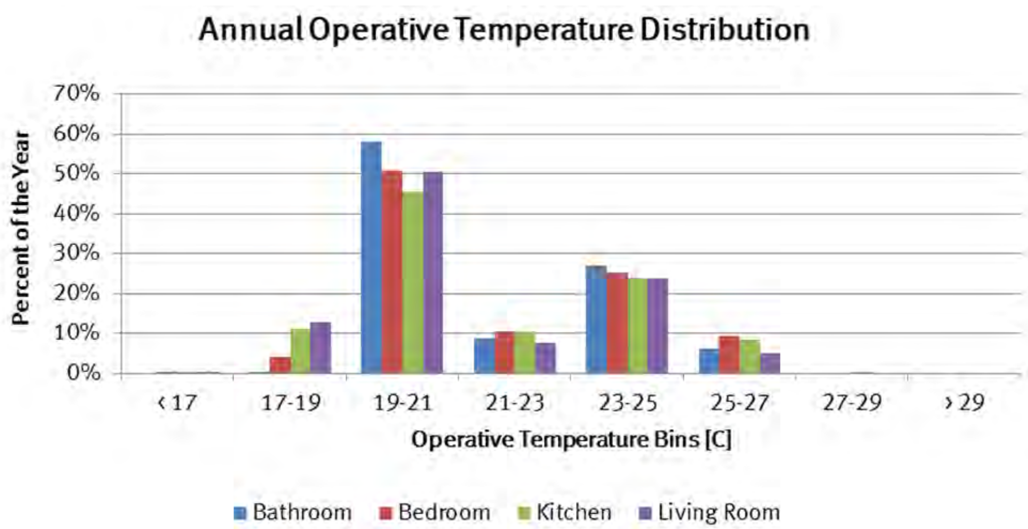


Fig. 9.4.9 D1 Yellowknife, Operative temperature distribution

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

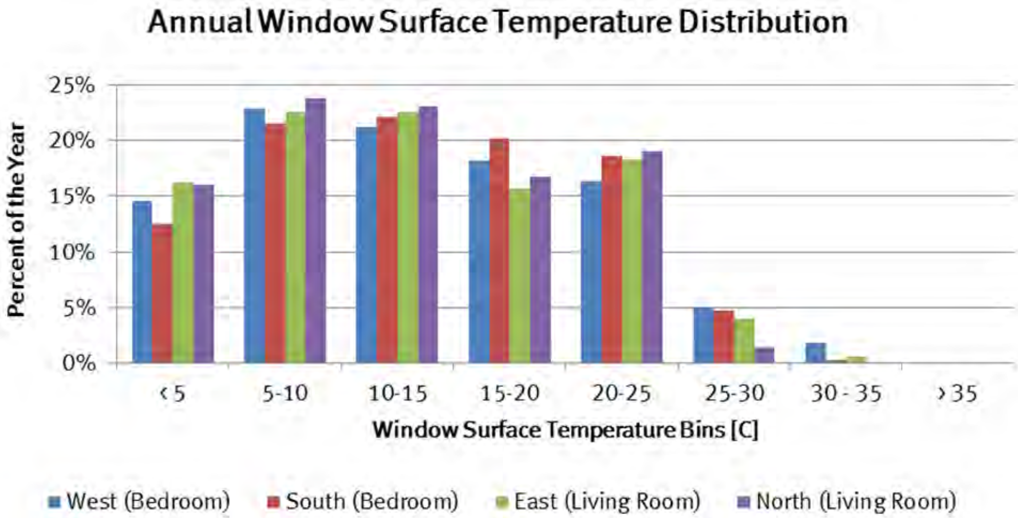


Fig. 9.4.10 D1 Yellowknife, Window surface temperature distribution

Room-by-Room

The results can also be reviewed for each individual room, to better understand how their individual parameters are affecting the thermal comfort within the space. The geometry is examined, particularly the size of the room and the relationship between the external surface areas (windows and walls) with respect to the room size (floor area).

Fig. 9.4.11 examines the number of hours per year that each room's operative temperature is below 19°C, divided by the area of the room. Five window iterations are included, ordered by lowest ER (W11) to highest ER (W15). The hours that occur in the winter (shown in blue) are separated from those that occur in the summer (shown in green), because the latter would likely not contribute to discomfort, as cool surfaces in the summer can improve rather than detract from thermal comfort. In addition, two geometric attributes are displayed for each room for comparison: the window to floor area ratio, and the exterior wall to floor area ratio. As the window to wall ratio remains constant at 15%, the two ratios follow the same trend when compared across rooms. The direction(s) faced by external wall(s) of each room are also listed on the chart.

For the D1 simulation, in Vancouver's mild climate, all of the rooms experience less than 10 hours per year of cool temperatures, all of which occur during the summer time. Due to the low number of hours, it is difficult to extrapolate significant trends from the data, and there does not appear to be any correlation between the exterior wall/window areas and the discomfort hours. The only window that causes any discomfort hours is type W11, which correlates somewhat to the energy rating system since this is the window with the lowest ER value; however, the cool hours only occur during the summer time so are less likely to contribute to thermal discomfort.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

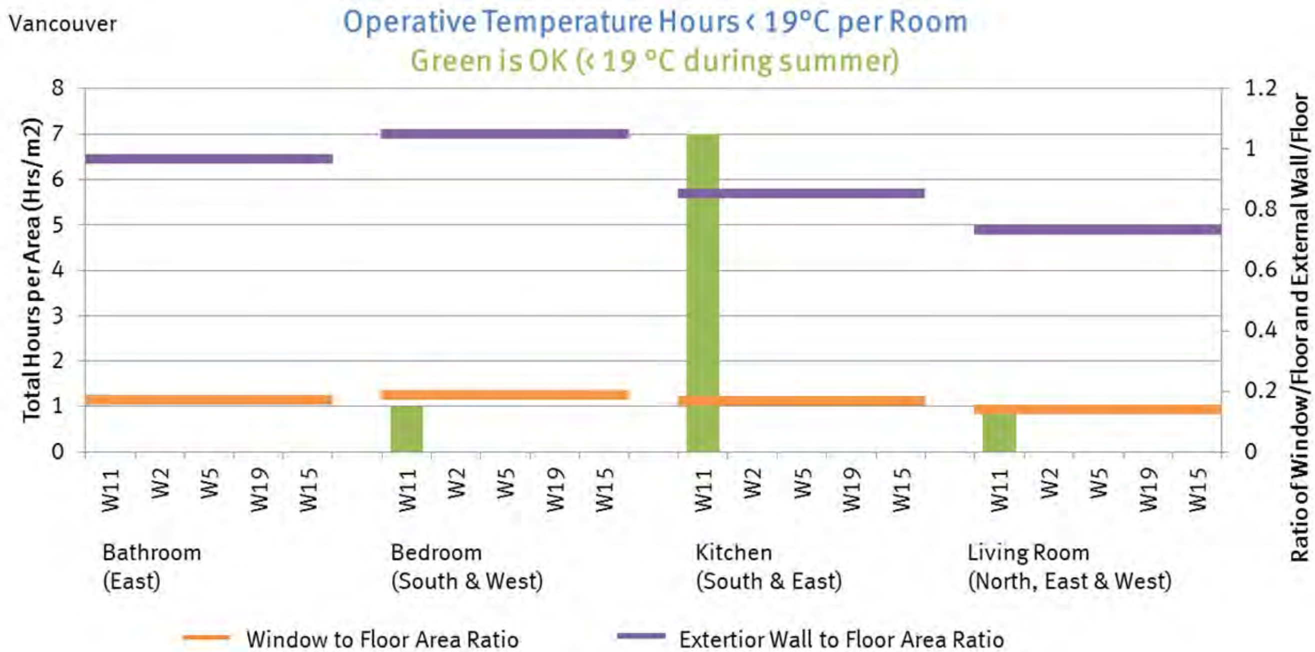


Fig. 9.4.11 D1 Vancouver, Individual room operative temperatures < 19°C

Similarly, the hours over the course of the year that each room's operative temperature is over 25°C, causing warm temperature conditions, are compared in Fig. 9.4.12. Warm hours occurring in the winter would be less likely to cause discomfort, so are shown in green. Again, the relationship between the room's window area, wall area and floor area are also displayed on the plot.

The number of hours that the operative temperature would be considered warm greatly exceeds the cool hours for Vancouver. The fact that the total operative temperature discomfort hours were predominantly warm hours was a common finding highlighted throughout the study and will be discussed in further detail in subsequent sections.

There is no obvious trend between the number of warm hours and the ratio between external wall/window area and floor area. However, there does appear to be a connection between the discomfort hours and the orientation of each room, as the south-facing rooms (bedroom and kitchen) generally experience the highest number of warm hours. This is expected due to the higher solar gains experienced on the south, and the impact of orientation is examined further in subsequent sections.

Examining the warm operative temperature hours, there is some correlation between the ER and the thermal comfort. When comparing windows W2, W5 and W19 a higher ER indicates better thermal comfort; however, the windows with the highest ER (W15) and lowest ER (W11) show an opposite trend as window W15 has worse thermal comfort.

Additional graphs showing warm and cool hours for each room in a cold climate (Toronto) and a northern climate (Yellowknife) are included in Appendix D. In general, the cool discomfort hours increase while the warm discomfort hours decrease as locations with higher HDDs are studied.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

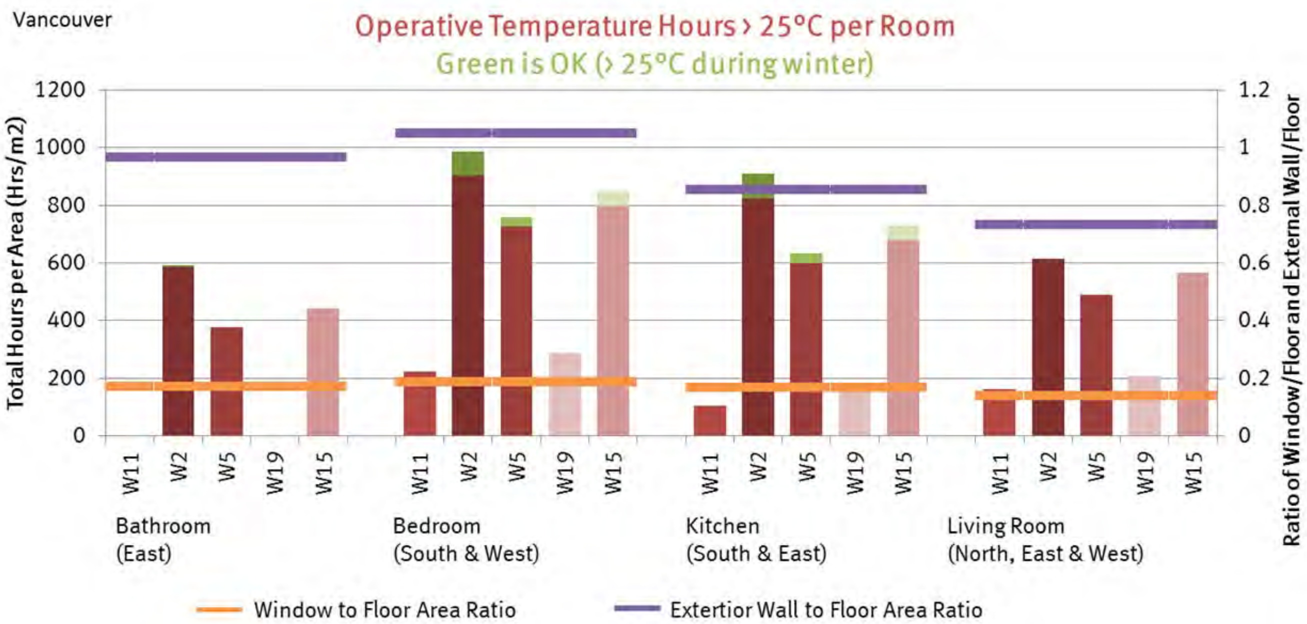


Fig. 9.4.12 D1 Vancouver, Individual room operative temperatures > 25°C

An individual room can also be studied on a monthly basis, to gather more detailed information on the comfort profile throughout the year. As an example, Fig. 9.4.13 presents the frequency of annual operative temperatures within the bedroom, which is located on the south-west corner of the building, window type W2 is used in the following simulations, as a representation of a typical existing house with double-glazing.

Similar to the overall house temperatures examined previously, the majority of time the operative temperature is between 19-21°C and 23-25°C. Again, these variances are impacted by the seasons, as the winter months (blue) contain the coldest temperatures, the summer months (red) represent the warmest, and the shoulder seasons (green and orange) make up the remaining hours between the extremes.

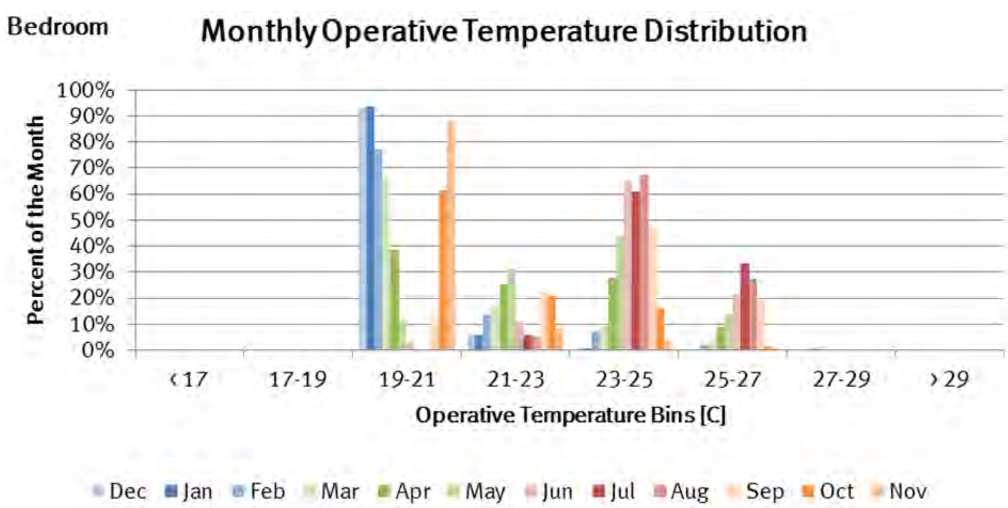


Fig. 9.4.13 D1 Vancouver, Bedroom operative temperatures throughout the seasons

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Another representation of the same data considers the cool, comfortable and warm hours for each month of the year. Fig. 9.4.14 shows that in Vancouver, a comfortable temperature can be reached for the majority of the year with window W2.

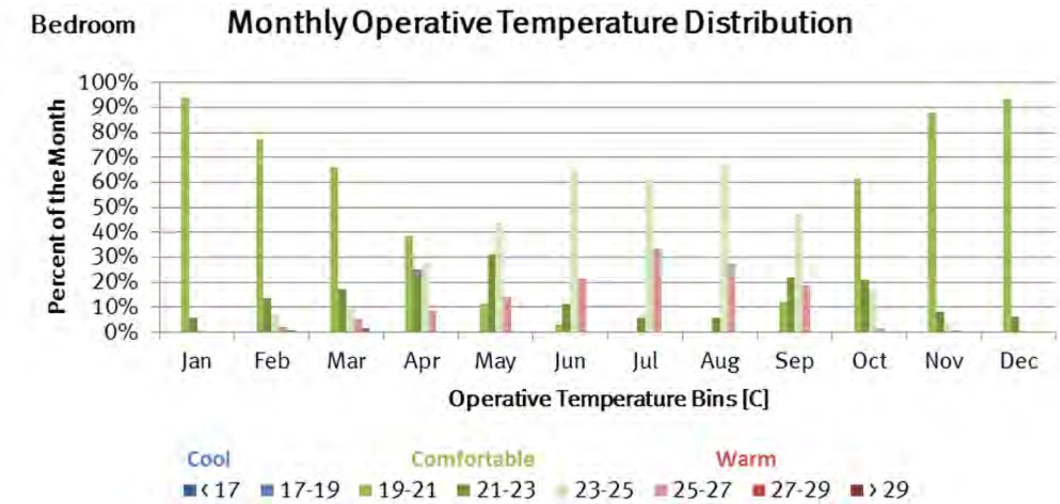


Fig. 9.4.14 D1 Vancouver, Bedroom monthly operative temperature comfort levels

A similar comparison for Yellowknife, shown in Fig. 9.4.15, indicates that cooler operative temperatures would be experienced in winter months, as would be anticipated for its northern climate.

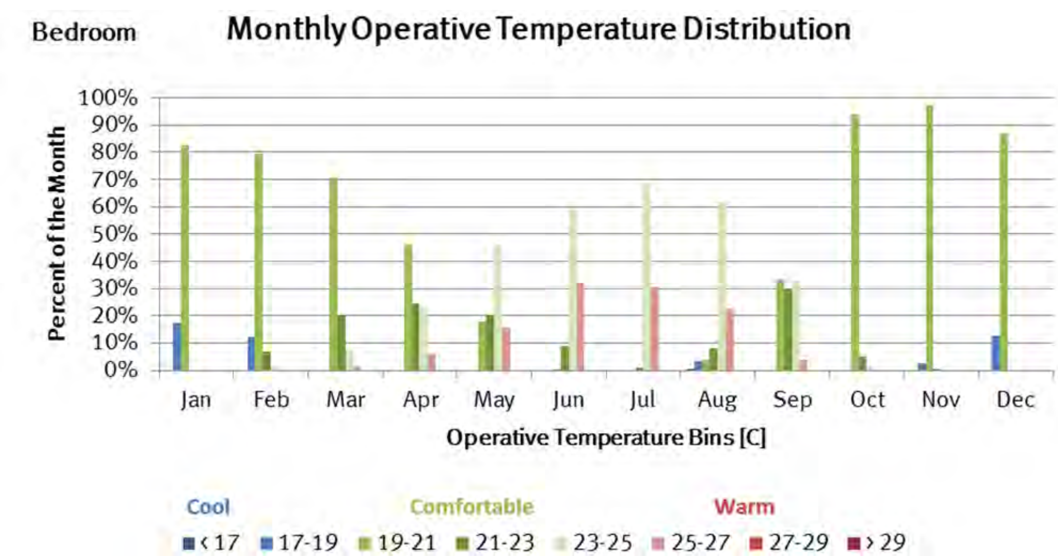


Fig. 9.4.15 D1 Yellowknife, Bedroom monthly operative temperature comfort levels

Similar to the operative temperature, the window surface temperature can be analyzed on a monthly basis to determine which months experience higher or lower temperatures. For all surface temperature analyses presented in this study, a window on each façade was selected and the discomfort hours for all four windows are summed over the year (4 x 8760 hours).

In Fig. 9.4.16, the window surface temperatures show some seasonal trending as more “cool” temperatures occur in the winter and more “warm” temperatures in the summer. However, the seasonality is not as clear as with the operative temperature, because the window surface temperature is highly impacted by solar radiation. As a result, north-facing windows have cooler temperatures throughout the year while south- and west-facing windows are warmer. Since both are represented here on the same graph, both cool and warm temperatures occur throughout the year due to north- and south-facing glazing, respectively.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

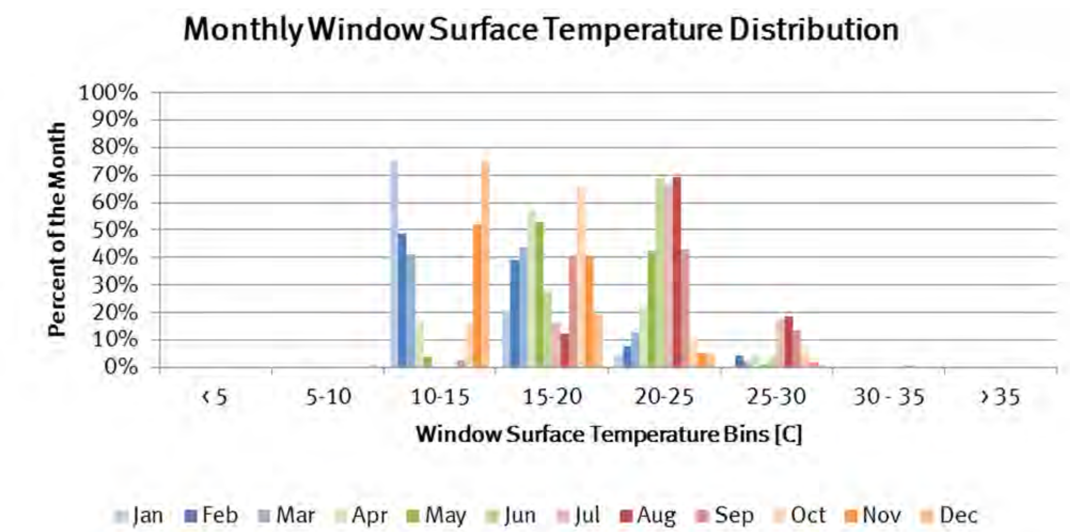


Fig. 9.4.16 D1 Vancouver, Window surface temperatures through the seasons

The window surface temperature data can also be represented on a comfort scale of cool, comfortable and warm, as shown below in Fig. 9.4.17. Similar to the operative temperature findings, this data shows that for this simulation in Vancouver with window type W2, a comfortable surface temperature for radiant symmetry can be achieved throughout the majority of the year.

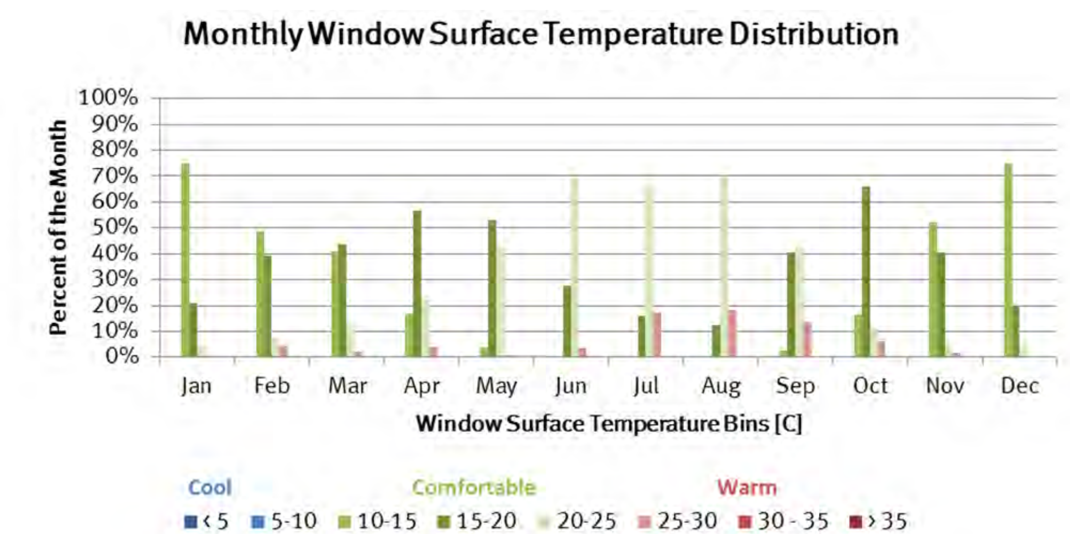


Fig. 9.4.17 D1 Vancouver, Bedroom monthly window surface temperature comfort levels

A similar comparison for Yellowknife, shown in Fig. 9.4.18, indicates that cooler operative temperatures would be experienced in winter months, as would be anticipated for its northern climate. In the winter months (November to March), a high proportion of the time, the window surface temperature would be considered uncomfortably cool. This could be handled in several ways by the occupants, such as increasing clothing insulation, drawing blinds to block the effect of the windows, or simply moving away from the windows.

As seen in the annual window surface temperature histograms, the window surface temperature results for Yellowknife are more significantly impacted by the cooler temperatures than operative temperature results.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

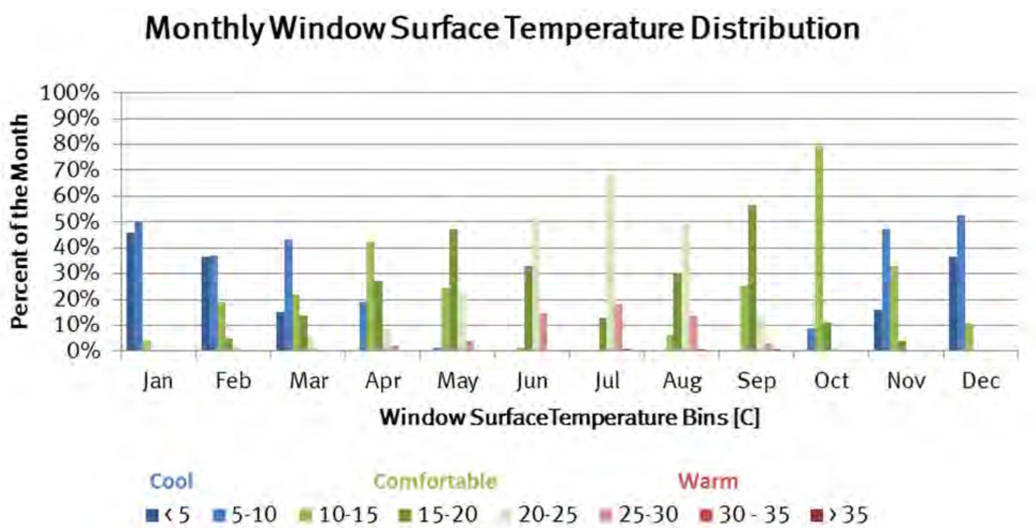


Fig. 9.4.18 D1 Yellowknife, Bedroom monthly window surface temperature comfort levels

Data for additional rooms, locations and window types are included in Appendix D, showing similar trends to those displayed here. Houses in locations with higher HDDs showed more cool hours and those in locations with higher CDDs experienced more warm hours, as would be expected.

9.4.2 Comparison of Geographic Locations

The level of thermal comfort was compared for the five windows across the 13 cities studied, and the resulting operative temperatures and window surface temperatures were examined separately. To better understand the impact of the U-value and SHGC, the parameters of each window type have been re-listed below in Table 9.4.2, ordered by ER. The similarities between windows are highlighted for clarity.

Table 9.4.2 Target 5 Window Parameters

Window #	ER	U-value		SHGC
		SI	IP	
11	8	2.00	0.35	0.2
2	14	2.83	0.50	0.64
5	26	2.00	0.35	0.5
19	32	0.90	0.16	0.2
15	49	0.90	0.16	0.5

Operative Temperature

Fig. 9.4.19 summarizes the total operative temperature discomfort hours, including both warm and cool, in each city. Similar to the Section 7 findings, there is some correlation between the discomfort hours and the window thermal properties. Depending on the location and whether the climate is heating or cooling dominant, trends appear related to both the U-value and the SHGC, with Prince Rupert and St John's showing up as anomalies for reasons discussed in subsequent sections of the report.

W2 consistently shows the worst performance (other than in Prince Rupert), with the highest number of hours outside the comfort range, while W19 shows the best performance, except in the warmest climates. In milder climates, houses containing

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

windows with the same SHGC value (W5/15 and W11/19) experienced similar discomfort hours. However, in cooler climates such as Winnipeg and Yellowknife, the impact of the U-value became more significant, as window W2 with the worst U-value (U_{SI}-2.83 [U-0.50]) caused the most discomfort hours, and the least discomfort was caused by window W19 with one of the best U-values (U_{SI}-0.9 [U-0.16]).

These trends do not correspond with the ER scale, as window type W11 has the lowest ER and W15 has the highest, yet they do not have the highest and lowest number of discomfort hours, respectively.

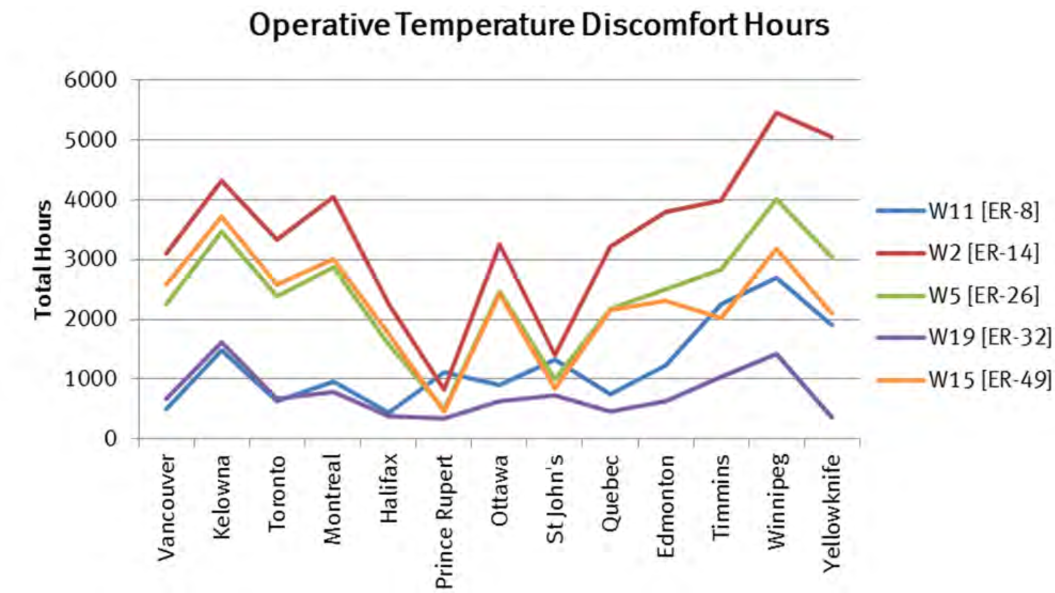


Fig. 9.4.19 D1 13 Cities, All windows' operative temperatures

Since the previous analyses include both warm and cool discomfort hours, trends due to both the U-value and SHGC are captured on the same graph; in order to isolate the effect of each variable, the temperatures must be isolated on subsequent charts. To examine the cool hours, cities have been re-ordered from lowest to highest Heating Degree Days (HDD), which is a commonly used indicator based on the outdoor air temperature profile for the city's standard CWEC weather file. HDDs determine the level of heating required in a typical year, allowing comparisons between different geographic locations; a higher number of HDDs indicates cooler average temperatures. The 13 study cities' Heating Degree Days are presented in Fig. 9.4.20, ordered from lowest to highest.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

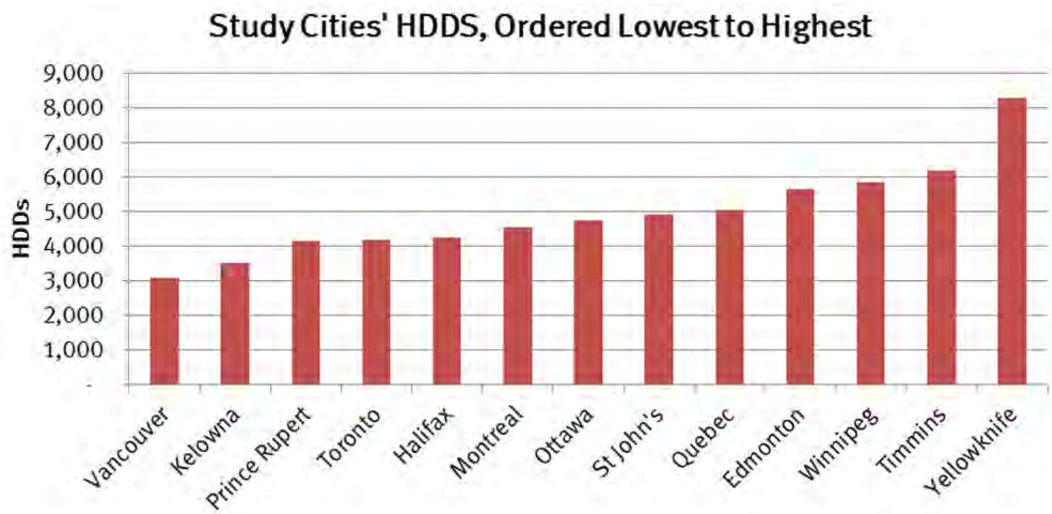


Fig. 9.4.20 All cities' heating degree days

A similar parameter to HDDs, Cooling Degree Days (CDDs) indicates the amount of cooling required in a particular location for a typical year, based on outdoor air temperature. The 13 study cities' Cooling Degree Days are presented in Fig. 9.4.21, ordered from lowest to highest; values are provided since the CDDs for Prince Rupert are so low they appear to be zero. When the warm hours are examined, the cities will be re-ordered based on CDDs. Prince Rupert and St John's are noticeable as the cities with the lowest CDDs, which is primarily due to the fact that they both have low levels of direct and diffuse solar radiation, as shown in Fig. 9.4.22, combined with higher than average levels of sky cover, as shown in Fig. 9.4.23.

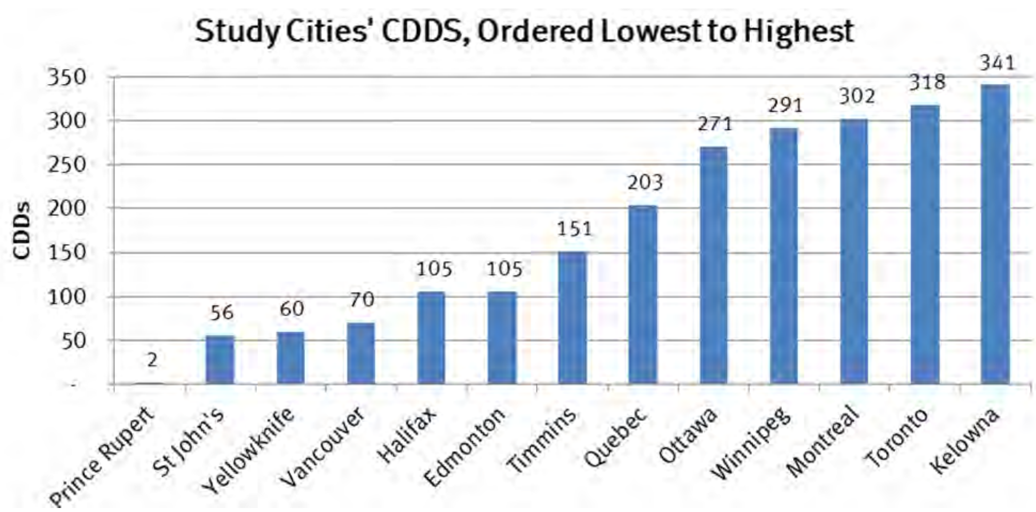


Fig. 9.4.21 All cities' cooling degree days

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

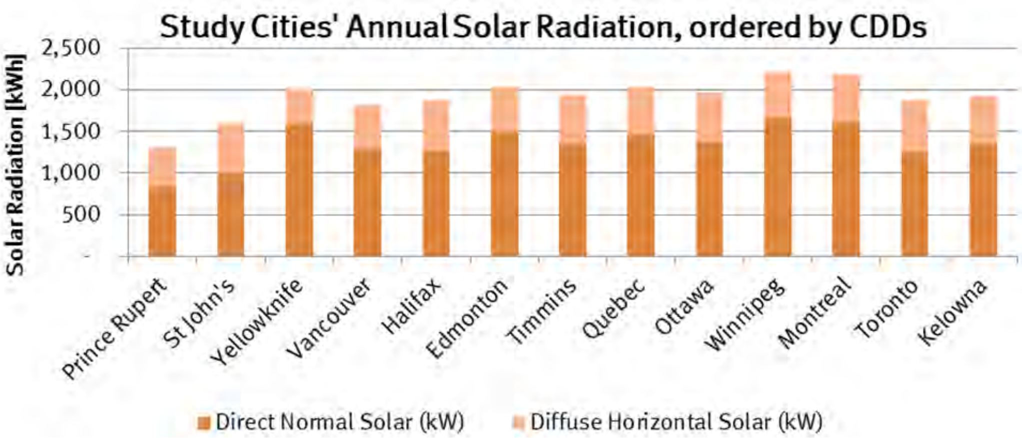


Fig. 9.4.22 All cities' annual solar radiation, ordered by CDD

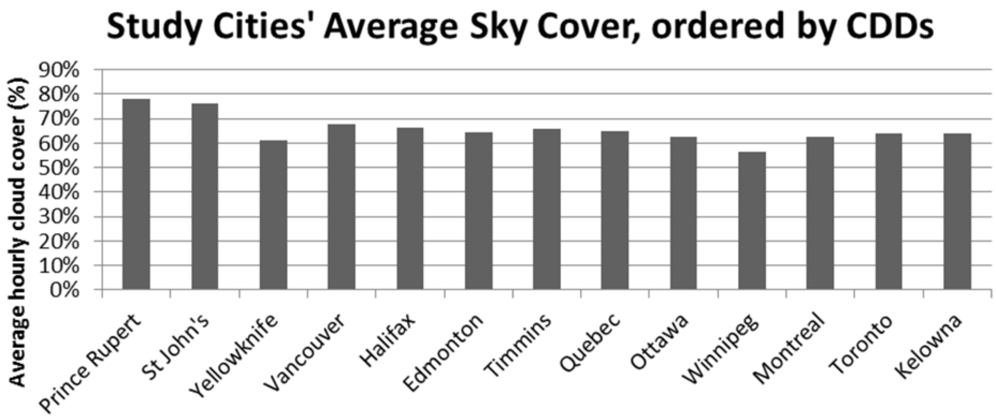


Fig. 9.4.23 All cities' average hourly sky cover, ordered by CDD

In Fig. 9.4.24, the cool hours when the operative temperature is below 19°C are isolated for each city. There is a general correlation between the number of HDDs and the number of cool discomfort hours, with a few exceptions. In Prince Rupert and St John's where the solar gains are extremely low the two windows with low SHGCs, W11/W19 (SHGC-0.2) show significantly worse performance, since there is very little free heating available due to solar radiation.

The effect of the U-value is more significant than the SHGC, particularly in the cooler climates, as window W2 (U_{SI}-2.83 [U-0.50]) generally has the worst performance, and windows W11/W5 (U_{SI}-2.0 [U-0.35]) are generally outperformed by windows W19/W15 (U_{SI}-0.9 [U-0.16]). In warmer cities, the lower total number of discomfort hours reduces the differential between the window options; however, the order of performance remains similar.

The SHGC also has some impact on the operative temperature cool hours, because it affects the amount of passive heating available by solar gains through the windows. This becomes apparent when two windows with the same U-value but different SHGCs are compared. For example, between windows W5/W11 (U_{SI}-2.0 [U-0.35]), W5 (SHGC-0.5) consistently performs better than W11 (SHGC-0.2) because it allows more passive solar gains in the winter. Similarly, W15 (U_{SI}-0.9 [U-0.16], SHGC-0.5) outperforms W19 (U_{SI}-0.9 [U-0.16], SHGC-0.2).

There is a fairly strong trend that better ER windows have better thermal comfort performance, however, it is not consistent across all locations. For example, window W11 with the lowest ER performs slightly better than window W2 in many of the cities. The trend is more visible in colder locations, such as Yellowknife, which further corroborates the impact of the U-value on cool thermal discomfort hours.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

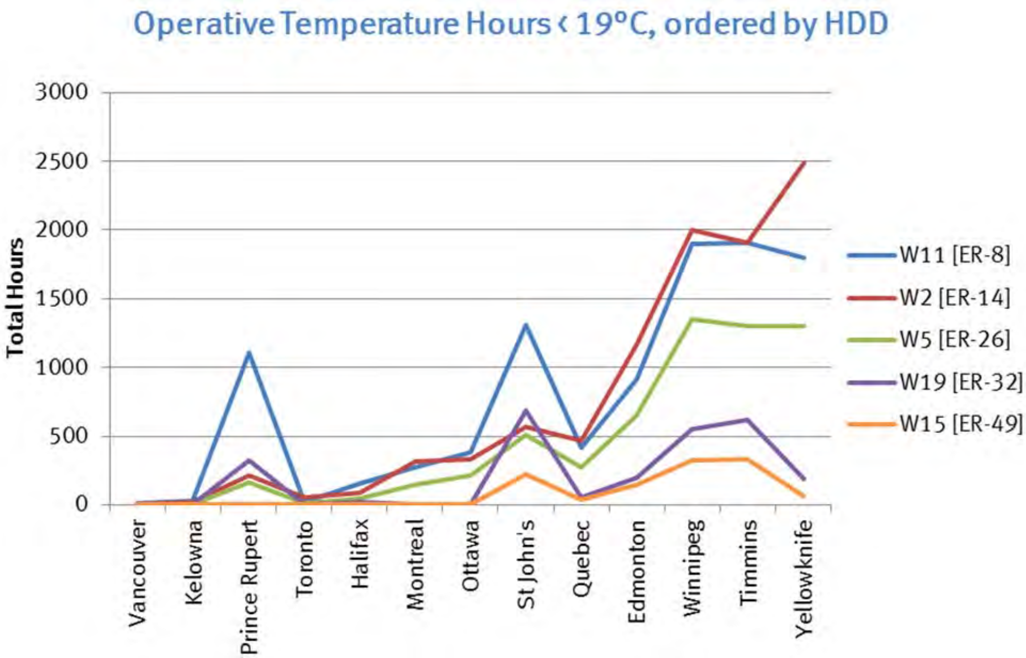


Fig. 9.4.24 D1 13 Cities, All windows' operative temperatures < 19°C, by HDD

During the summer time, if the operative temperature is below 19°C the temperature might not be considered uncomfortable. Therefore, Fig. 9.4.25 isolates the cool hours that occur during the summer (shown in green) from those occurring in the winter time (shown in blue). The plot clearly shows that windows with higher ER generally have lower cool discomfort hours in all locations. In addition, it is noticeable that both Prince Rupert and St John's generally have cooler hours occurring in the summer, whereas all of the other cities experience them in the winter time. This is yet another effect of the low solar radiation in these two cities.

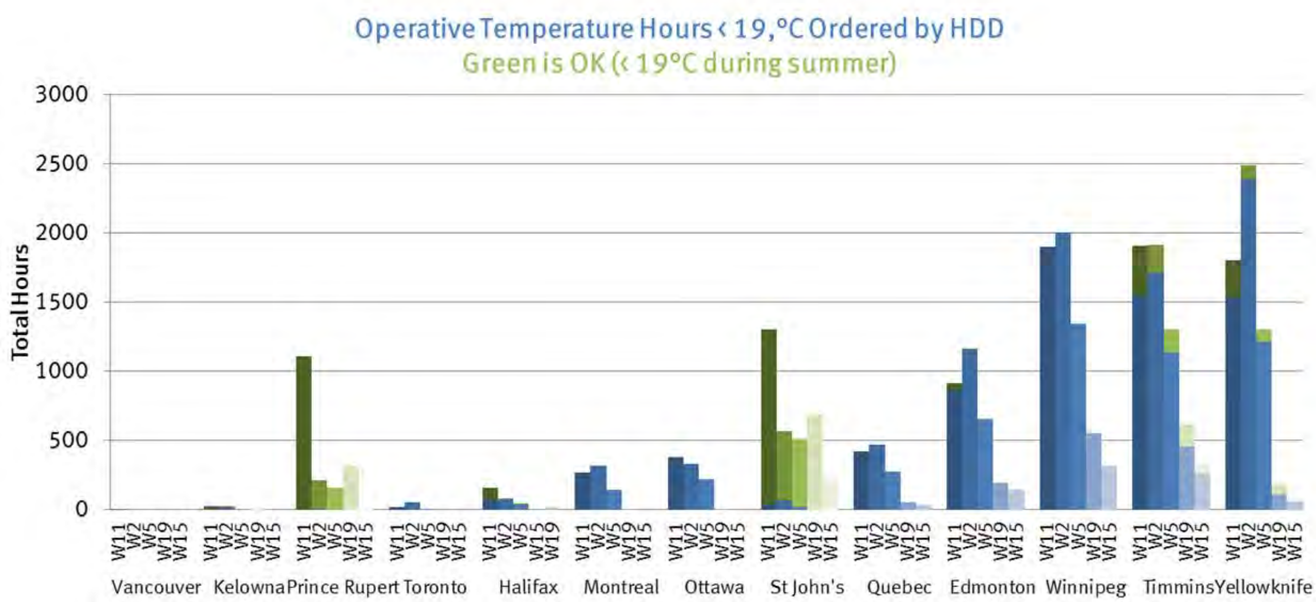


Fig. 9.4.25 D1 13 Cities, All windows' operative temperatures < 19°C in summer or winter, by HDD

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

In Fig. 9.4.26, the warm hours when the operative temperature is above 25°C are isolated for each city and ordered by CDDs; the results show a correlation between increasing CDDs and a higher number of warm hours.

In the case of warm hours, the solar heat gain coefficient plays a more significant role as windows with the same SHGC have similar number of hours above a comfortable temperature. For example, windows W15/W5 (SHGC-0.5) and windows W11/W19 (SHGC-0.2) follow similar trends, respectively. The U-value has less impact on the number of warm discomfort hours than it did when comparing cool discomfort hours.

Consistent with the analysis for the cool hours, although there is a trend relating the operative discomfort hours to the SHGC, this does not directly translate to the ER value of each window. Window W15 with the highest ER has the second worst thermal comfort performance, while window W11 with the lowest ER has the best thermal comfort performance.

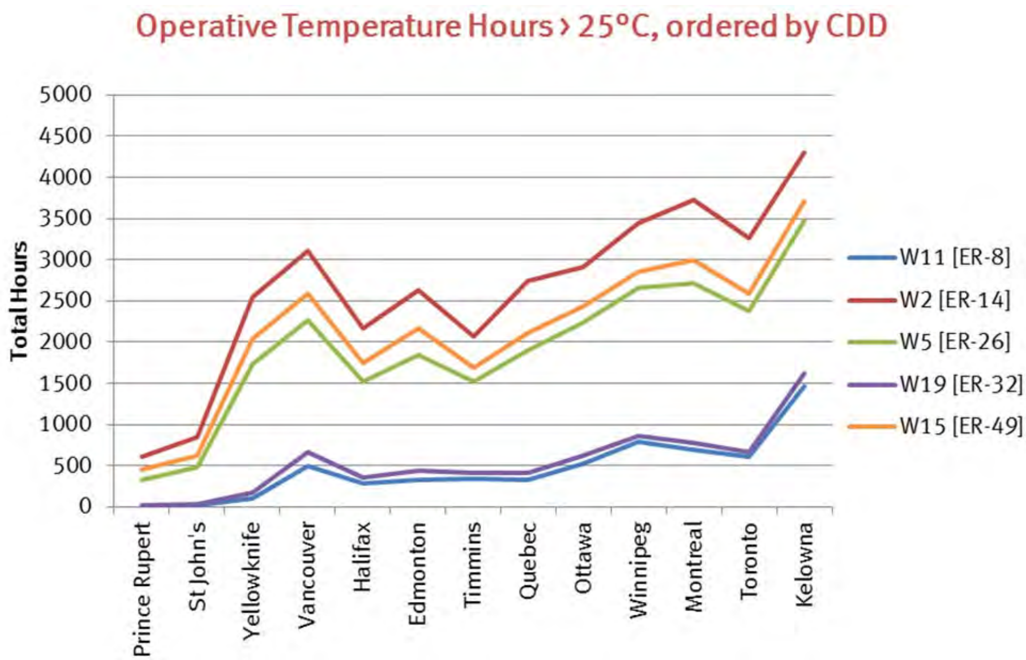


Fig. 9.4.26 D1 13 Cities, All windows' operative temperatures > 25°C, by CDD

The warm hours are separated by season in Fig. 9.4.27, which demonstrates that most of the warm hours occur in the summer (red), rather than the winter (green), and will therefore be uncomfortable. Window type W2 consistently shows a few warm hours during the winter because it allows the most solar gains to the space (SHGC-0.64) during the winter.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

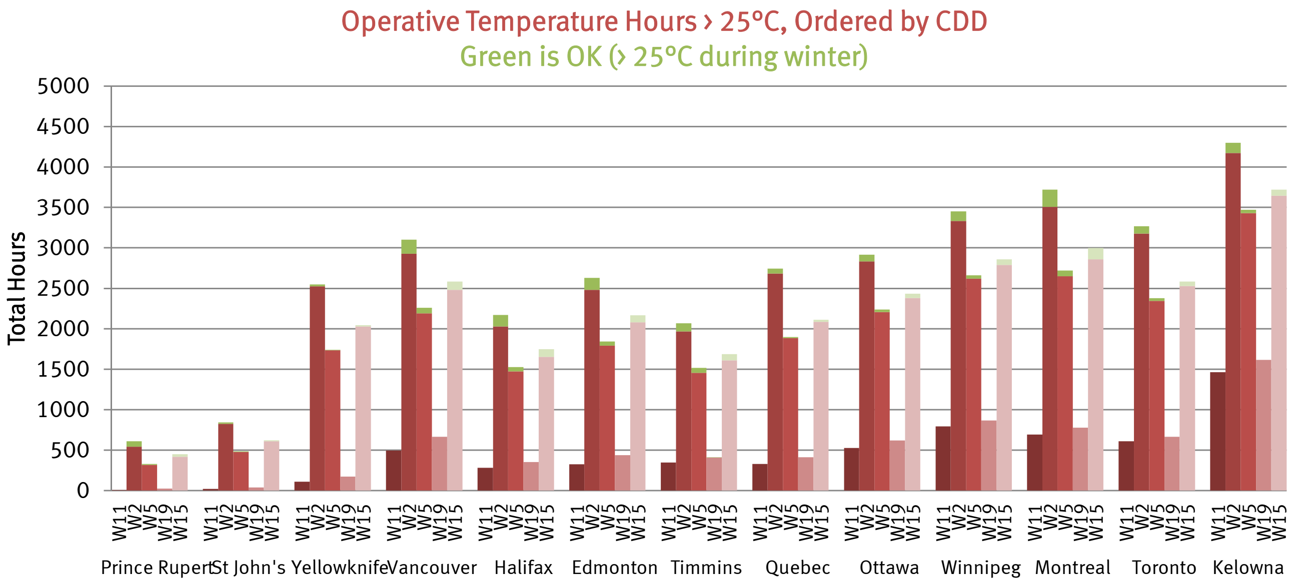


Fig. 9.4.27 D1 13 Cities, All windows' operative temperatures > 25°C in summer or winter, by CDD

It is also useful to compare the relative cool and warm hours for each city. Fig. 9.4.28 demonstrates that for each of the 13 locations there are more warm discomfort hours than cool discomfort hours when considering operative temperature. However, the relative difference changes significantly between cities. In warmer cities the warm hours greatly outnumber the cool while in colder climates, although the warm hours still outnumber the cool, the difference is relatively much smaller.

Once again, Prince Rupert and St John's are significant anomalies, where the total number of cool hours exceeds that of the warm hours for each window type.

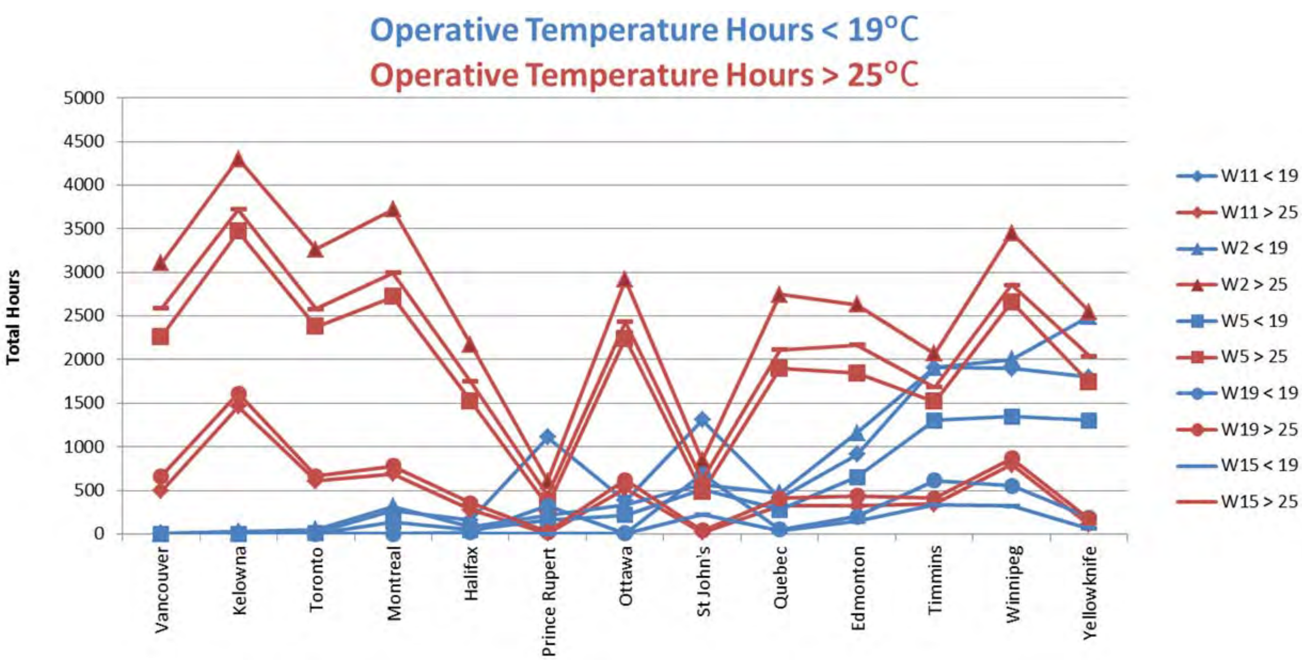


Fig. 9.4.28 D1 13 Cities, All windows' operative temperatures, warm or cool

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Window Surface Temperature

The same analyses can be performed for the window surface temperature results in each city.

Fig. 9.4.29 summarizes the total hours that the window surface temperatures are outside of the comfort range (defined as between 15°C and 30°C for radiant symmetry) for each city. Windows with the same U-values have similar trends across the cities and almost identical discomfort hours. The similarity is more striking than with operative temperatures, showing that U-value has more significant impact on window surface temperatures than operative temperatures.

Although the pattern is different from the operative temperatures, window W2 (U_{SI}-2.83 [U-0.50]) is still the worst performing compared to windows W5/W11 (U_{SI}-2.0 [U-0.35]) and the best performing windows W15/W19 (U_{SI}-0.9 [U-0.16]). The anomalies in Prince Rupert and St John's are lessened, because even the lower intensity of solar radiation in those two cities still has direct impact on window surface temperature.

However, similar to operative temperatures, there is no clear trend that aligns with the energy rating, because the ER is dependent upon more than just U-value.

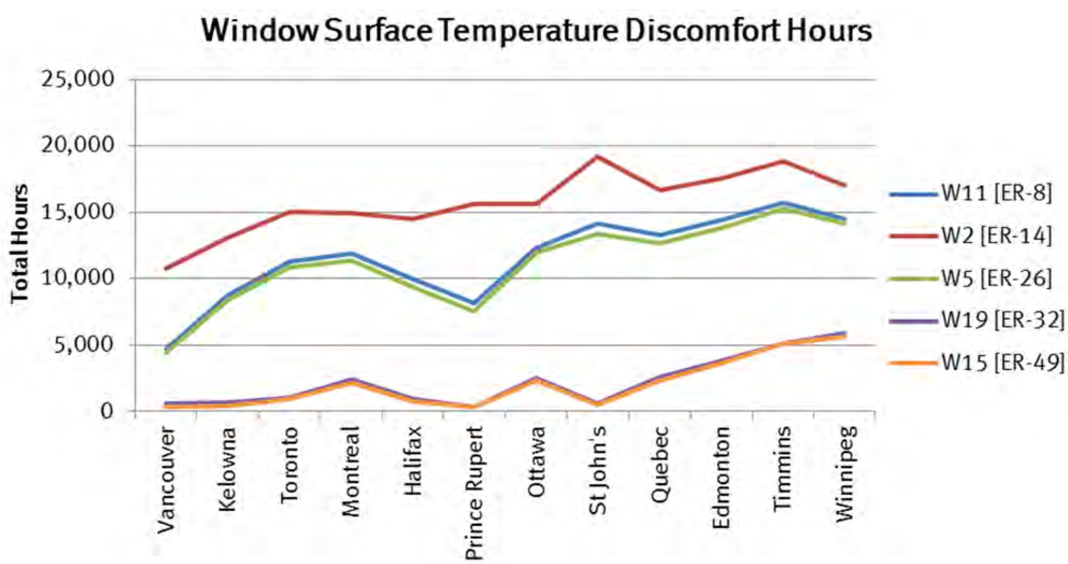


Fig. 9.4.29 D1 13 Cities, All windows' surface temperatures

Examining the cool hours only in Fig. 9.4.30 shows a pattern very similar to that of the overall hours, suggesting that the total discomfort hours are dominated by cool hours. The number of discomfort hours is higher in the colder climates, although this graph is not ordered in terms of HDDs.

The cool discomfort hours have some relation to the ER, as the windows with the highest ER have the best thermal comfort performance. The trend is not consistent across all windows. Window W2 is an anomaly because it performs worse than W11, the window with the lowest ER.

However, the performance does correlate with the windows' U-values, which relates to the findings of Section 7. This suggests that the U-value plays an important role in heating-dominant climates for both energy and thermal comfort, when the cities are ordered by HDD. There is a trend of increasing discomfort hours with higher HDDs; the other trends with respect to the ER and the U-value remain the same.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

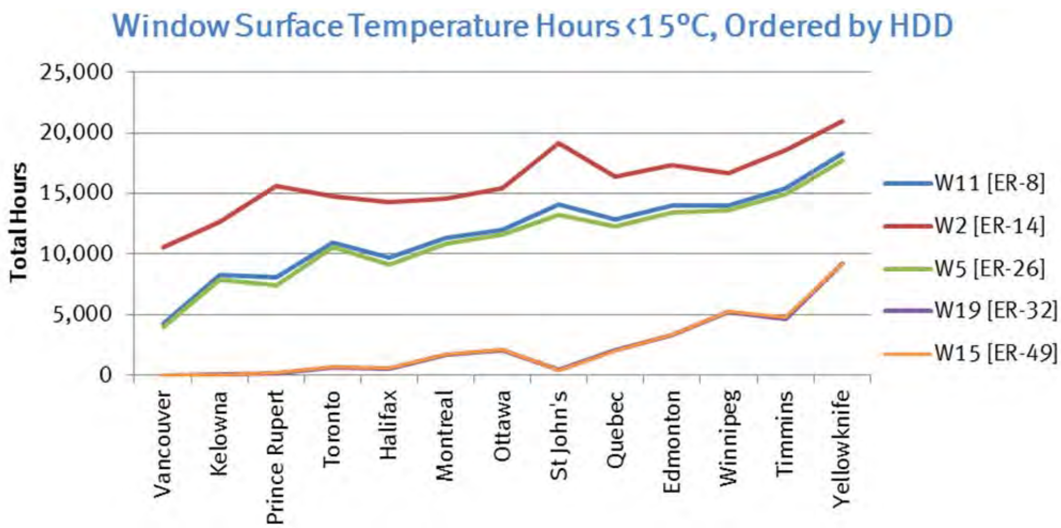


Fig. 9.4.30 D1 13 Cities, All windows' surface temperatures < 19°C, Ordered by HDD

The warm window surface temperature hours, defined as > 30°C (Fig. 9.4.31), are an order of magnitude lower than the cool hours so have less impact on the total discomfort hours. The number of warm hours generally increases with a higher CDD.

Window W2 (second lowest ER) has the best thermal comfort performance while window W19 (second highest ER) continually has the worst thermal comfort performance. There is a general trend suggesting that a higher ER window can cause more warm discomfort hours.

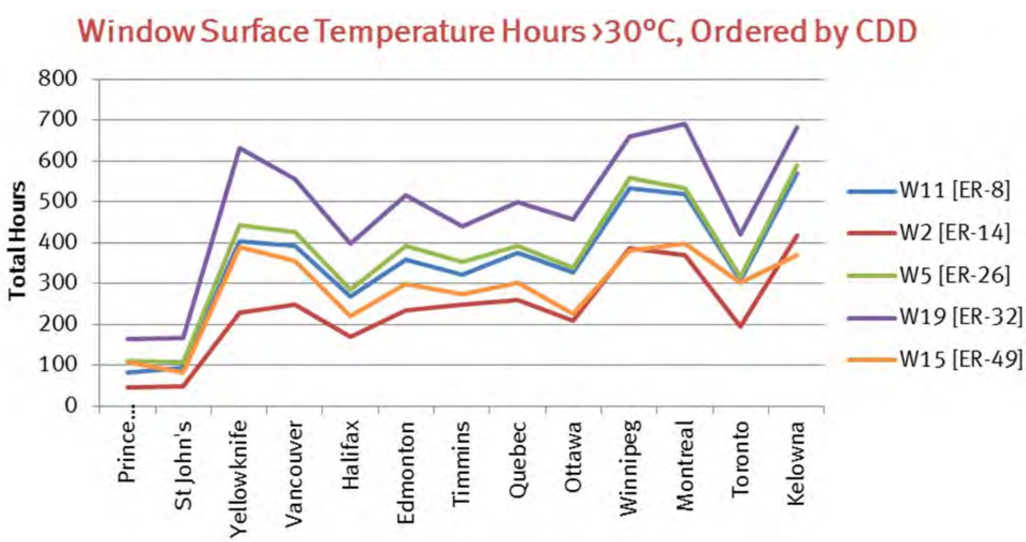


Fig. 9.4.31 D1 13 Cities, All windows' surface temperatures > 30°C, Ordered by CDD

This order of magnitude difference is also obvious when the warm and cool hours are compared in the same graph, as shown in Fig. 9.4.32, where it becomes obvious that the window surface temperature discomfort hours are dominated by cool hours.

The operative temperatures were dominated by warm hours. As the windows are generally the building element with the least thermal resistance, their internal surface temperatures reflect the cold outdoor air temperature and discomfort hours are predominantly cool.

The operative temperature is calculated by DesignBuilder as the "mean of the internal temperature and radiant temperatures",

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

which also includes assumptions that a) the person is in the middle of the space, and b) there is no weighting for any particular surface. This weights the calculation with a number of temperatures that are warmer, including: internal wall, floor and ceiling surface temperatures, and the dry-bulb temperature, which has been conditioned by the mechanical system. Therefore, it is expected that the operative temperature would have thermal discomfort hours that are predominantly warm.

Another interesting point to take from the definition is that the operative temperature results do not account for radiant asymmetry. For example, if one wall was 5°C warmer than a comfortable temperature setpoint and the opposite wall was 5°C colder, the operative temperature would appear to be comfortable. This further highlights the need for examining the window surface temperatures as part of the study.

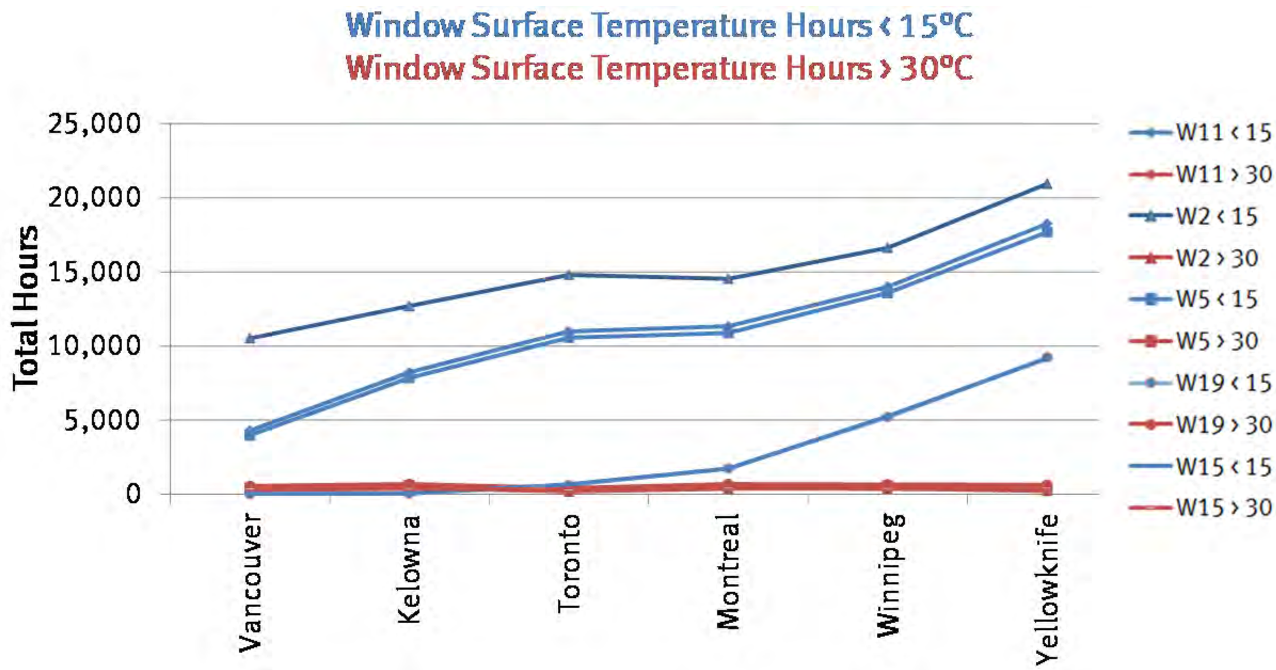


Fig. 9.4.32 D1 13 Cities, All windows' surface temperatures, Warm or cool

9.4.3 Comparison of all Iterations (D1-E2)

The significant differences between the nine iterations are summarized below in Table 9.4.3.

Table 9.4.3 Thermal Comfort Energy Model Iterations, Summarized

Iteration	Difference from D1 Baseline	Iteration	Difference from D1 Baseline
D1	Baseline	E1	2 Storeys
D2	Natural Ventilation	E2	2 Storeys & Natural Ventilation
D3	Electric Baseboard Heating		
D4	Thermal Mass		
D5-90/180/270	Rotated 90, 180 and 270 degrees from north		

Before examining the particulars of the iterations, a general comparison between all iterations simulated in Vancouver is provided for both operative temperature and window surface temperature discomfort hours. Because there are both single and two-storey houses in the set of iterations, which contain different numbers of rooms (four and 12, respectively), the number of

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

discomfort hours presented in this section has been divided by the number of rooms in the house.

The operative temperature results of the nine iterations are graphically compared in Fig. 9.4.33. While all of the iterations follow the same trends across the five window types, there is no simple correlation with respect to the energy rating. When comparing windows W2, W5 and W19, there are fewer discomfort hours when the ER improves, however, the two windows with the lowest and highest ERs, windows W11 and W15 respectively, do not follow this trend.

Results are provided for Toronto and Yellowknife in Appendix D, showing trends similar to Vancouver.

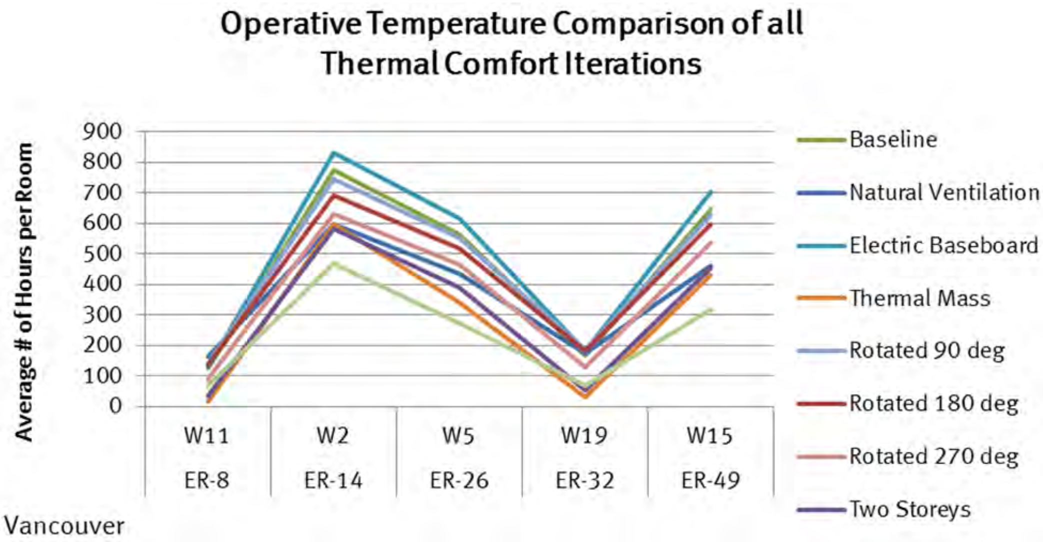


Fig. 9.4.33 Vancouver, All iterations operative temperature discomfort hours

The window surface temperature results for the same iterations are provided in Fig. 9.4.34. In this case, the windows with a higher ER do have lower discomfort hours, with the exception of W11. If the window types were re-ordered by U-value rather than ER (switching the position of windows W2 and W11), a higher U-value would align with lower discomfort hours.

Results are provided for Toronto and Yellowknife in Appendix D, showing trends similar to Vancouver. The trends are generally more exaggerated in other locations when compared to Vancouver, due to the latter’s temperate climate. For example, in the comparison for Toronto, which has higher CDDs than Vancouver, the warm hours due to natural ventilation (iteration D3) are more significant. In Yellowknife, which has higher HDDs than Vancouver, the increase in cool hours due to the electric baseboard scenario (iteration D3) is more visible.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

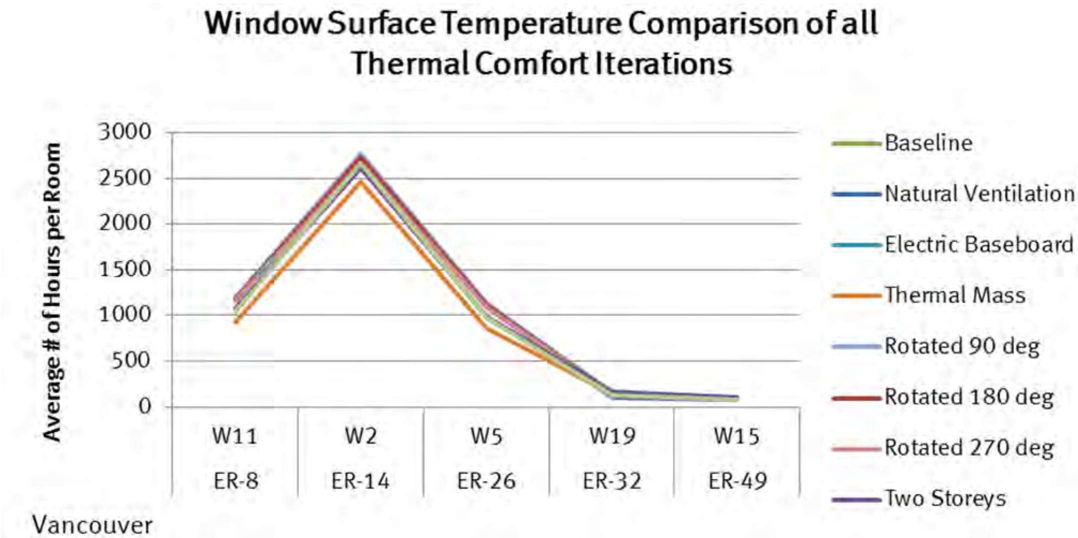


Fig. 9.4.34 Vancouver, All iterations window surface temperature discomfort hours

9.5. Individual Iterations

As previously discussed, the iterations were performed for a representative five of the 13 selected cities: Vancouver, Toronto, Montreal, Winnipeg and Yellowknife. The cities are ordered from lowest-to-highest HDD, unless otherwise noted.

The five windows were examined for each of the locations; all of the results are presented ordered by lowest-to-highest ER, unless otherwise noted.

The impact of each of the variables is examined in this section, with respect to the baseline simulation (D1). In order to facilitate comparison between the two, the baseline results are often presented alongside the iteration's results.

9.5.1 Baseline Summary (D1)

The operative temperature results from the baseline iteration, D1, are summarized in Fig. 9.5.1 and Fig. 9.5.2 for the selected cities and windows. As previously noted, in milder climates the impact of the SHGC is more significant as windows with the same value such as W5/W15 (SHGC-0.5) and W11/W19 (SHGC-0.2) follow similar trends. However, in colder climates the U-value plays a more important role in improving overall thermal comfort levels.

Another notable finding from this analysis is the opportunity available for improving thermal comfort by window selection. In each city, the number of operative discomfort hours varies significantly between the best and worst-performing window. The percentage reduction between the windows of lowest and highest thermal comfort performance from the baseline simulations are listed alongside the corresponding graph in Fig. 9.5.1.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

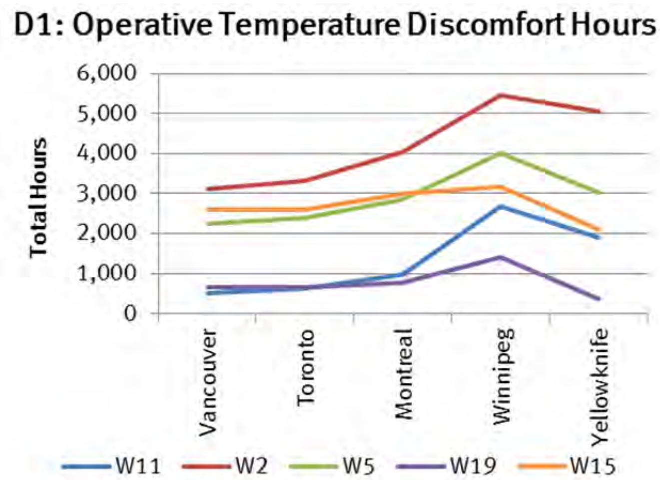
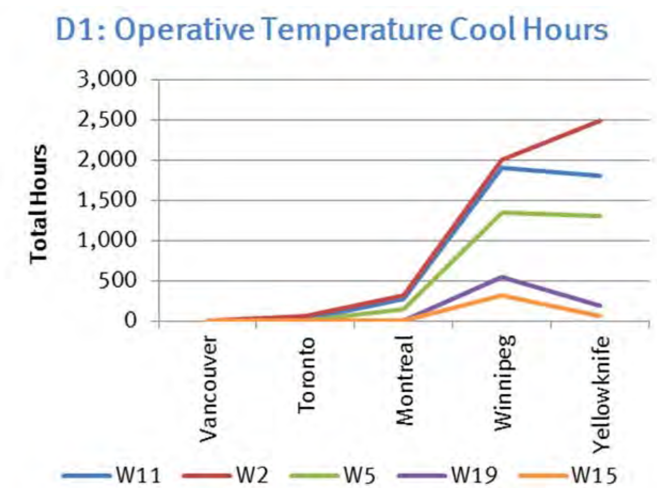


Fig. 9.5.1 D1 Total operative temperature discomfort hours

Table 9.5.1 Potential Thermal Comfort Improvement by Window Selection

Location	Potential % thermal comfort improvement
Vancouver	84%
Toronto	81%
Montreal	81%
Winnipeg	74%
Yellowknife	93%
Average	*83%*



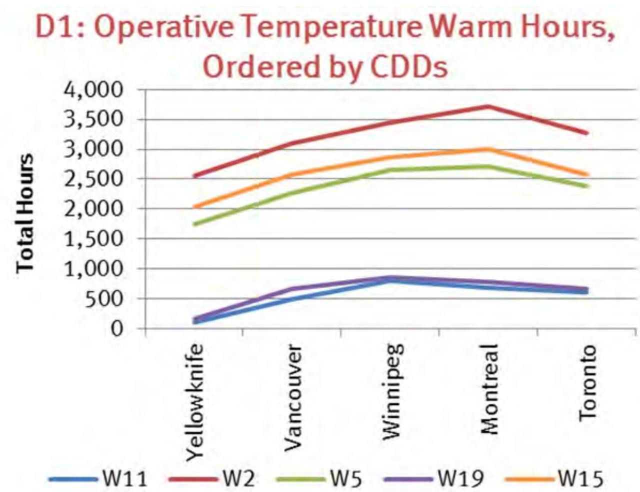


Fig. 9.5.2 D1 Operative temperature cool and warm hours

The window surface temperature results for the selected cities' baseline simulations are summarized in Fig. 9.5.3 and Fig. 9.5.4. As seen in the previous section, the total window surface temperature discomfort hours are dominated by cool hours, as the total profile is similar to that of cool hours rather than warm, and the former are an order of magnitude higher than the latter.

There is no direct correlation between the level of thermal comfort and the ER.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

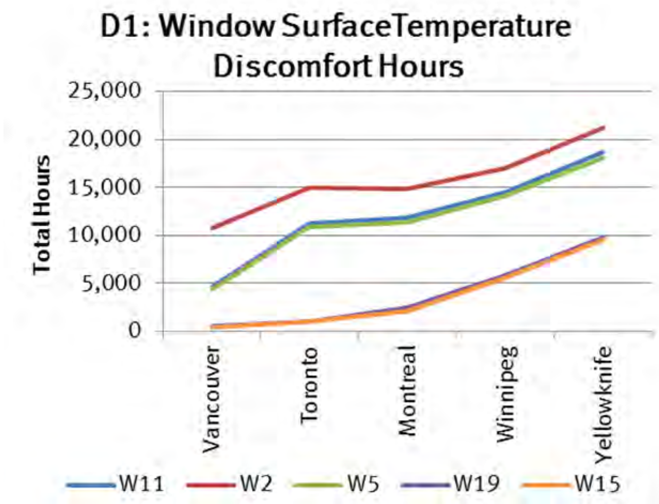


Fig. 9.5.3 D1 Total window surface temperature discomfort hours

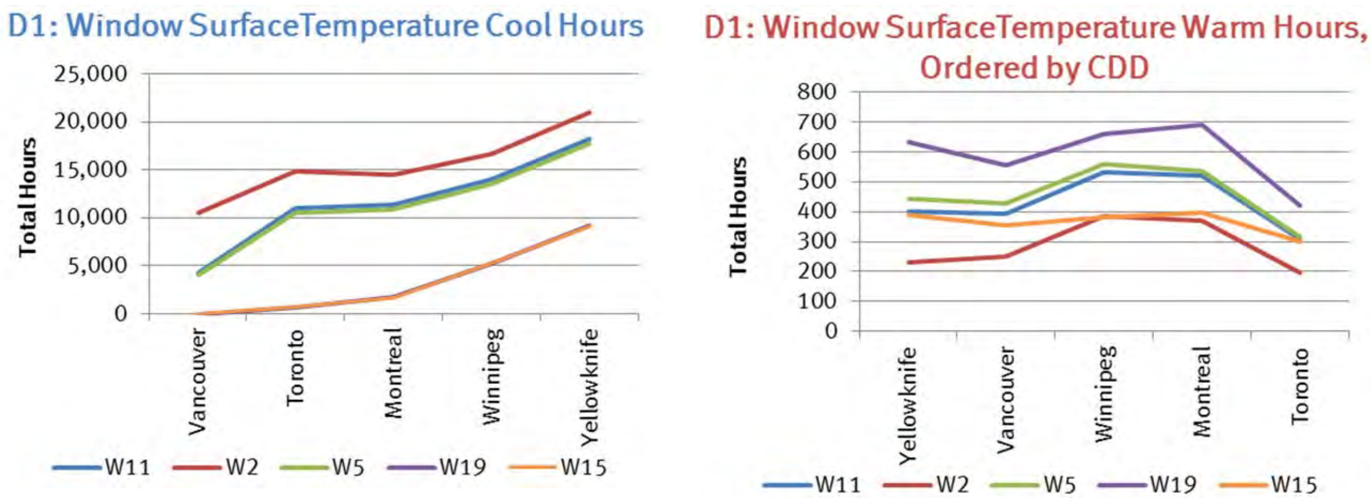


Fig. 9.5.4 D1 Window surface temperature cool and warm hours

9.5.2 Natural Ventilation (D2)

In these simulations, the mechanical cooling was disabled from the single-storey house, and natural ventilation was added to minimize overheating. The intent of these simulations was to be representative of the areas of the country, and the houses that do not typically install mechanical cooling.

The operative temperature results are provided in Fig. 9.5.5, Fig. 9.5.6 and Fig. 9.5.7.

The operative temperature total discomfort hours are examined in Fig. 9.5.5, alongside the comparable baseline results. The number of discomfort hours increases significantly in Toronto, Montreal and Winnipeg, locations with higher CDDs, when mechanical cooling is disabled and natural ventilation is used instead. The impact is lower in Vancouver and Yellowknife, where less cooling is required during summer months.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

The use of natural ventilation does not have a significant impact on the operative temperature cool hours as outlined in Fig. 9.5.6, which is expected since no changes were made to the mechanical heating system from the baseline simulation. The cool hours generally reflect a trend that relates to the ER, as the two windows with the highest ERs (W19 and W15) generally have the lowest discomfort hours, while the windows with the lowest ERs (W11 and W2) have the highest.

The number of warm hours increases substantially, as seen in Fig. 9.5.7, particularly in locations with higher CDDs, such as Winnipeg, Montreal and Toronto. The results were re-ordered by CDDs to better reflect this. These results show less of a correlation to the ER, as the lowest ER window (W11) has the best thermal comfort performance, while the second lowest ER window (W2) has the worst thermal comfort performance.

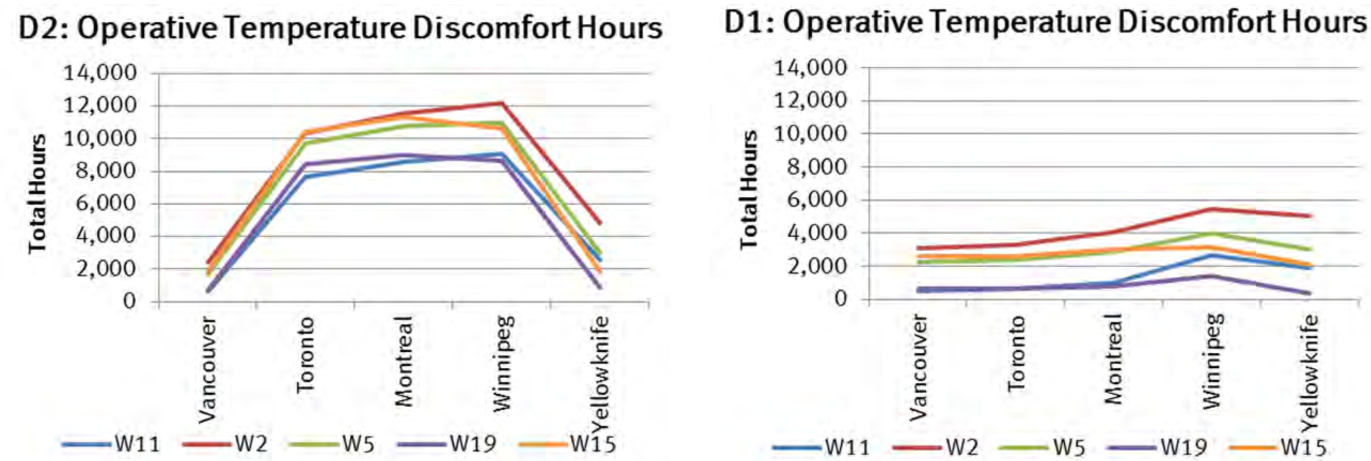


Fig. 9.5.5 D2, Operative temperature discomfort hours compared with D1

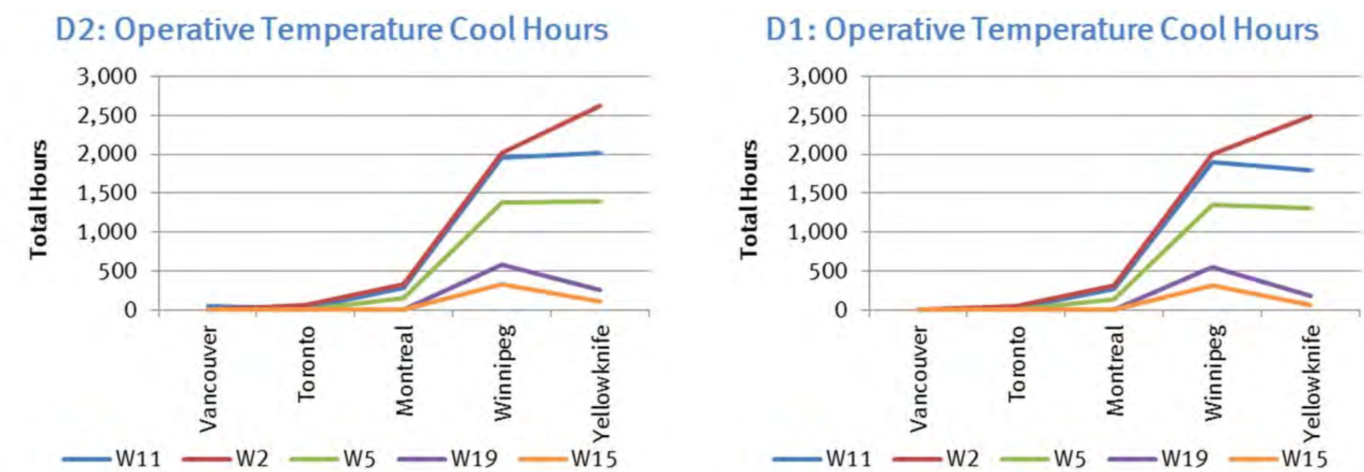


Fig. 9.5.6 D2, Operative temperature cool hours compared with D1

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

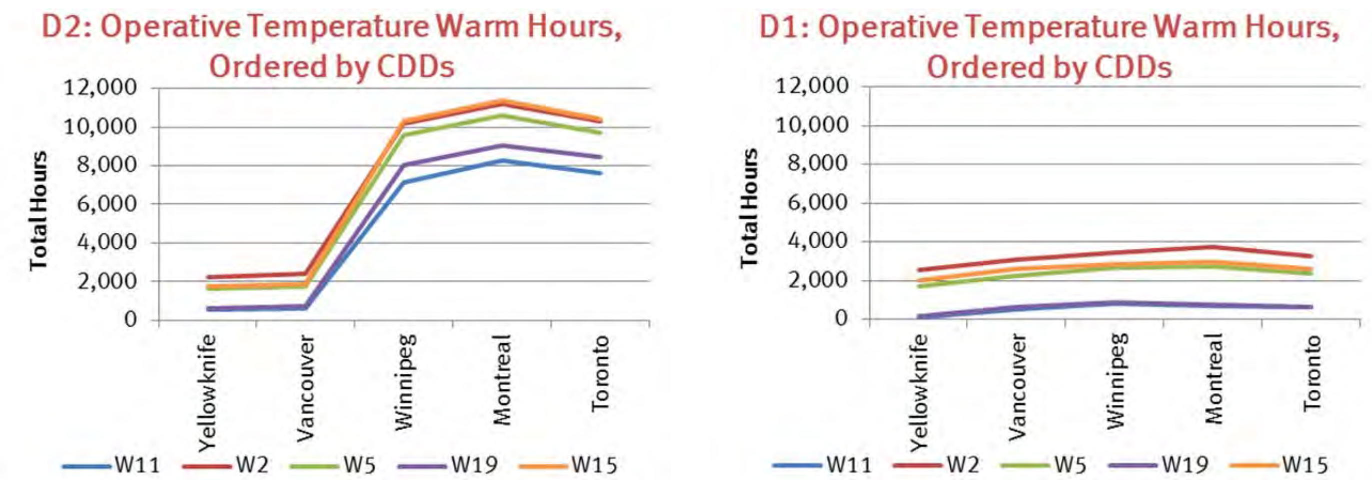


Fig. 9.5.7 D2, Operative temperature warm hours compared with D1

The window surface temperature results are provided in Fig. 9.5.8, Fig. 9.5.9 and Fig. 9.5.10.

The window surface temperature total discomfort hours follow a similar profile to the baseline simulation and fall within the same order of magnitude. The window surface temperatures were less affected by the natural ventilation because, as noted in the previous section, their discomfort levels are more impacted by cool hours than warm hours. However, there is some change in Toronto, Montreal and Winnipeg, locations with higher CDDs, which will be examined further. The relationship between the U-value and the total discomfort hours is visible, as window pairs W11/W15 (U_{SI}-2.0 [U-0.35]) and W19/W15 (U_{SI}-0.9 [U-0.16]) follow nearly identical trends. A trend is visible between the ER and the level of thermal comfort, as the two windows with the highest ERs (W19 and W15) have the lowest discomfort hours; however, the window with the lowest ER (W11) performs better than other windows in some of the locations.

Similar to the operative temperature results, the cool hours are not significantly impacted when natural ventilation is introduced, as shown in Fig. 9.5.9. The trend between the ER and the thermal comfort performance is the same as was observed in the total hours, again suggesting that the cool hours have more impact on the total.

The window surface temperature warm hours increase when natural ventilation is implemented, similar to the operative temperature findings, particularly in locations with higher CDDs. The resulting impact on the overall discomfort hours is not as large as in the operative temperature results, because the cool hours still greatly outnumber the warm. In these locations, there is a direct relationship between the ER and the number of thermal discomfort hours. Installing windows with the lowest ER (W11) produces the lowest number of uncomfortably warm hours; by improving the ER, the number of thermal discomfort hours increases. This is expected as the ER is not anticipated to correlate with warm hours.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

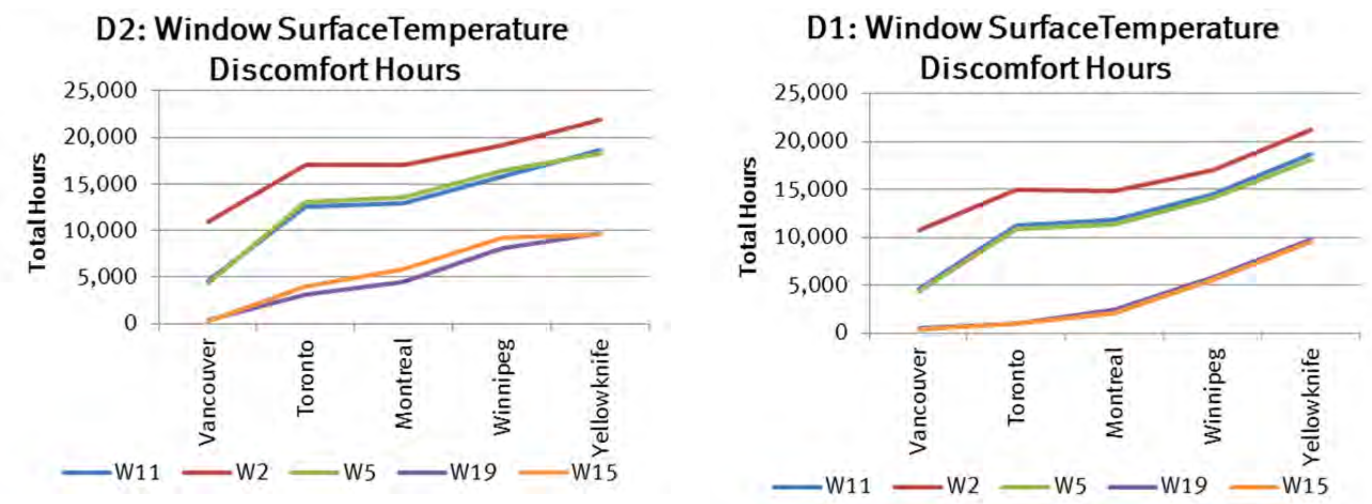


Fig. 9.5.8 D2, Window surface temperature discomfort hours compared with D1

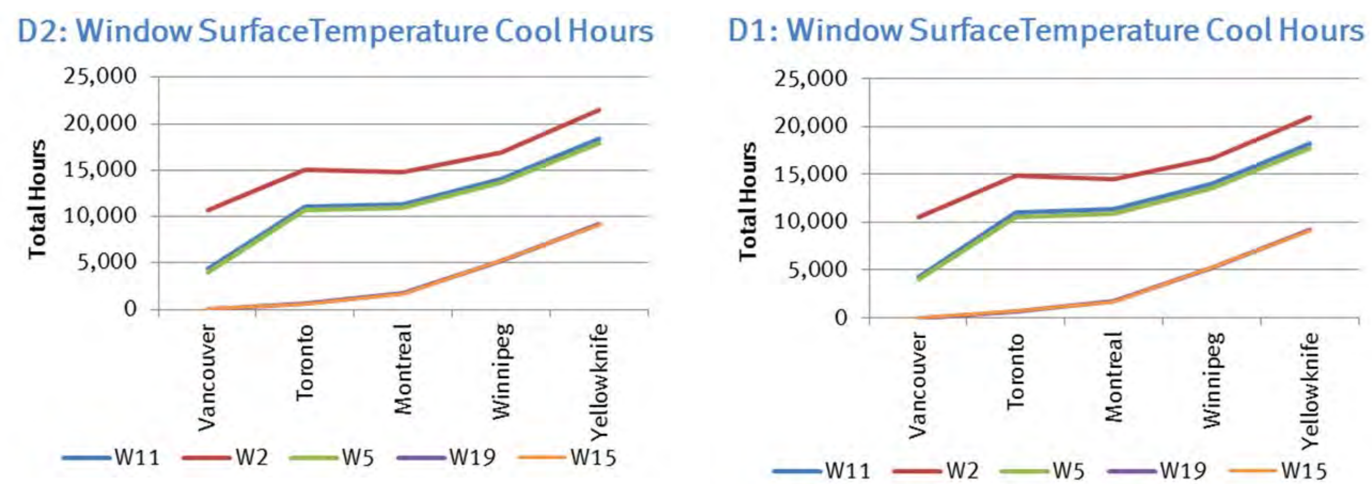


Fig. 9.5.9 D2, Window surface temperature cool hours compared with D1

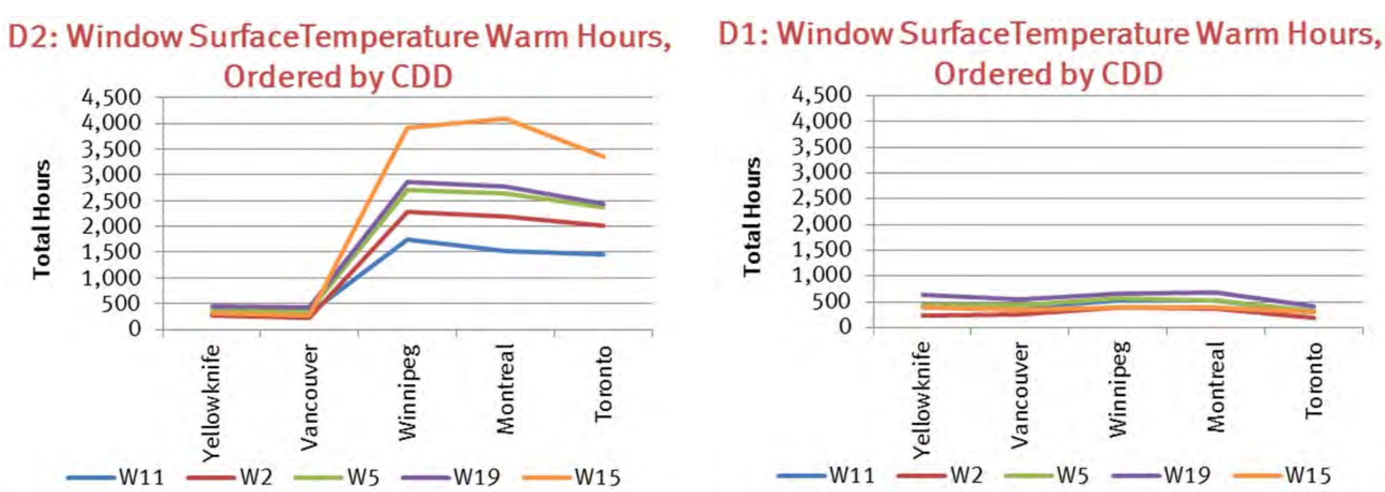


Fig. 9.5.10 D2, Window surface temperature warm hours compared with D1

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Conclusions

Using natural ventilation will increase the operative temperature warm hours, mostly in locations with higher CDDs. This has significant impact on the overall thermal discomfort hours. The operative temperature cool hours do not change significantly. The overall thermal comfort performance of the windows varies between many of the cities; however, the cool hours show some correlation with the ER as windows with higher ERs generally show better thermal comfort than those with lower ERs.

The window surface temperature warm hours are also increased in areas with higher CDDs. However, the effect on the overall thermal discomfort hours is minimal because the cool hours are still dominant and are not changed significantly by natural ventilation. In these locations, there is a direct relationship between the ER and the level of thermal comfort, where a higher ER indicates more thermal discomfort hours.

9.5.3 Electric Baseboard Heating (D3)

The mechanical heating system was modified for the single-storey house to electric baseboard heaters rather than a natural gas furnace. One electric baseboard heater was defined for each room, sized to meet the space's peak heating requirements.

The operative temperature results are presented in Fig. 9.5.11, Fig. 9.5.12 and Fig. 9.5.13.

The total operative temperature discomfort hours experienced in the electric baseboard simulations are shown in Fig. 9.5.11, alongside the baseline simulation. Other than Yellowknife, all cities have similar profiles as the baseline simulation, and the total discomfort hours are within range of the baseline results.

In Yellowknife there is an increase in the number of cool hours, as seen in Fig. 9.5.18. This is expected because baseboard heaters are less efficient at heating than a mixed-air system and less able to handle the extreme cold in this location; they are therefore less commonly used in such climates. Examining the cool hours between windows shows that, similar to D1, a higher ER will generally show better thermal comfort performance, although the comparable window performances are not consistent across all cities.

The operative temperature warm hours do not change significantly for any of the cities. The inverse relationship between the number of warm discomfort hours and the ER, present in iteration D1, is again visible in the D3 scenario as generally, a window with a higher ER will provide less thermal comfort.

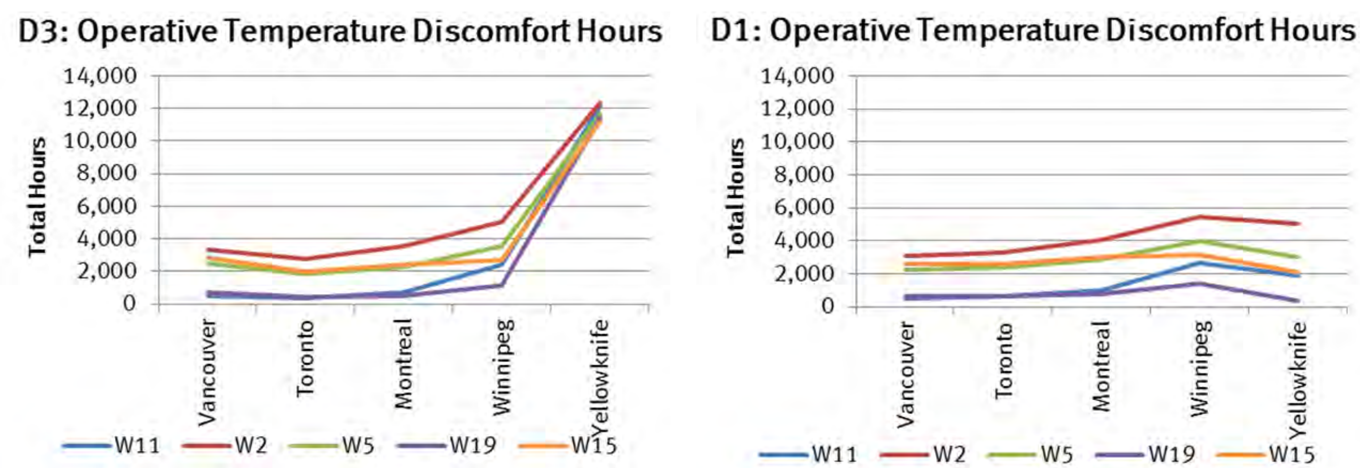


Fig. 9.5.11 D3, Operative temperature discomfort hours compared with D1

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

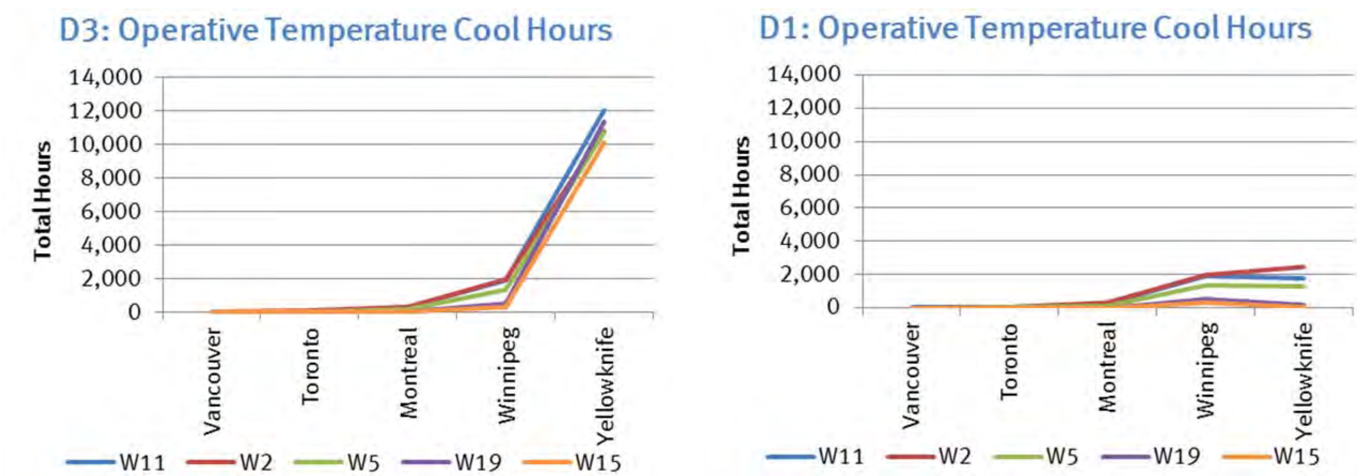


Fig. 9.5.12 D3, Operative temperature cool hours compared with D1

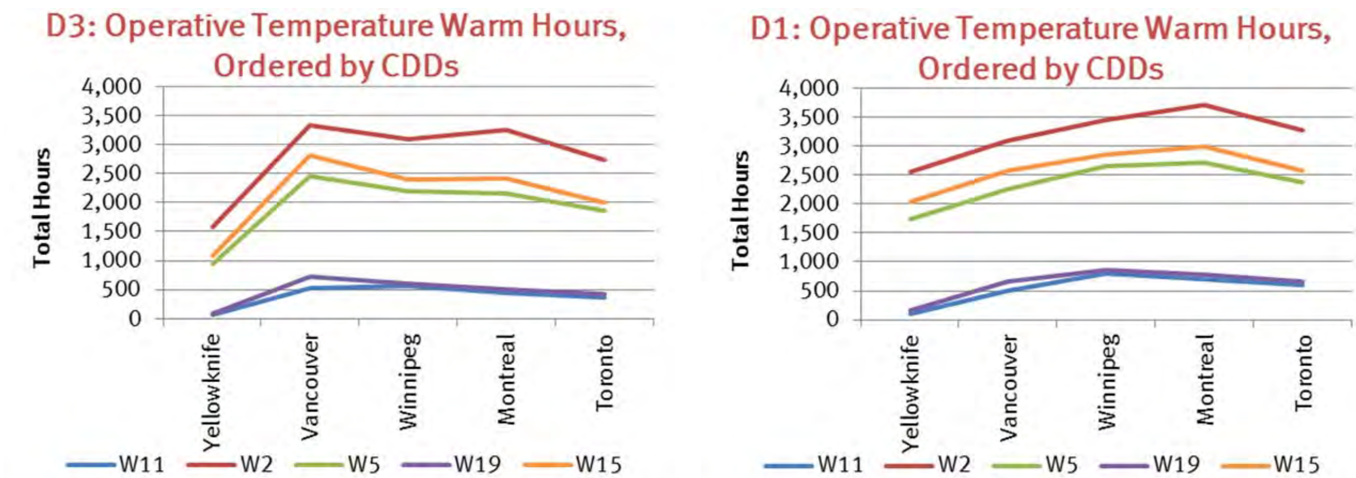


Fig. 9.5.13 D3, Operative temperature warm hours compared with D1

The window surface temperature results are provided in Fig. 9.4.14, Fig. 9.4.15 and Fig. 9.4.16.

The total window surface temperature discomfort hours, shown in Fig. 9.4.14, follow the same profiles as the baseline simulations for all locations and are nearly the same value. Similar to D1, there is a general trend between the ER and thermal comfort, particularly when comparing the cool discomfort hours, in Fig. 9.4.15. This correlation is due to U-values and has been noticed in other iterations; that is, the window with the highest value, W2 (U_{SI}-2.83 [U-0.50]) has the worst thermal comfort, followed by windows W11/W5 (U_{SI}-0.2.0 [U-0.35]) and windows W19/W15 (U_{SI}-0.9 [U-0.16]) demonstrate the best thermal comfort.

The trend is less visible, but generally opposite in warm hours, in Fig. 9.4.16, as a higher ER denotes worse thermal comfort, with a few exceptions. This correlation is due to the SHGC; however, since the warm discomfort hours are an order of magnitude lower than the cool hours, they have less impact on the overall trends.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

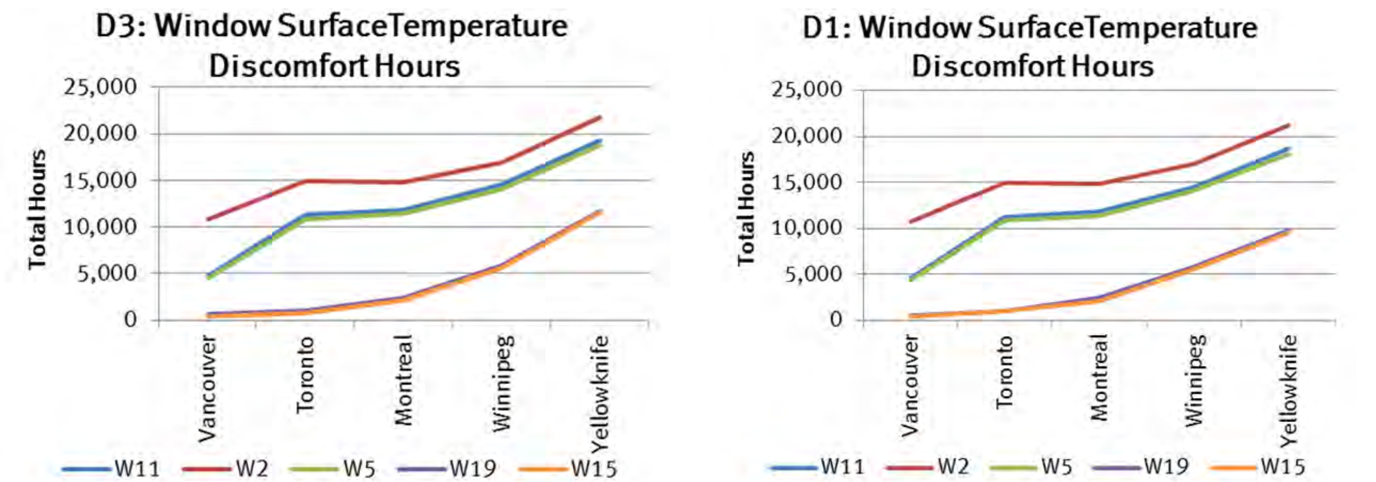


Fig. 9.5.14 D3, Window surface temperature discomfort hours compared with D1

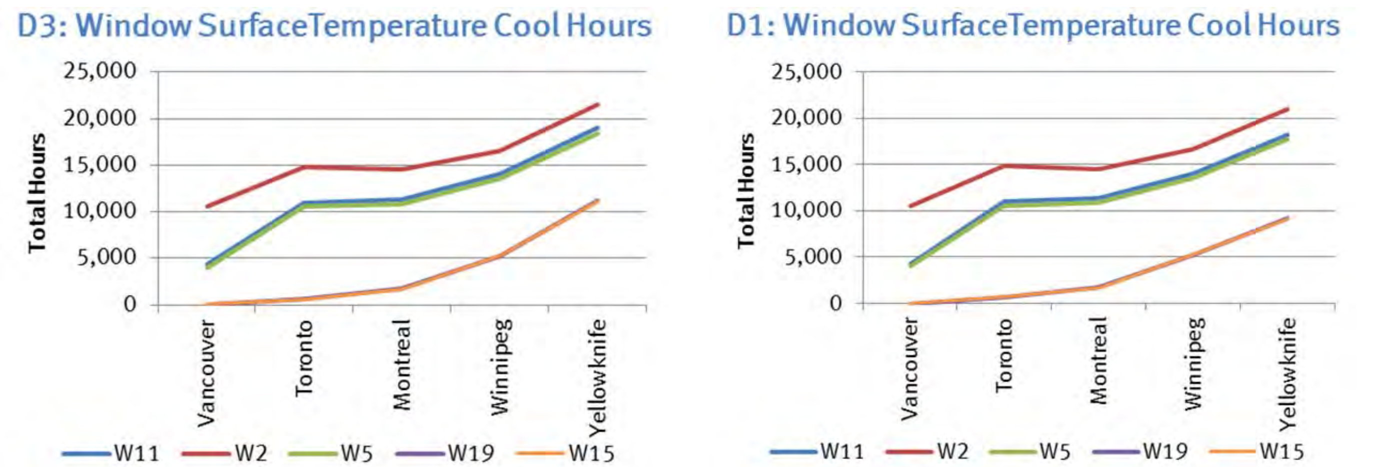


Fig. 9.5.15 D3, Window surface temperature cool hours compared with D1

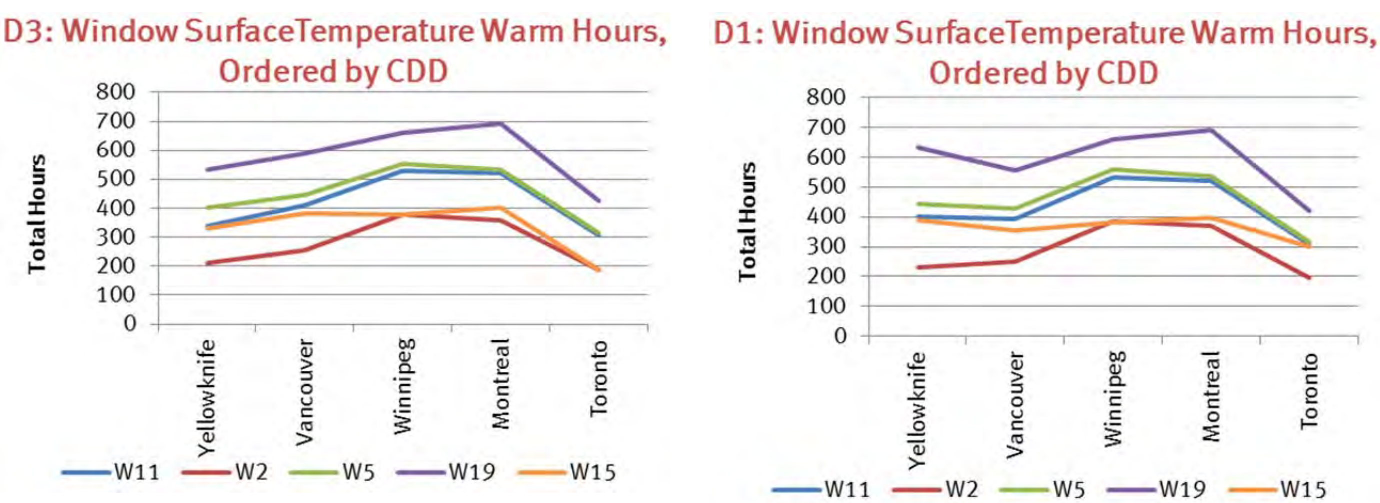


Fig. 9.5.16 D3, Window surface temperature warm hours compared with D1

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Conclusions

The use of electric baseboard heaters instead of a forced-air furnace most significantly affects the operative temperature discomfort hours in Yellowknife, a northern climate zone, because the operative temperature cool hours increase substantially. This is likely because baseboard heaters are less efficient at heating than a mixed-air system. The operative temperature warm hours are not significantly impacted, which is expected since the cooling system was not modified.

The total window surface temperature discomfort hours and profiles for each window did not change much from those of the baseline. The trends observed between a window's ER and thermal comfort performance were similar to the baseline case when electric baseboard heating was used.

9.5.4 Thermal Mass Construction (D4)

In these simulations, the construction parameters for the external walls were modified from the baseline wood-frame construction, to a concrete wall to determine the impact of a construction with high thermal mass. The walls were externally insulated so that the thermal mass would be exposed to the interior, covered only by a layer of drywall.

The operative temperature thermal comfort results are presented in Fig. 9.5.17, Fig. 9.5.18 and Fig. 9.5.19.

With thermally massive walls the overall operative temperature discomfort hours, shown in Fig. 9.5.17, are reduced. However, a trend is visible with respect to windows that have the same SHGC, as windows W5/W15 (SHGC-0.5) and windows W11/W19 (SHGC-0.2) have nearly the same number of discomfort hours. Vancouver is somewhat of an anomaly and will be examined separately.

A high thermal mass construction has a greater capacity to store heat. Therefore, high thermal mass constructions impact the thermal comfort of a space by dampening out the high and low temperatures due to outdoor temperature swings. Heat is absorbed during warm periods to reduce the warm discomfort hours, and is subsequently released during cold periods.

Across all cities the cool hours, shown in Fig. 9.5.18, are reduced to zero except in the case of Yellowknife with window type W2, however, the magnitude (35 hours per year) is still so low that it can be considered zero. The reductions in all locations are a result of the heat absorption and release described above.

Similarly, the warm hours are reduced by the thermal mass dampening the temperature swings. In all locations except Vancouver, the warm hours are reduced significantly, though are still not zero. This is likely due to the operative temperature definition discussed earlier, which makes the operative temperature discomfort dominated by warm hours.

Vancouver is the only city where the impact of the thermal mass does not significantly change the thermal discomfort hours from the baseline scenario. This is likely due to Vancouver's temperate climate that has much fewer temperature swings than the other cities included in the study, thereby reducing the opportunity for thermal mass to impact thermal comfort. The annual outdoor dry-bulb temperatures for the five locations are shown in Fig. 9.5.20, in order to see how the annual range of temperatures for Vancouver is significantly lower than all other locations.

As seen in the earlier comparison between all iterations (Fig. 9.4.34), the most significant improvement in overall thermal comfort occurs with higher ER windows; this suggests that if the thermal comfort is addressed by a high performing window, adding thermal mass is less important. The overall thermal discomfort hours, in Fig. 9.5.17, and the warm thermal discomfort hours, in Fig. 9.5.18, show similar trends to the baseline simulation in terms of ER, however, the cool hours are so low (or zero) that it is not possible to determine significant trends.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

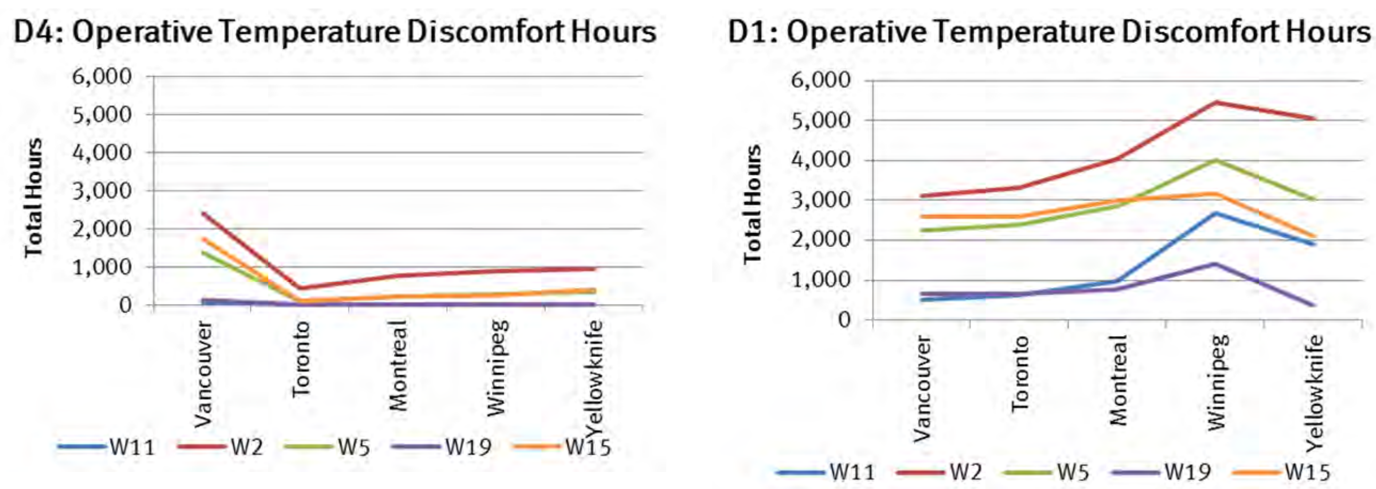


Fig. 9.5.17 D4, Operative temperature discomfort hours compared with D1

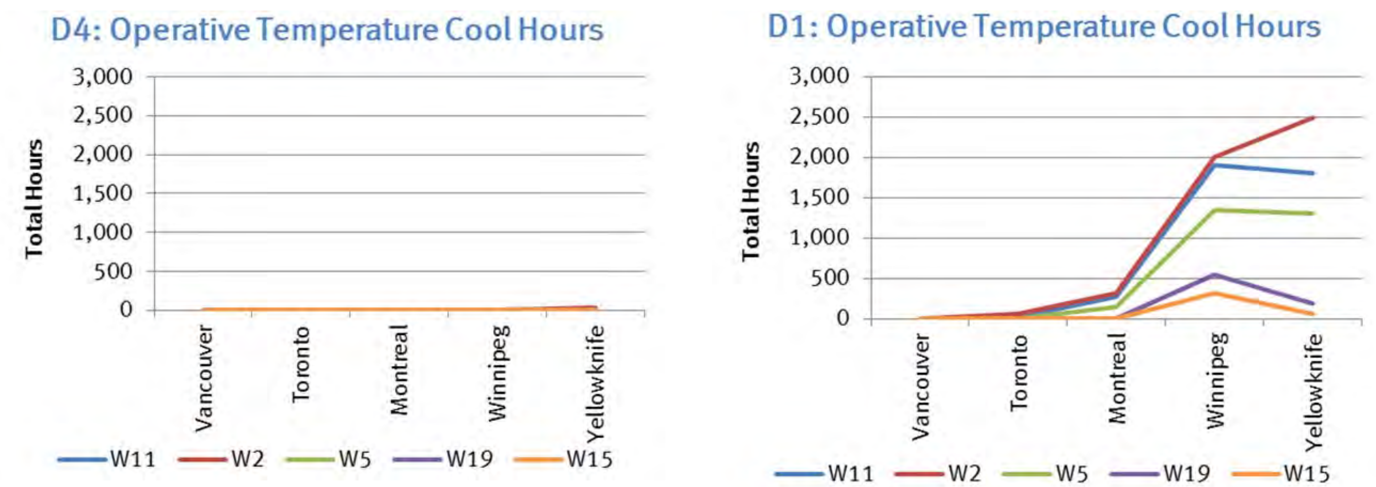


Fig. 9.5.18 D4, Operative temperature cool hours compared with D1

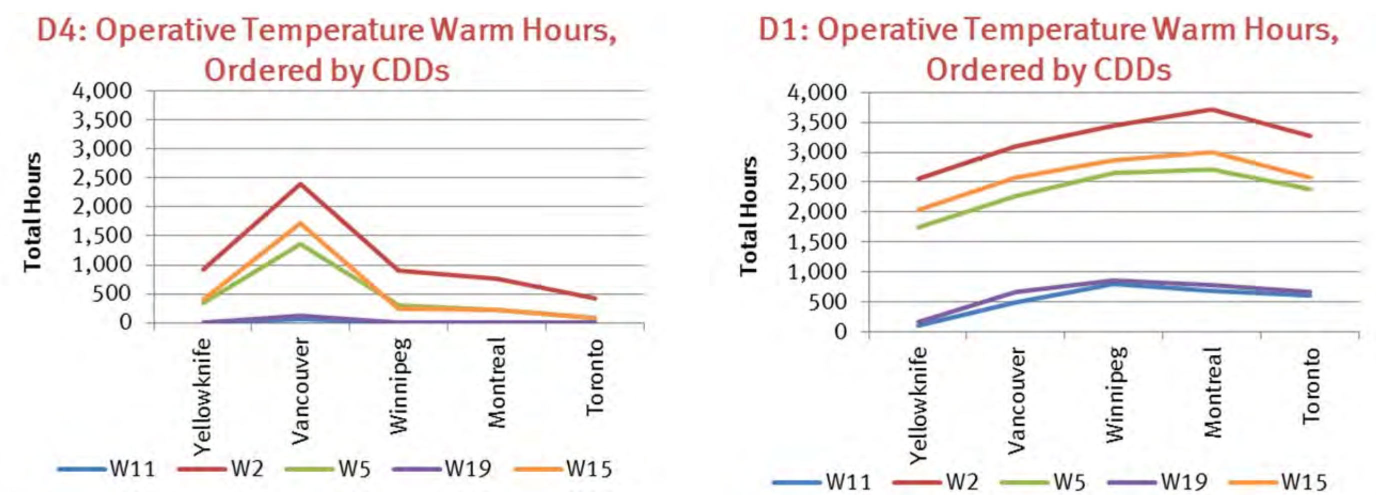


Fig. 9.5.19 D4, Operative temperature warm hours compared with D1

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

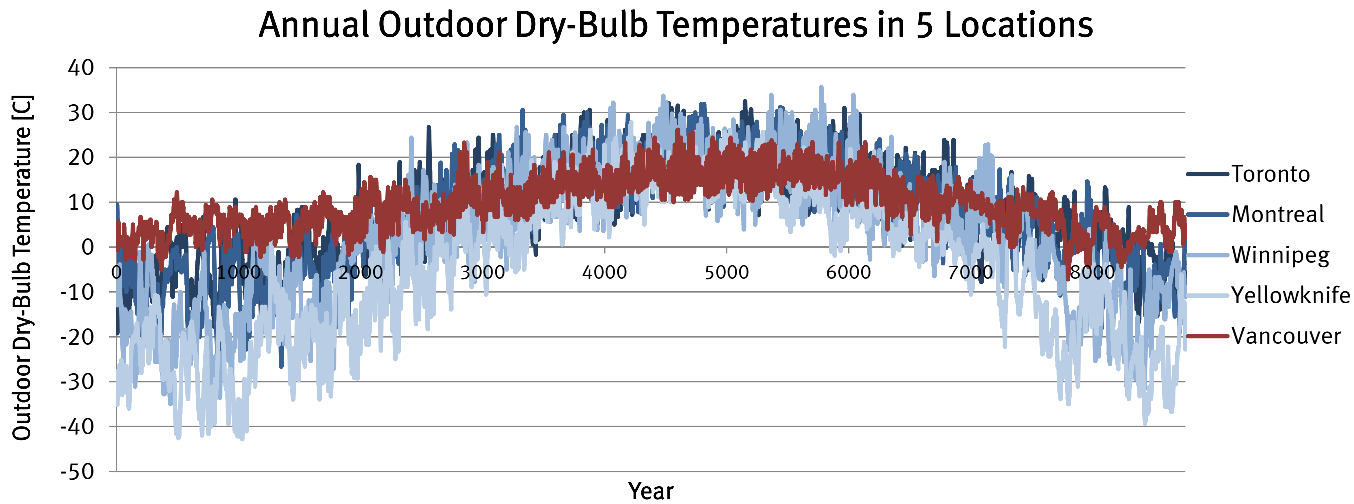


Fig. 9.5.20 5 Cities, Annual temperature outdoor dry-bulb temperatures

The window surface temperature thermal comfort results are presented in Fig. 9.5.21, Fig. 9.5.22 and Fig. 9.5.23.

The total window surface temperature discomfort hours and profiles are very similar to the baseline case. Similar to D1, there is a general trend between the ER and thermal comfort, particularly when comparing the cool discomfort hours, in Fig. 9.5.22. This correlation is due to U-values and has been noticed in other iterations; that is, the window with the highest value, W2 (U_{SI}-2.83 [U-0.50]) has the worst thermal comfort, followed by windows W11/W5 (U_{SI}-0.2.0 [U-0.35]) and windows W19/W15 (U_{SI}-0.9 [U-0.16]) demonstrate the best thermal comfort.

The trend is less visible, but generally opposite in warm hours, in Fig. 9.5.23, as a higher ER denotes worse thermal comfort performance, with a few exceptions. This correlation is due to the SHGC; however, since the warm discomfort hours are an order of magnitude lower than the cool hours, they have less impact on the overall trends.

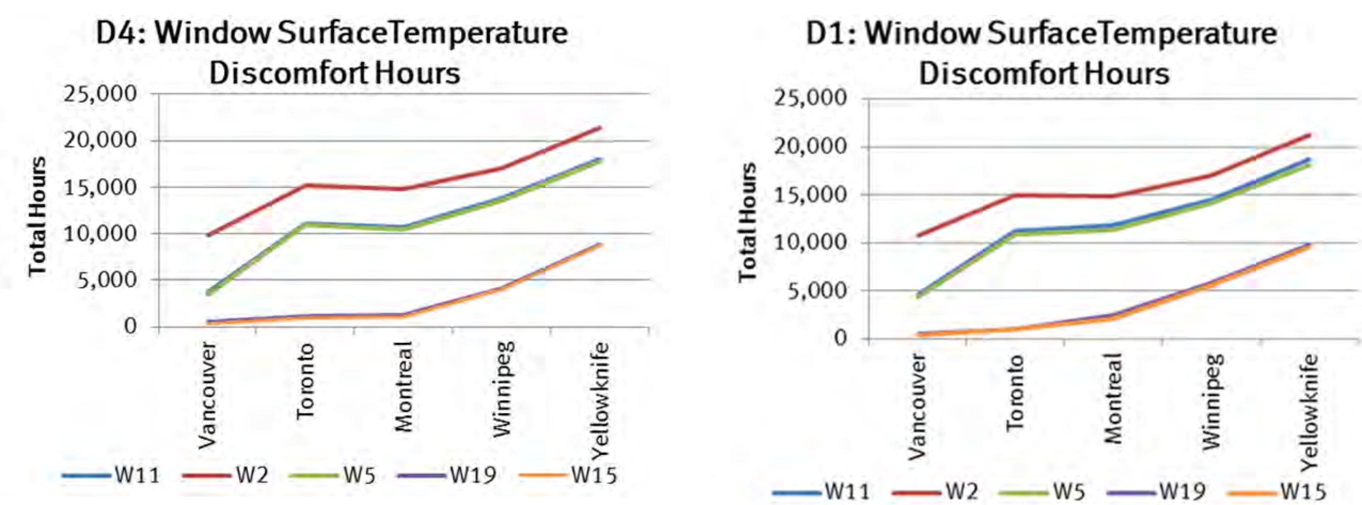


Fig. 9.5.21 D4, Window surface temperature discomfort hours compared with D1

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

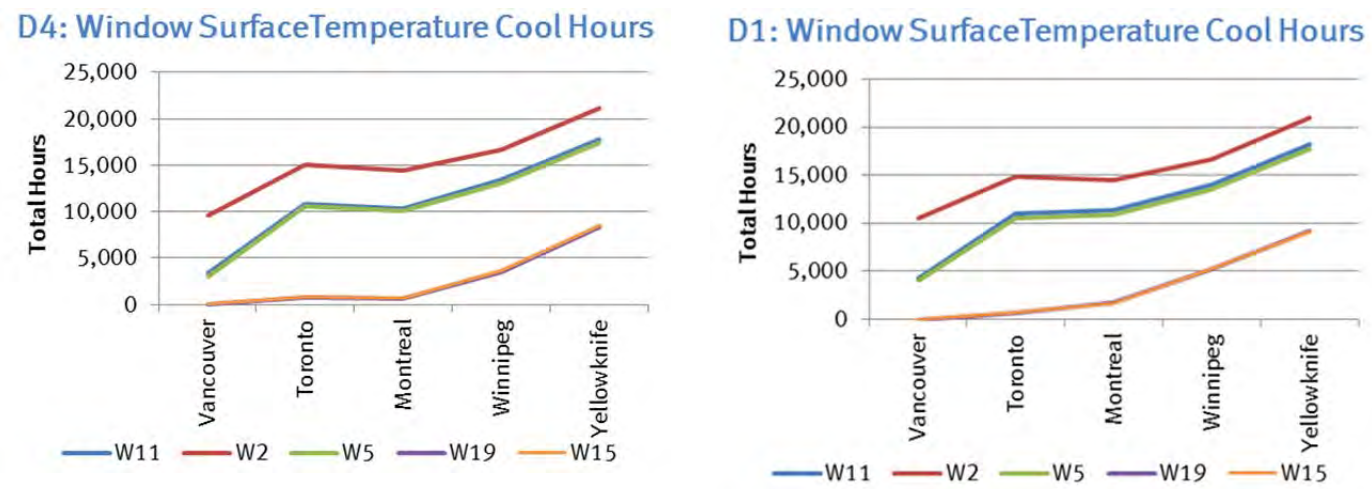


Fig. 9.5.22 D4, Window surface temperature cool hours compared with D1

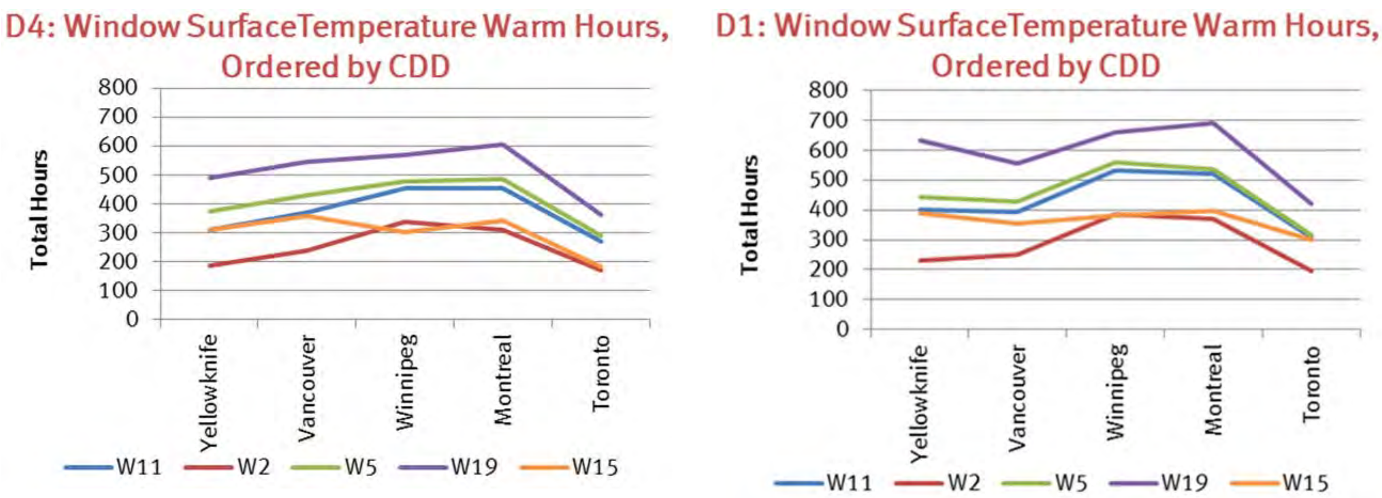


Fig. 9.5.23 D4, Window surface temperature warm hours compared with D1

Conclusions

Thermally massive construction elements that are exposed to the interior significantly improve the level of thermal comfort, when evaluated by operative temperature. Operative temperature warm and cool hours are both reduced by the effect of the thermal mass dampening out temperature swings; however, this effect is less noticeable in Vancouver due to its more temperate climate with fewer cyclical highs and lows. Thermal discomfort caused by extreme window surface temperatures is not significantly affected through the introduction of thermal mass. Although thermal comfort is improved, the improvements do not show any major differences from the trends outlined in the baseline simulations.

9.5.5 Building Rotation (D5)

These simulations examined the impact of rotating the building through the cardinal axes, which primarily caused variations in solar gain experienced in each room. Three cities are examined: Vancouver, Toronto and Yellowknife, representing increasingly cold climate conditions. Three rooms are examined: the bathroom (facing a single direction), the bedroom (a corner room facing two directions) and the living room (an end room facing three directions).

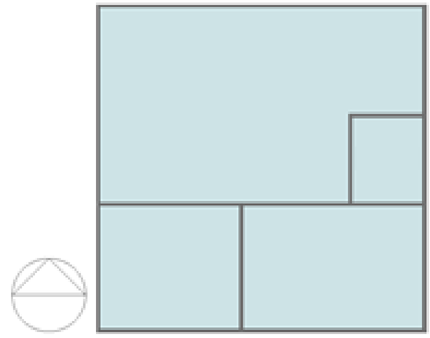
	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Bathroom

The initial analysis focuses on the bathroom because it is the only room that is located on a single façade; therefore, rotating it through the four axes will isolate the impact of facing each direction. The direction that the bathroom faces for each rotation is described in Table 9.5.2.

Table 9.5.2 Bathroom rotations

Simulation	0 degrees	90 degrees	180 degrees	270 degrees
Bathroom faces:	East	South	West	North



The total operative temperature discomfort hours are shown in Fig. 9.5.24 for the five windows, ordered by lowest to highest ER for each location. Similar to previous iterations, a higher ER tends to indicate better thermal comfort performance, with the exceptions of the windows with the lowest and highest ERs, W11 and W15 respectively.

However, rotating the building does impact the overall thermal comfort level, because for each window the four bars (showing the results of the four rotations) are not equal. There is no consistent pattern for which rotation shows the most discomfort hours because the variable solar gains affect both warm and cool hours. More specifically, the increased solar gain on the south façade would cause both increased warm hours and decreased cool hours, and the ratio between the two are not consistent across all of the iterations. Therefore, the warm and cool hours are reviewed separately in further detail in a subsequent section.

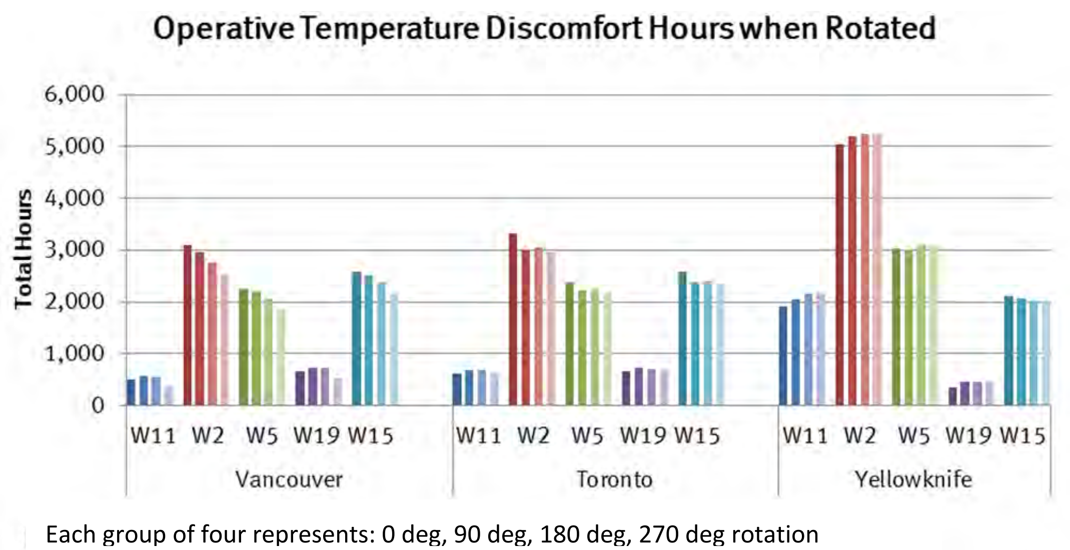


Fig. 9.5.24 D5, three cities, Bathroom operative temperatures when rotated

The window surface temperature discomfort hours are shown in Fig. 9.5.25 and also show no correlation between the ER and the level of thermal comfort. However, there is a consistent relationship between the direction that the bathroom faces and the discomfort hours that are visible across all window types. Each 90-degree simulation (when the bathroom faces south) has the highest number of discomfort hours. Conversely, each 270-degree simulation (when the bathroom faces north) has the lowest number of discomfort hours. This is due to the solar gains; the south-facing windows consistently heat up enough to cause a large enough increase in warm discomfort hours to over-ride any cool discomfort hour reduction. The reverse is true for the north-facing windows.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

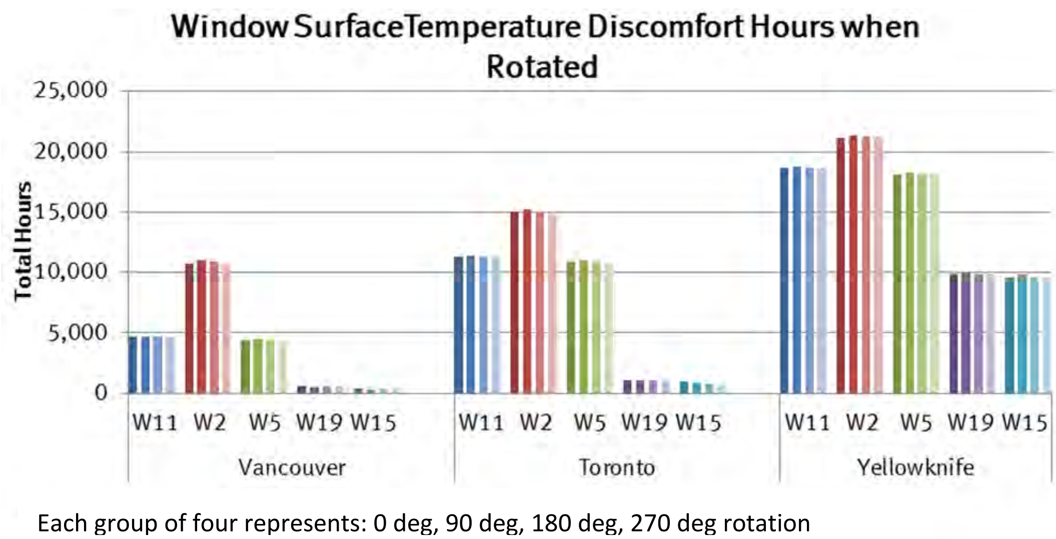


Fig. 9.5.25 D5, three cities, Bathroom window surface temperatures when rotated

Bedroom

Since the bathroom results showed little variation between locations, the analysis is only provided for Vancouver. The parameters of the bedroom are described in Table 9.5.3.

Table 9.5.3 Bedroom window, wall and floor areas

Original Rotation	Wall Area	Window Area	Floor Area
South	10.8 m^2	1.6 m^2	16.4 m^2
West	9.5 m^2	1.4 m^2	

The directions that the bedroom walls face for each rotation is described in Table 9.5.4

Table 9.5.4 Bedroom rotations

Simulation	0 degrees	90 degrees	180 degrees	270 degrees
Bedroom faces:	South and West	North and West	North and East	South and East

The total operative temperature discomfort hours for the bedroom are shown for each rotation in Fig. 9.5.26.

In general, when the bedroom was in the south-west corner of the house it experienced the highest level of operative temperature discomfort hours; the lowest level of discomfort occurred when it faced north-east. This is caused by the level of solar gains experienced when facing those directions, in the south-west higher solar gains caused more warm discomfort hours, while in the north-east the solar gains were at their lowest. These trends were captured in the overall operative temperature discomfort hours since they are highly dependent on the warm discomfort hours.

The trends for the south-east and north-west are more complex to analyze because the bedroom has two windows facing two different directions, so the respective warm/cool hours change with the different window types.

Once again, these results highlight the fact that operative temperature discomfort is dominated by warm hours rather than cool hours. Fig. 9.5.27 shows this more clearly in a histogram, as the cool hours and the warm hours are separated to the left and right of the graph, respectively.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Similar to earlier findings, the ER has a general relationship to thermal comfort, where the three windows W2, W5 and W19 show improved thermal comfort with a higher ER. However, the windows with the lowest and highest ERs, W11 and W15, respectively, do not follow this trend.

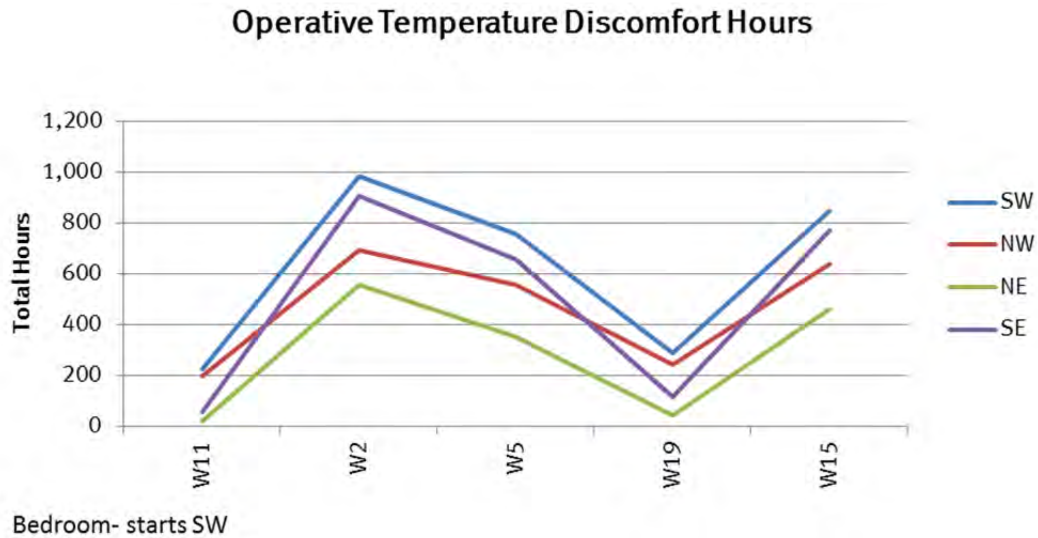
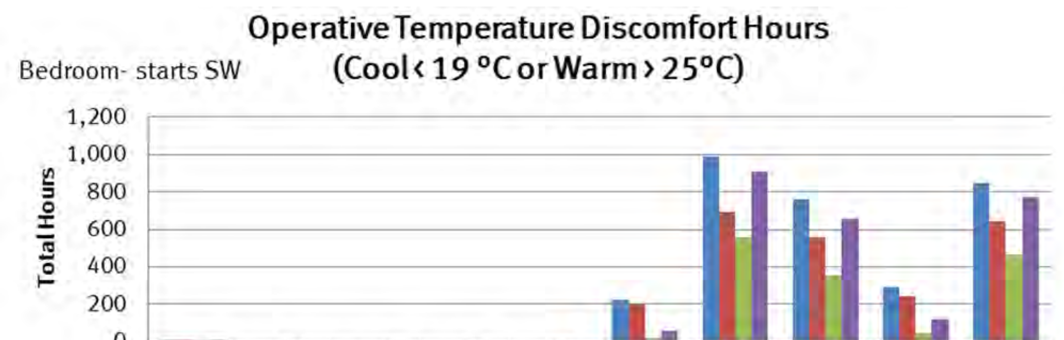


Fig. 9.5.26 D5, Bedroom operative discomfort hours when rotated



	<19 W11	<19 W2	<19 W5	<19 W19	<19 W15	>25 W11	>25 W2	>25 W5	>25 W19	>25 W15
SW	1	0	0	0	0	225	987	758	289	848
NW	1	0	0	0	0	198	693	558	244	642
NE	2	0	0	0	0	19	558	356	43	464
SE	2	0	0	0	0	59	909	657	116	772

Fig. 9.5.27 D5, Bedroom operative warm or cool hours when rotated

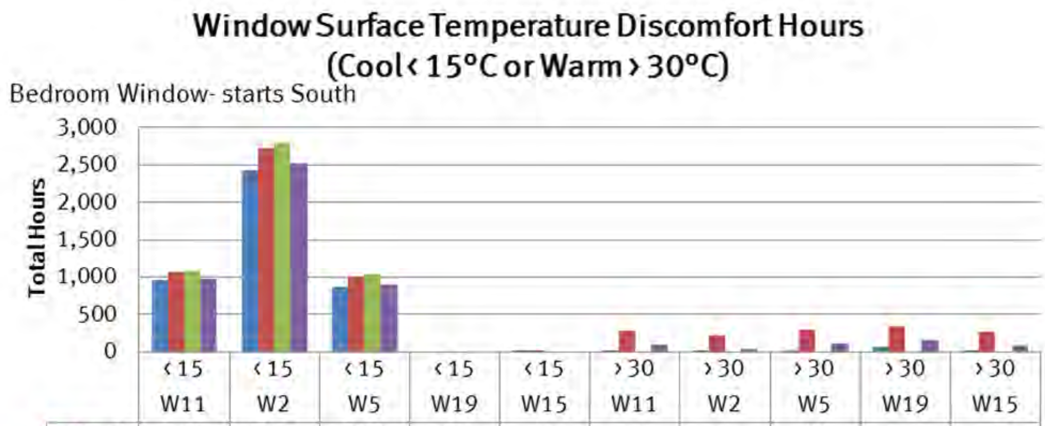
In the window surface temperature analysis, only one of the two bedroom windows was examined: the "south" window highlighted in Fig. 9.3.2 in the original study description.

A similar histogram in Fig. 9.5.28 for the window surface temperatures once again corroborates that while operative temperature is consistently warm, window surface temperatures are dominated by cool hours. Therefore, the results are opposite to operative temperature results; for each window type the south-facing windows have the fewest cool hours (due to the highest solar gains), followed by the west, east then north facades.

Although there are trends between the window orientation and the level of thermal comfort, there is no correlation between

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

the ER and the thermal comfort.



	< 15 W11	< 15 W2	< 15 W5	< 15 W19	< 15 W15	> 30 W11	> 30 W2	> 30 W5	> 30 W19	> 30 W15
South	962	2425	862	0	1	11	1	21	57	4
West	1067	2717	1013	0	3	277	212	294	336	269
North	1077	2797	1031	0	0	0	0	0	0	0
East	972	2515	891	0	0	101	29	107	150	74

Fig. 9.5.28 D5, Bedroom window surface warm or cool hours when rotated

Living Room

Similar to the bedroom analysis, the data below is only provided for Vancouver. The parameters of the living room are described in Table 9.5.5.

Table 9.5.5 Living room window, wall and floor areas

Original Rotation	Wall Area	Window Area	Floor Area
East	8.2 m^2	1.2 m^2	52.8 m^2
North	24.5 m^2	3.8 m^2	
West	15.0 m^2	2.2 m^2	

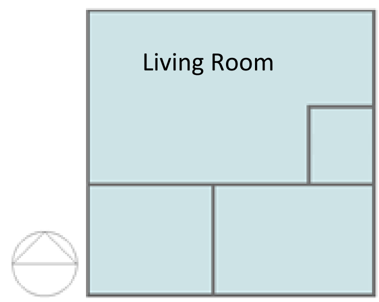


Table 9.5.6 describes the directions that the living room walls are exposed to for each rotation. The primary direction that the largest wall faces in each rotation is also noted.

Table 9.5.6 Living room rotations

Simulation	0 degrees	90 degrees	180 degrees	270 degrees
Living room faces:	West, North (primary) & East	North, East (primary) & South	East, South (primary) & West	South, West (primary) & North

The total operative temperature discomfort hours are summarized in Fig. 9.5.29. The trends are more complex to dissect since there are now three walls under analysis.

For three of the window types: W2, W5 and W15, the discomfort hours are highest when the primary living room wall faces south. The common factor between these windows is a higher solar heat gain coefficient, of SHGC-0.64, SHGC-0.5 and SHGC-0.5, respectively. This is similar to the results seen for the bedroom, where the warm hours caused by high solar gains on the south dominated the operative discomfort hours.

However, for windows W11 and W19 that allow less solar gain due to a SHGC of 0.2, the living room experiences the highest

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

discomfort when the primary wall faces west. This is probably due to the more complex geometry and the analysis of three walls at once. When the primary wall faces west, the second largest wall faces south; therefore, the gains from the south window still have significant impact on the total. With the lower SHGC, the total amount of solar gain admitted to the space will decrease; as a result, the second largest window will have more impact on the total.

Although the variations between the orientations were not as clear for the living room (three external walls) as for the bedroom and bathroom, Fig. 9.5.30 shows that the total operative temperature discomfort hours are still dominated by warm hours.

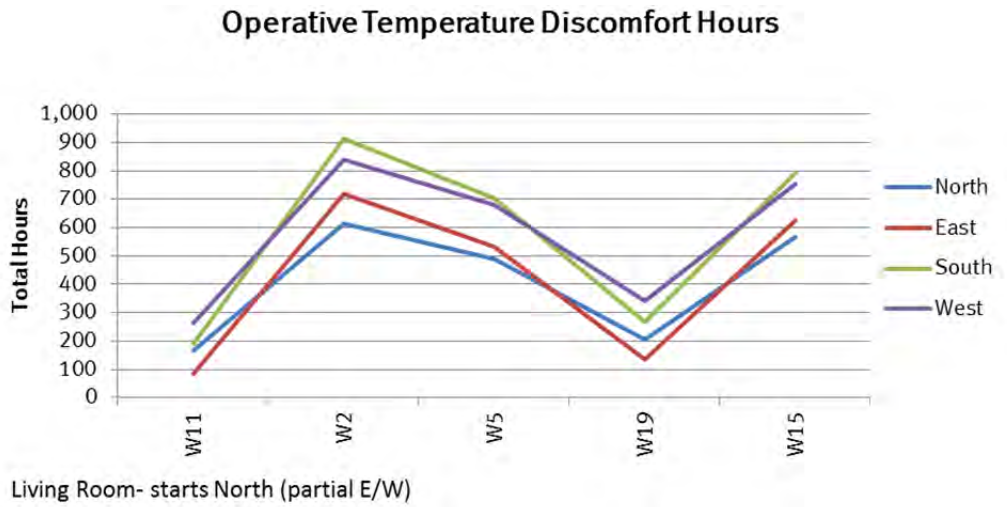
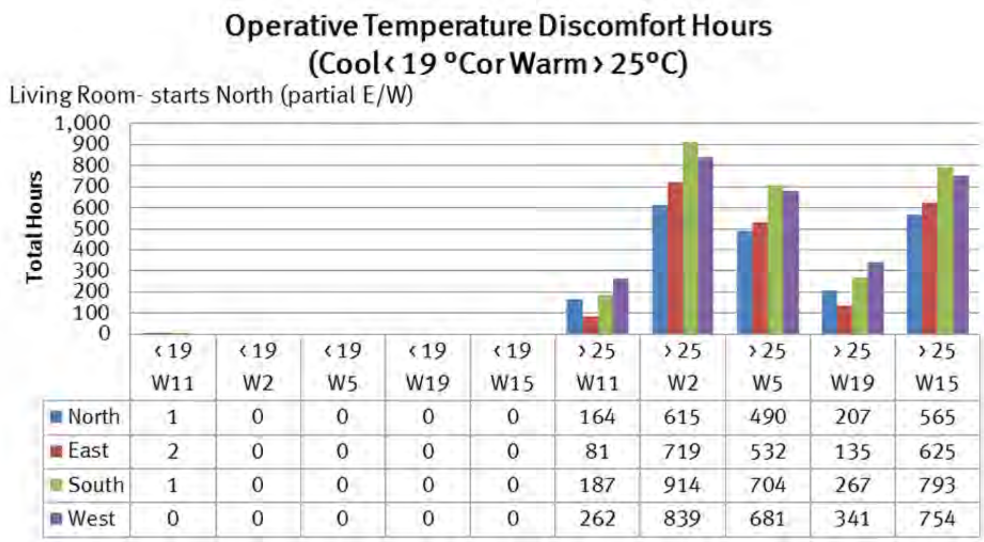


Fig. 9.5.29 D5, Living room operative discomfort hours when rotated



	< 19 W11	< 19 W2	< 19 W5	< 19 W19	< 19 W15	> 25 W11	> 25 W2	> 25 W5	> 25 W19	> 25 W15
North	1	0	0	0	0	164	615	490	207	565
East	2	0	0	0	0	81	719	532	135	625
South	1	0	0	0	0	187	914	704	267	793
West	0	0	0	0	0	262	839	681	341	754

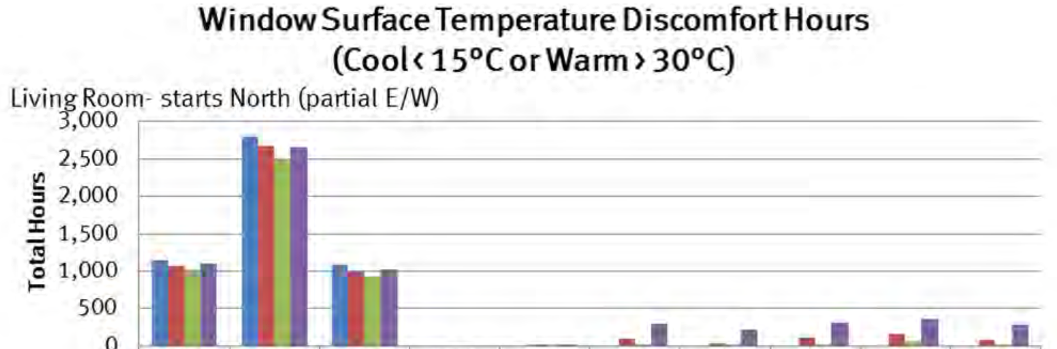
Fig. 9.5.30 D5, Living room operative warm or cool hours when rotated

The window surface temperature results for the living room are presented in Fig. 9.5.31 when rotated through the cardinal axes. The window examined was the one that originally faces north, as described in Fig. 9.3.2.

The findings are the same as with the bedroom analysis, which would be expected since each window faces a single direction so is not affected by the more complex geometry of the individual rooms. The window surface temperature discomfort hours are still dominated by cool hours, the highest of which occur when the window faces north due to the least amount of solar gains and the lowest when the window faces north.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Although there are trends between the window orientation and the level of thermal comfort, there is no correlation between the ER and the thermal comfort.



	‹15 W11	‹15 W2	‹15 W5	‹15 W19	‹15 W15	›30 W11	›30 W2	›30 W5	›30 W19	›30 W15
North	1145	2805	1085	0	0	0	0	0	0	0
East	1069	2672	993	0	8	103	29	107	150	73
South	1020	2496	930	0	1	14	2	24	65	7
West	1103	2660	1016	0	1	289	221	307	353	283

Fig. 9.5.31 D5, Living room window surface warm or cool hours when rotated

Conclusions

Rotating the building around the cardinal axes primarily impacts thermal comfort due to the varying level of solar gains. As expected, the south and west façades will experience higher levels of solar radiation, while the north receives the lowest as would be expected. The former experience the highest number of warm discomfort hours and the fewest cool discomfort hours; because both the warm and cool hours are affected by different magnitudes, the total discomfort hours do not increase or decrease consistently across rotations. A higher ER correlates to better thermal comfort for all windows other than W11 and W19, similar to findings from other simulations.

Examining rooms individually further demonstrated the previously outlined relationships, however, rooms that had more than one external wall were more challenging to analyze because of the varying impact of the multiple facades.

9.5.6 Two-Storey (E1)

The two-storey house, described in Section 9.3.1 was simulated to examine the impact of adding a second storey on thermal comfort conditions. Two simulations were performed; the first used the same mechanical systems as the baseline single-storey simulation so that only the geometry was different (D1), while the second incorporated natural ventilation instead of mechanical cooling, similar to the single-storey natural ventilation model (D2). This second option was chosen in order to examine any potential effects of heat rising to the upper storey.

Since the single- and two-storey houses have a different number of rooms (four and 12, respectively), summing the discomfort hours (8760 per year) across all rooms would give different totals (4 x 8,760 = 35,040 versus 12 x 8,760 = 105,120). In a side-by-side comparison this would skew the results and suggest that the single-storey house always had better thermal comfort. Therefore, for any comparison between the houses of different sizes, the number of discomfort hours has been divided by the number of rooms, for consistency.

The average operative temperature discomfort hours per room are displayed in Fig. 9.5.32, Fig. 9.5.33 and Fig. 9.5.34, compared to the baseline simulation.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

The total operative discomfort hours in Fig. 9.5.32 follow the same profile as the baseline simulation, and are around the same order of magnitude. Since the rooms have significantly different geometry (e.g. in the two-storey house there are hallways that have little exterior wall surface) the individual rooms are analyzed separately in a subsequent section.

The operative temperature cool hours profile from Fig. 9.5.33 are also similar to the baseline simulation, however, the number of hours per room is lower. This is because a significant amount of heat loss (causing cooler temperatures) occurs through the roof, via the attic and through the basement. In the single-storey model, each room is connected to both the attic and the basement. However, in the two-storey model, each room is connected to either the attic or the basement; therefore, the loss per room is decreased. Effectively, in the two-storey model the ratio of enclosure-to-floor area is decreased, thereby decreasing the impact of the enclosure on overall losses. This is also examined later when individual rooms are analysed.

Similarly, the operative temperature warm hours per room, shown in Fig. 9.5.34, follow similar trends to the single-storey baseline model, yet at a lower order or magnitude due to the higher number of rooms. As seen in earlier iterations, the warm hours are related to the SHGC of the windows.

The trends between a window's ER and its thermal comfort performance are also the same for the two-storey house as in the baseline single-storey simulations. In general, a higher ER corresponds to better thermal comfort performance, however, not all windows follow this trend.

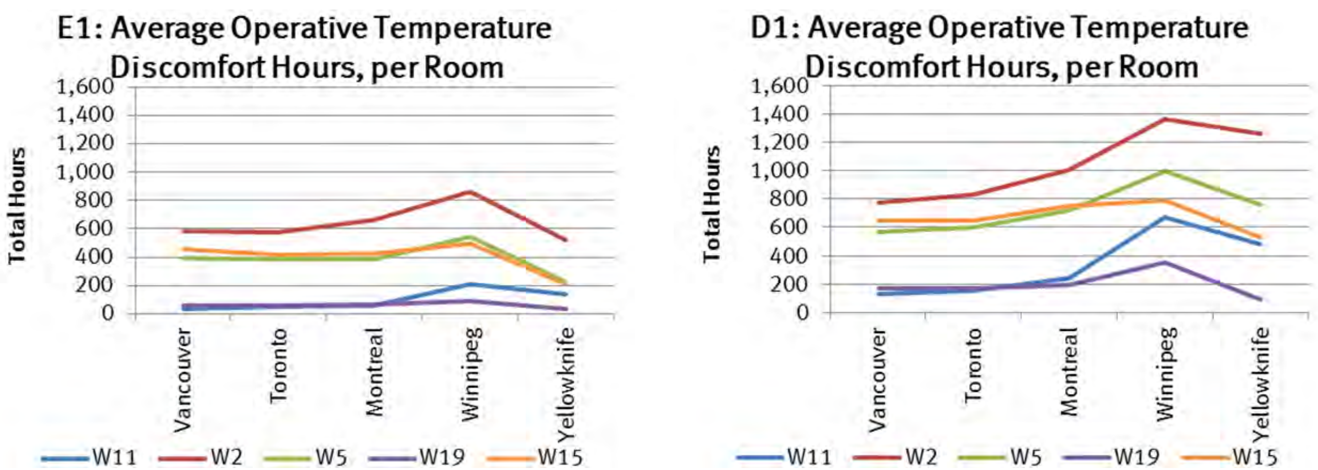


Fig. 9.5.32 E1, Operative temperature discomfort hours per room compared with D1

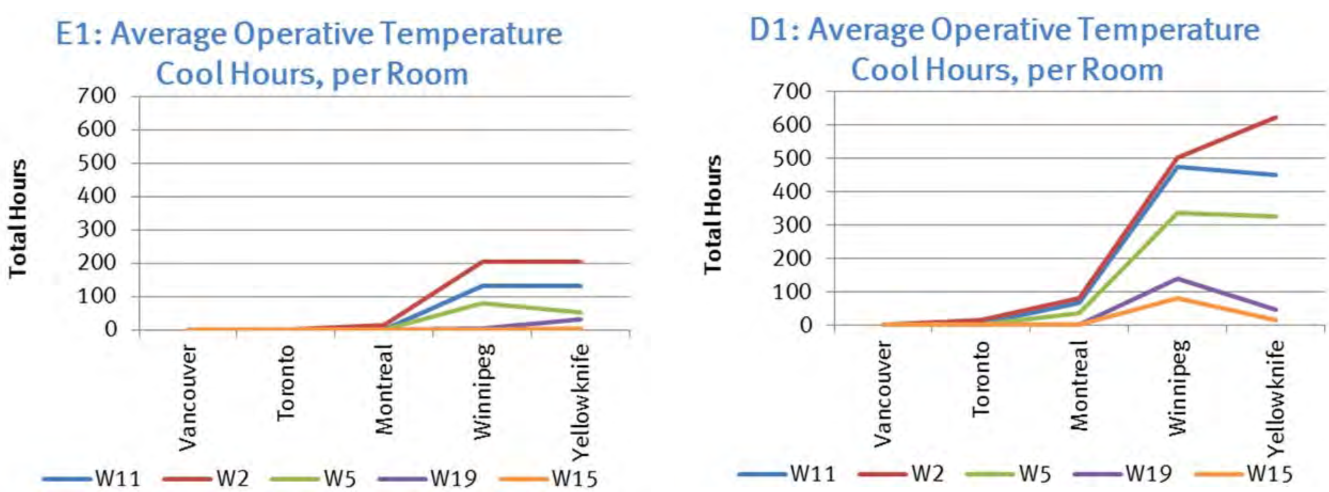


Fig. 9.5.33 E1, Operative temperature cool hours per room compared with D1

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

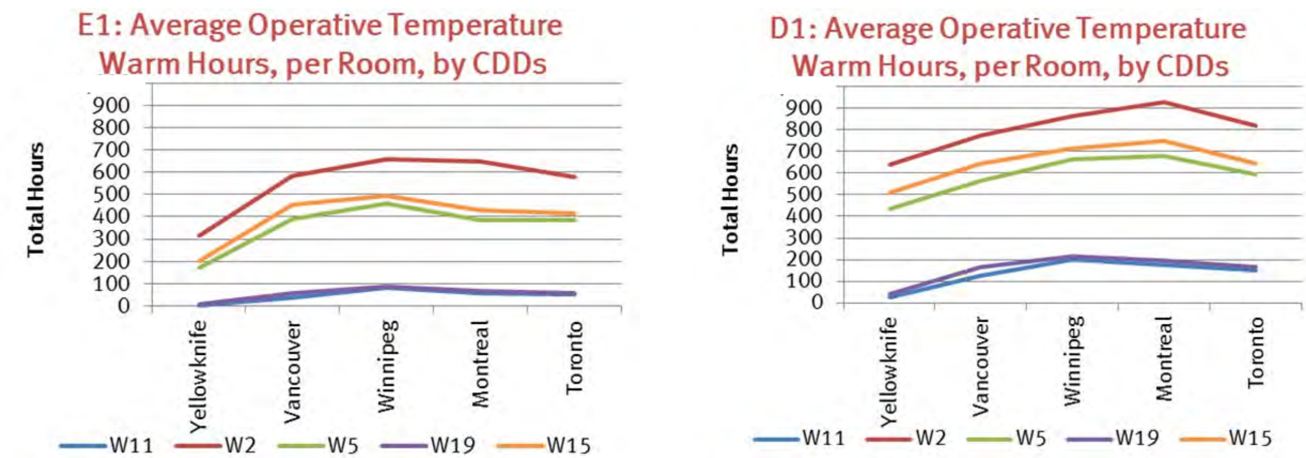


Fig. 9.5.34 E1, Operative temperature warm hours per room compared with D1

For the window surface temperature analysis, a window was selected on each façade on both the upper and lower levels, as indicated in Fig. 9.3.2. Therefore, as the two-storey house analysis includes eight windows while the single-storey only included four, the number of discomfort hours has been divided by the number of windows to allow for consistent comparison.

The average window surface temperature discomfort hours per window are displayed in Fig. 9.5.35, Fig. 9.5.36 and Fig. 9.5.37 compared to the baseline simulation. The total window surface temperature discomfort hours per window, shown in Fig. 9.5.35, are very similar between the single- and two-storey houses. This is expected since the windows face a single direction so are not affected by changing internal geometry; in other words, the main difference between the two scenarios is that the two-storey house examined twice as many windows, however, by dividing the results by the number of windows this effect was negated.

As seen in previous simulations, the window surface temperature discomfort hours are dominated by cool hours, therefore, the trends seen in Fig. 9.5.36 are also nearly identical between the single- and two-storey houses. The relationship between a window's U-value and its thermal comfort performance also remains the same for these simulations.

The window surface temperature warm hours in Fig. 9.5.37 vary slightly from the baseline simulation, but the variance is quite small (within 10% for most cases). As well, since the warm discomfort hours are an order of magnitude smaller than the cool hours, they do not significantly impact the overall discomfort hours.

The thermal comfort performance of the windows follow the same trends with respect to the ER as the baseline case, where in general, a higher ER indicates a better performance.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

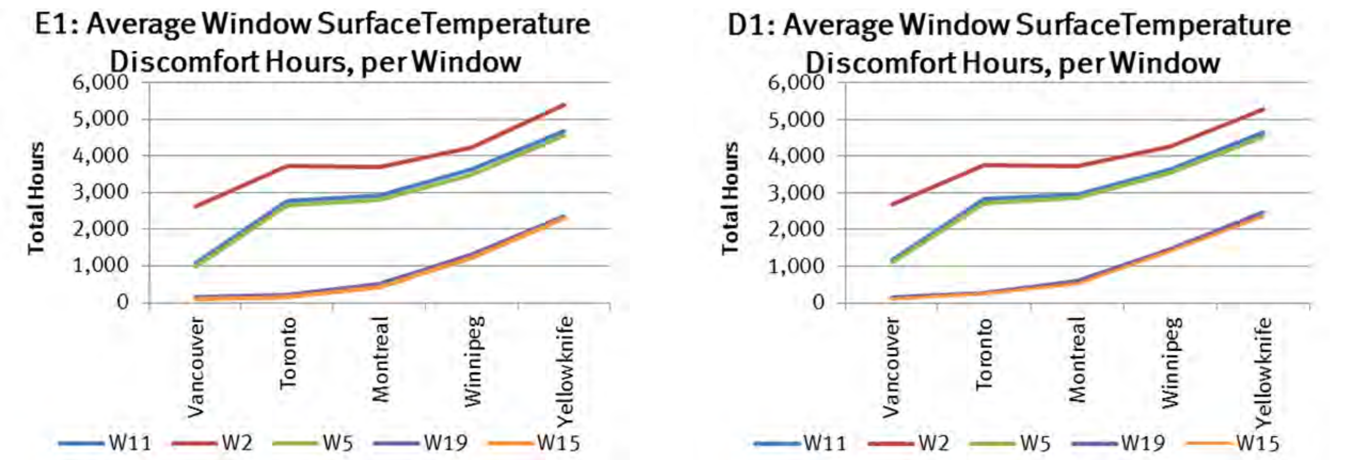


Fig. 9.5.35 E1, Average window surface temperature discomfort hours compared with D1

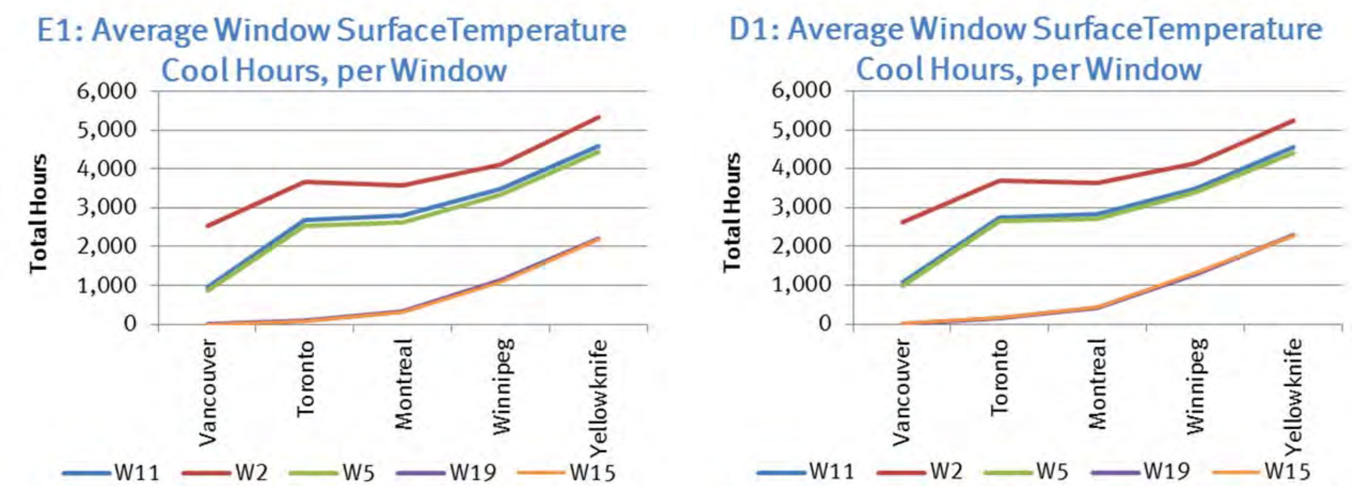


Fig. 9.5.36 E1, Average window surface temperature cool hours compared with D1

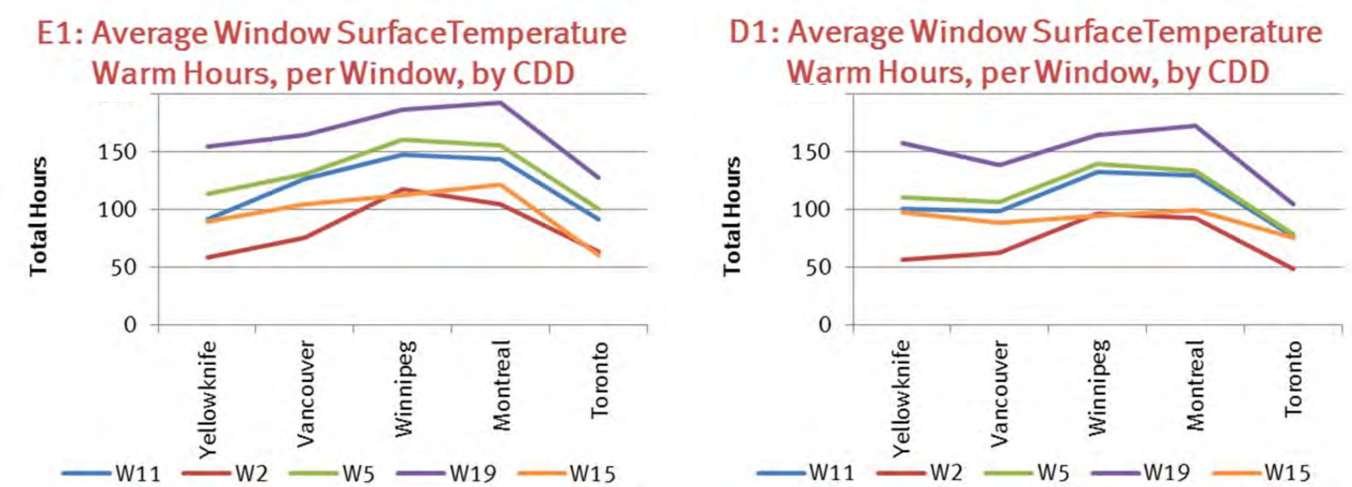


Fig. 9.5.37 E1, Average window surface temperature warm hours compared with D1

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Room-by-Room

The results from the two-storey house can also be reviewed for each individual room to better understand how their individual parameters are affecting the thermal comfort within the space. The geometry is examined, particularly the size of the room and the external wall and window surface area with respect to the room size. The results are comparable to those for the single-storey house, provided in Fig. 9.4.11 and Fig. 9.4.12.

Fig. 9.5.38 examines the number of hours per year that each room's operative temperature is below 19°C, divided by the area of the room for each window type. The hours that occur in the winter (shown in blue) are separated from those that occur in the summer (shown in green), because the latter would likely not contribute to discomfort, as cool surfaces in the summer can improve rather than detract from thermal comfort. In addition, two geometric parameters are displayed for comparison: the window to floor area ratio, and the exterior wall to floor area ratio. As the window to wall ratio remains constant at 15%, the two ratios follow the same trend when compared across rooms.

The findings for the two-storey house align with those of the single-storey house. For the E1 simulation, in Vancouver's mild climate, all of the rooms experience less than 10 hours per year of cool temperatures, all of which occur during the summer time. Due to the low number of hours, it is difficult to extrapolate significant trends from the data, and there does not appear to be any correlation between either of the ratios displayed on the graph and the discomfort hours. However, it is noticeable that only window type W11 causes any discomfort hours, not unreasonable since it has the lowest ER.

In addition, there are more cool hours in the upper storey than the lower storey; this could be due to the different heat losses to/gains from the adjacent spaces. The upper floor is connected to the attic, an unconditioned space that will transfer heat with the outside air. The lower floor is connected to the basement, a fully conditioned space that is connected to the ground, which experiences fewer temperature fluctuations over the course of the year than the outside air.

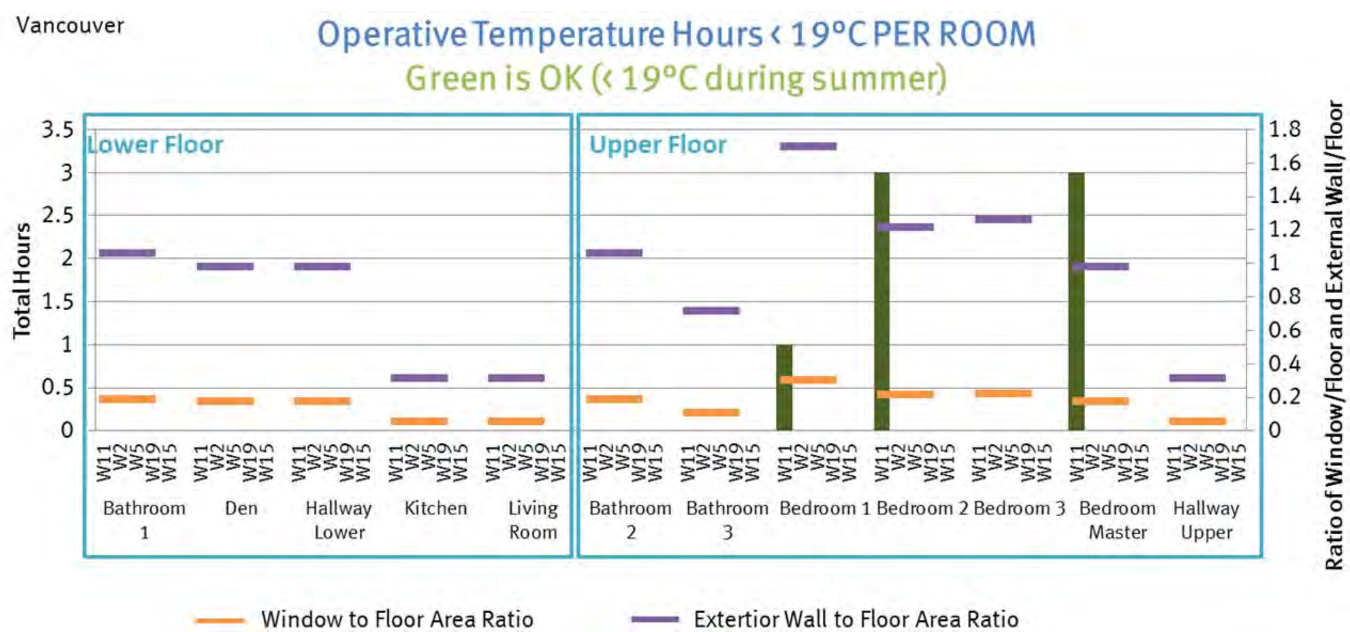


Fig. 9.5.38 E1 Vancouver, Individual room operative temperatures < 19°C

Similarly, the hours over the course of the year that each room's operative temperature is over 25°C, which would be considered "warm," are compared in Fig. 9.5.39. Warm hours occurring in the winter would be less likely to cause discomfort, so are shown in green. The relationship between the room's window area, wall area and floor area are also displayed on the plot.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

As noted in the single-storey analysis, the operative temperature warm hours greatly exceed the cool hours for Vancouver.

There appears to be a trend between the number of warm hours and the ratio between external wall/window area and floor area, particularly in the upper floor where rooms with higher ratios have more warm hours. It is possible that this trend was not visible in the single-storey model because either the lower number of rooms made it more challenging to identify, or in the two-storey model the upper floor gets warmer (due to heat rising through the stairwell) thereby accentuating the trends.

Similar to the single-storey house, there does not appear to be any correlation between the ER and the number of operative temperature warm hours; that is, window type W11 does not consistently have the highest number of discomfort hours.

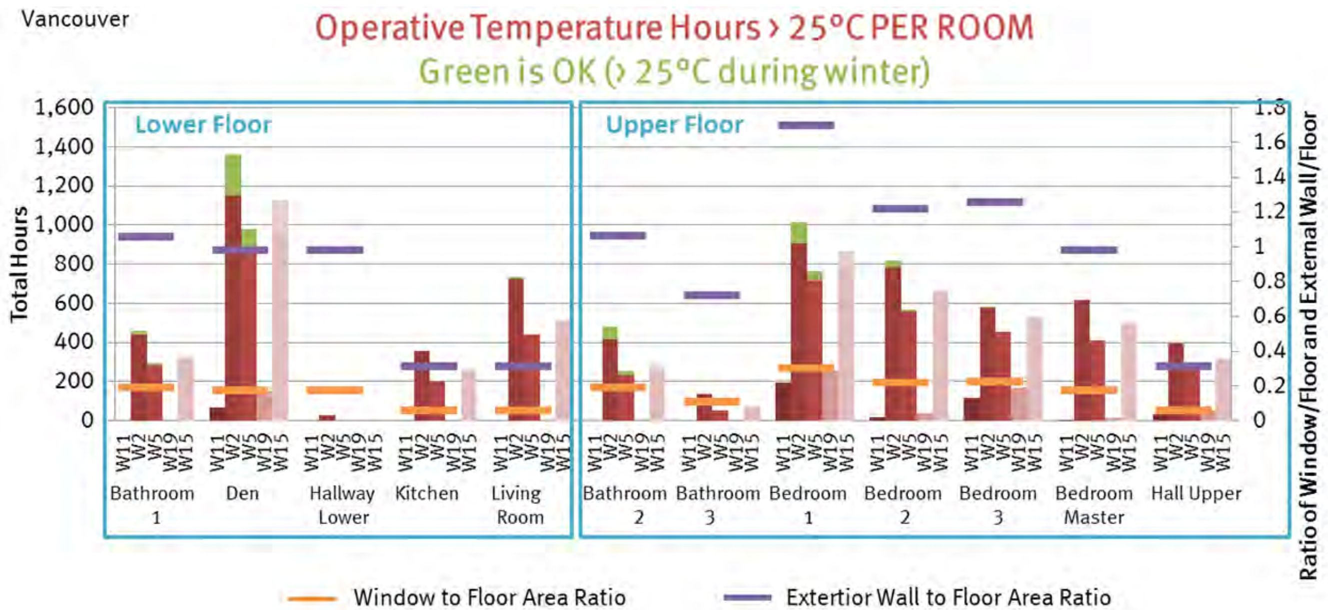


Fig. 9.5.39 E1 Vancouver, Individual room operative temperatures > 25°C

Conclusions

The two-storey house generally showed the same level of thermal comfort per room or per window as a single-storey house. Operative temperature warm and cool hours had the same profiles, although the two-storey house had slightly lower discomfort hours, likely due to the lower enclosure-to-interior volume ratio.

The total window surface temperature discomfort hour profiles also remained the same as the single-storey, still dominated by the significantly higher number of cool hours than warm hours. The latter profiles changed slightly, due to the difference in average window size between the two houses.

When operative temperature discomfort was examined at a room-by-room level for Vancouver, the results also appeared similar to the single-storey house. The cool hours have a minor correlation to the ER, as window type W11 (with the lowest ER) was the only window to cause any uncomfortable temperatures below 19C.

There was no direct correlation between the ER and the warm hours; however, a higher level of warm hours did occur in rooms with higher exterior-to-floor area ratios, particularly on the upper level.

9.5.7 Two-Storey Natural Ventilation (E2)

A second set of iterations was performed on the two-storey house using natural ventilation rather than mechanical cooling,

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

similar to the simulations D2 for the single-storey house. These models were chosen in order to examine whether the stack effect of the taller building would have impact on thermal comfort, particularly on the upper floor. For any comparison between the two-storey and the single-storey results, the number of discomfort hours has been divided by the number of rooms (four and 12, respectively), for consistency.

The operative temperature results are provided in Fig. 9.5.40, Fig. 9.5.41 and Fig. 9.5.42.

The total operative temperature discomfort hours follow similar trends to the single-storey house with natural ventilation, where the number of hours increases greatly in areas of high CDDs. This is due to the increase in warm hours (over E1), while the cool hours remain nearly the same, and is expected because the natural ventilation is less effective at cooling the space than a mechanical cooling system.

Similar to the single-storey house, although there is a general trend that a higher ER corresponds to better thermal comfort, it is not consistent across all windows.

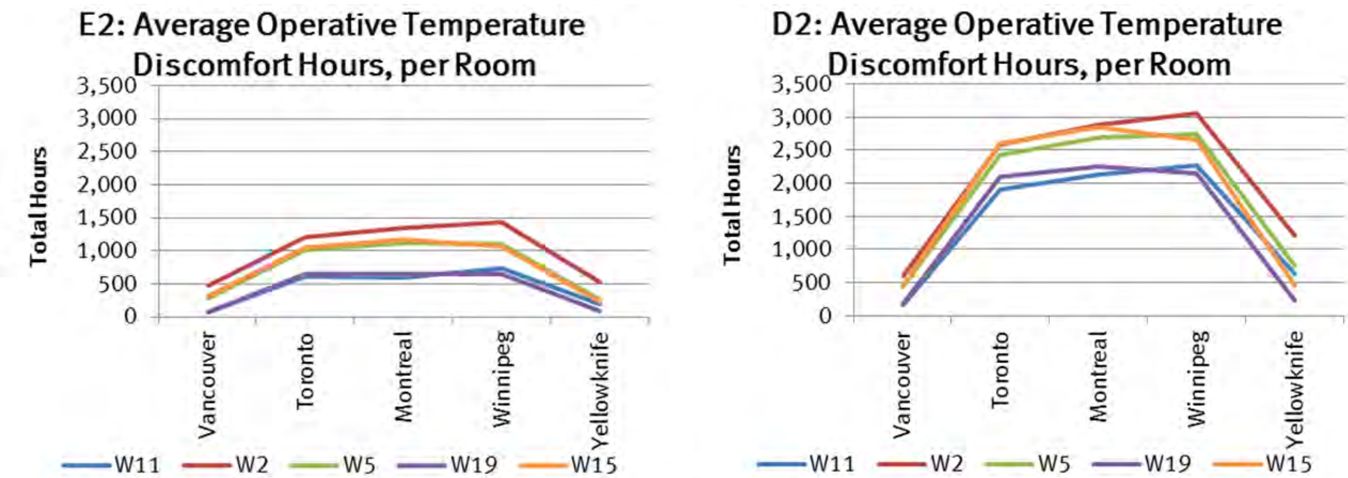


Fig. 9.5.40 E2, Operative temperature discomfort hours per room compared with D2

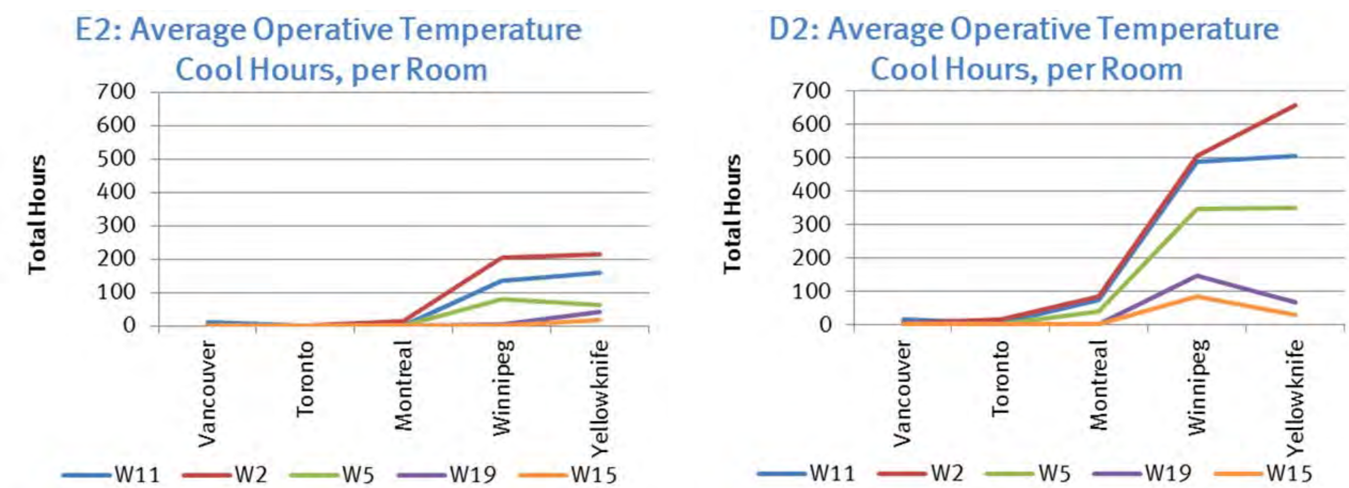


Fig. 9.5.41 E2, Operative temperature cool hours per room compared with D2

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

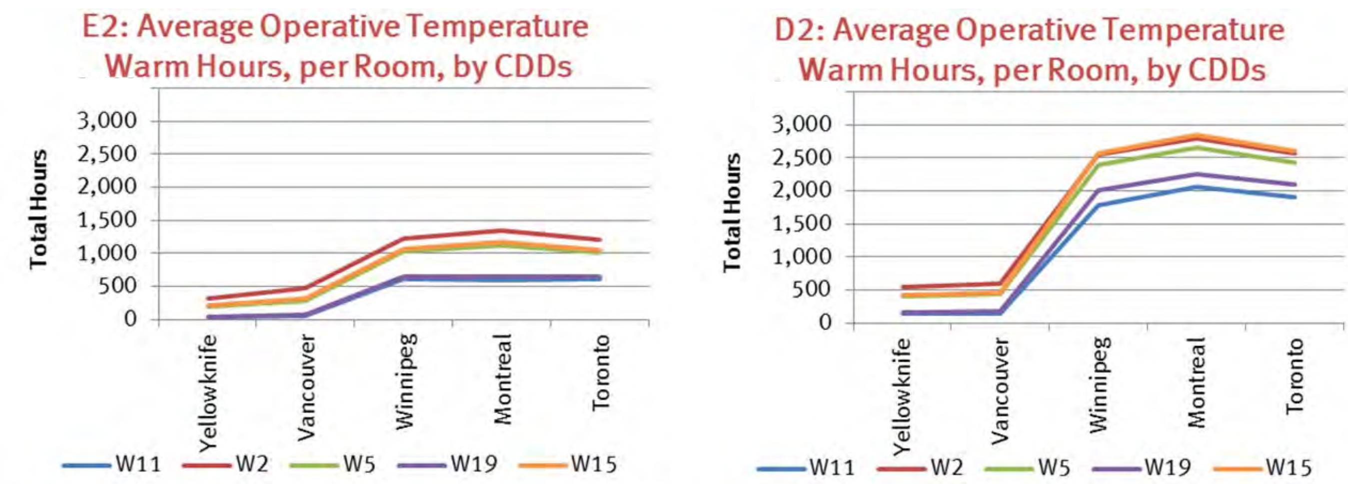


Fig. 9.5.42 E2, Operative temperature warm hours per room compared with D2

The window surface temperature results are provided in Fig. 9.5.43, Fig. 9.5.44 and Fig. 9.5.45.

The window surface temperature average discomfort hours per window follow a profile similar to the single-storey results, and are dominated by cool hours.

The window surface temperature cool hours do not change significantly with the introduction of natural ventilation, which is anticipated since the natural ventilation replaces mechanical cooling (affecting warm hours), while the mechanical heating system (affecting cool hours) remains the same.

Similar to the single-storey house, although the warm hours do increase over the simulation with mechanical cooling (E1), the overall impact is negligible because of the greater number of warm hours.

Interestingly, the single-storey natural ventilation (D2) warm hours was the only scenario where there was an exact relationship between the ER and the level of thermal comfort; W11 (with the lowest ER) also had the lowest warm discomfort hours, which increased as the ER improved (to W2, W5, W19 and W15). This trend is not visible in the two-storey model and suggests that the trend seen previously had to do with other factors, and that the ER was not a true predictor of thermal comfort under these circumstances.

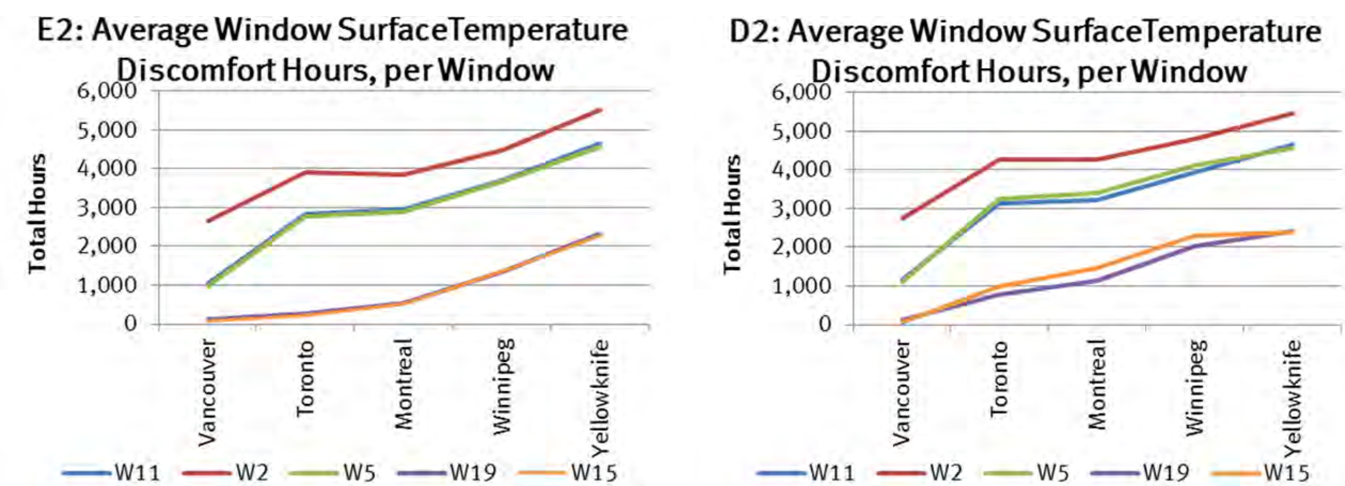


Fig. 9.5.43 E2, Average window surface temperature discomfort hours compared with D2

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

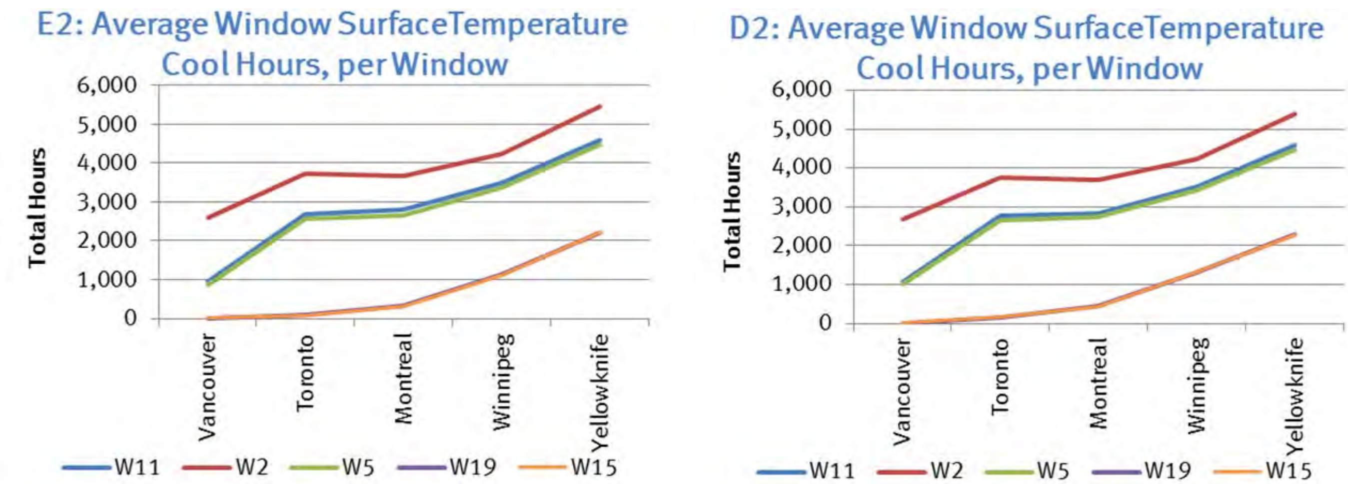


Fig. 9.5.44 E2, Average window surface temperature cool hours compared with D2

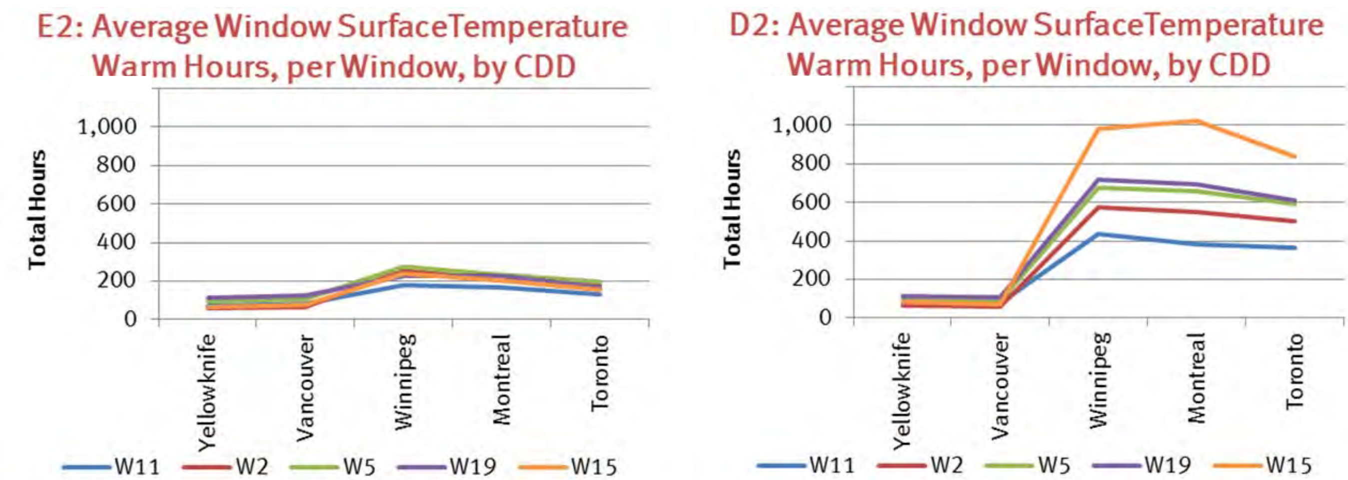


Fig. 9.5.45 E2, Average window surface temperature warm hours compared with D2

Conclusions

In the two-storey house, the total operative discomfort hours due to natural ventilation followed the same trends as the single-storey house. The warm discomfort hours increased significantly, over the baseline two-storey house with mechanical cooling, particularly in locations with higher CDDs, which would be expected since mechanical cooling was removed.

The window surface temperature results also followed the same trends as the single-storey house with natural ventilation. The cool discomfort hours were not significantly impacted, as anticipated, since the switch to natural ventilation was replacing mechanical cooling (which prevents the space from over-heating).

9.6. Interpreting Results for Canada

The results have been discussed in terms of correlation between the ER, U-value, SHGC and thermal comfort. However, as the ER was originally intended to assist in window selection for a "high level" goal of heating energy savings, this section is included to review the impact of window selection on thermal comfort from a similar perspective.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Equivalent Days

As previously discussed in Section 9.5.1, a significant improvement in thermal comfort is possible in each city based on window selection. By substituting the worst performing window with the best, an average reduction of 83% in total discomfort hours could be achieved. Re-examining the number of discomfort days, rather than hours, provides a basis of comparison that may be more intuitive; although it should be emphasized that the discomfort hours (warm or cool) are not expected to occur in consecutive days.

The maximum number of “equivalent days” (of the five window types examined) that the operative temperature would be expected to be warm or cool is summarized in Table 9.6.1. The window causing the highest number of uncomfortable days is also shown. Varying shades of blue and red indicate the extent to which the cool and warm hours are experienced, and the table demonstrates the familiar pattern that operative temperatures are typically dominated by warmer hours.

Table 9.6.1 Operative temperature discomfort equivalent days

DAYS	Annual "cool" days		Min $T_{operative}$	Annual "warm" days		Max $T_{operative}$
	# Days	Window	[C]	# Days	Window	[C]
Vancouver	0.1	W11	18.5	6.3	W2	28.77
Kelowna	0.3	W11	17.83	8.8	W2	27.55
Prince Rupert	11.6	W11	15.95	26.5	W2	27.08
Toronto	0.6	W2	18.79	32.3	W2	26.76
Halifax	1.6	W11	16.37	22.6	W2	27.56
Montreal	3.3	W2	18.63	27.4	W2	27.92
Ottawa	4.0	W11	18.64	21.5	W2	27.51
St John's	13.6	W11	13.45	28.6	W2	26.08
Quebec	4.9	W2	18.42	30.4	W2	26.39
Edmonton	12.1	W2	17.04	35.9	W2	27.65
Winnipeg	20.9	W2	18.18	38.8	W2	27.11
Timmins	19.9	W2	15.1	34.0	W2	29.03
Yellowknife	26.0	W2	14.99	44.8	W2	27.16

The minimum and maximum operative temperatures are also included in Table 9.6.1, and in Fig. 9.6.2, and show that although some cities experience many cumulative days of operative temperatures higher than the comfort range, defined at 25°C, the amount by which they exceed the comfort range is not great. For example, the highest operative temperature, 29.0°C occurs in Timmins, at which time the outdoor air temperature is 34.7°C, and the recorded operative temperature would therefore feel comfortable to most people.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

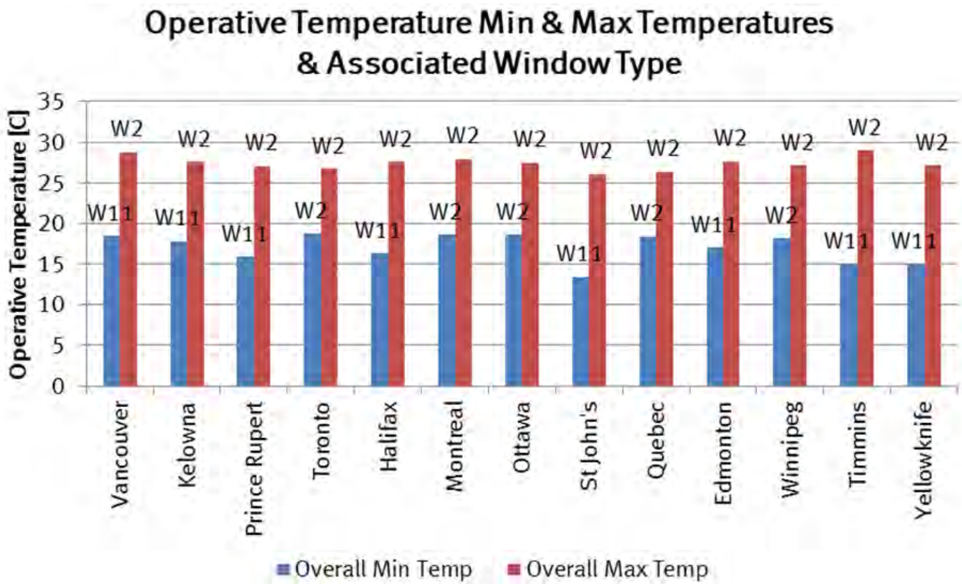


Fig. 9.6.2 Minimum & maximum operative temperatures per city

A similar analysis is performed for the window surface temperature results in Table 9.6.2, showing the equivalent cool and warm days, the associated window causing the peak number of days, and the maximum and minimum temperatures experienced (also shown in Fig. 9.6.3). Once again, the results indicate that window surfaces will experience predominately cool temperatures, and the numbers seem fairly high. For example, window type W2 will cause at least 100 cool hours in all locations, which translates to just over three months. However, when the worst-case window surface temperatures are examined, it can be seen that the amount by which the comfort range is exceeded is not great. For example, the lowest surface temperature experienced in one hour occurs in Yellowknife, where the window surface drops to -1.5C. Since the setpoint temperature is 21C, the delta T is 21.5C. Referring again to the ASHRAE 55-2010 chart on radiant asymmetry (Fig. 9.3.6) and extrapolating the “cool wall” curve, it can be seen that approximately 50% of people will be dissatisfied with the comfort conditions. While this is a high amount, it is also the worst-case window in the coldest climate, for a single hour of the year.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Table 9.6.2 Window surface temperature discomfort equivalent days

DAYS	Annual "cool" days		Min $T_{surface}$	Annual "warm" days		Max $T_{surface}$
	# Days	Window	[C]	# Days	Window	[C]
Vancouver	109.6	W2	9.72	1.7	W19	35.77
Kelowna	132.2	W2	7.57	1.7	W19	37.39
Prince Rupert	162.5	W2	6.85	6.6	W19	35.3
Toronto	154.2	W2	5.31	5.8	W19	35.67
Halifax	149.3	W2	4.94	4.1	W19	36.84
Montreal	151.4	W2	3.62	5.4	W19	37.26
Ottawa	160.5	W2	3.78	4.6	W19	35.92
St John's	199.2	W2	4.45	5.2	W19	34.42
Quebec	170.7	W2	2.66	4.8	W19	37.02
Edmonton	180.6	W2	0.44	6.9	W19	36.11
Winnipeg	173.2	W2	0.28	7.2	W19	37.61
Timmins	193.4	W2	1.14	4.4	W19	37.35
Yellowknife	218.2	W2	-1.51	7.1	W19	36.05

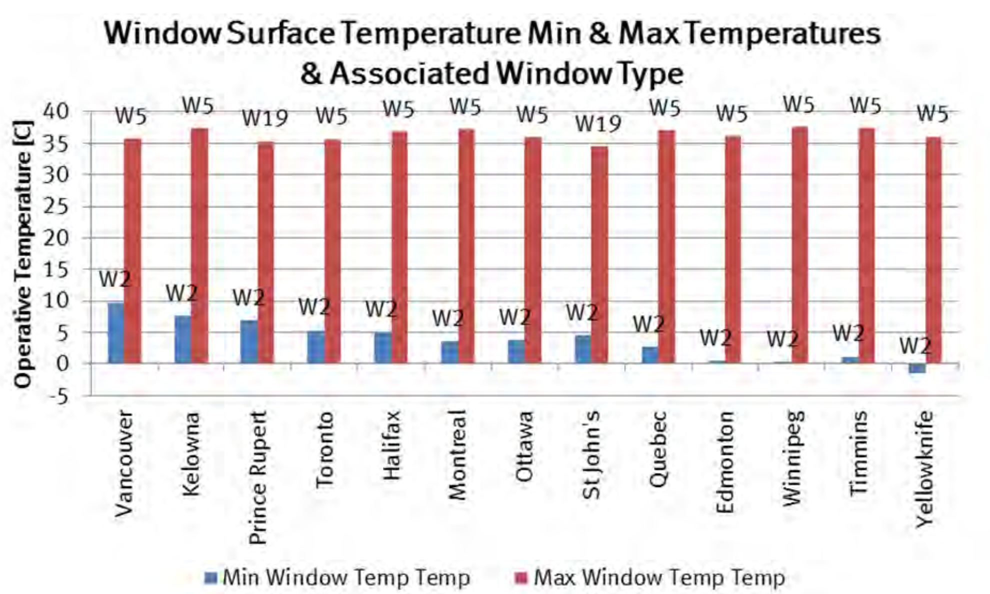


Fig. 9.6.3 Minimum & maximum window surface temperatures per city

Temperature Variance

To understand the average variance from the comfort range (rather than the worst-case scenario), Table 9.6.3 summarizes the average number of degrees Celsius (delta T) by which the operative temperature is above the comfort range, and the average delta T by which the window surface temperature is below the comfort range. It is noticeable in all cases, that the window providing the worst thermal comfort performance is type W2.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Table 9.6.3 Operative & Window Surface Temperature Average variance from Comfort Range

	Operative Temperatures		Window Surface Temperatures	
	Average Temp Over Max [°C]	**Window**	**Average Temp below Min [°C]**	**Window**
Vancouver	0.41	W2	1.46	W2
Toronto	0.35	W2	3.10	W2
Montreal	0.40	W2	3.81	W2
Winnipeg	0.44	W2	5.39	W2
Yellowknife	0.39	W2	6.78	W2

Temperature Distribution

The temperature distribution within the room at the time of the worst-case temperatures, described above, can be reviewed using computational fluid dynamic (CFD) analysis. The results for the warmest and coldest cities, Vancouver and Yellowknife respectively, are presented to provide an understanding of the extent of the impact caused by the cold window in the different climates. Two typical Canadian windows will be examined (W2 and W15), chosen to represent an existing window and an energy efficient upgrade option, to examine the impact of window selection on thermal comfort.

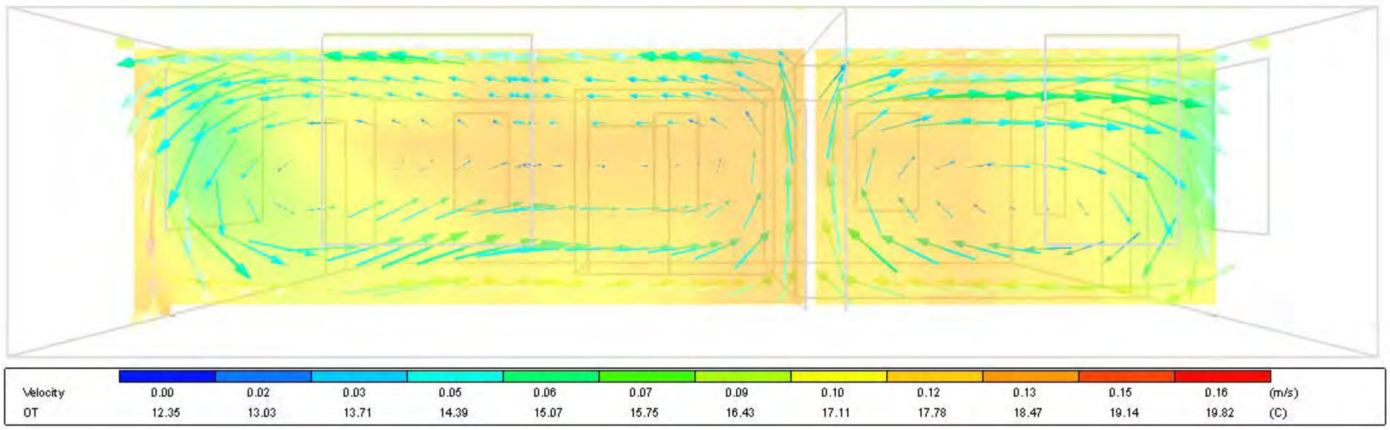
The CFD analyses were generated from results of the energy simulation at the hour when the coldest internal window surface temperature was recorded, using window type W2. By extracting data directly from the simulation, it was possible to ensure better accuracy for the temperature boundary conditions (that is, all surface temperatures were calculated, rather than manually approximated). Two sets of results are presented for each location: operative temperature and the percentage of people dissatisfied (PPD).

- Vertical Operative Temperature distribution:
  - These graphics view the house from the west, and show the operative temperature distribution (what a person will "feel" inside the space) across a plane within the house along the north-south axis. The plane is a cross-section through the living room and the bedroom, and intersects windows in both rooms. Also shown are velocity vectors, indicating air movement within the space. Scales are provided along the bottom of each graphic.
  - Comparing the results for Yellowknife and Vancouver shows that the temperature and velocity profiles within the two houses will be similar. In both cases, the windows with cold interior surface temperatures will cool the air, causing it to drop at the external walls, and transfer along the floor into the middle of the house (which will be experienced by occupants as "draughts"). However, the extent to which this affects thermal comfort varies between locations.
  - In Yellowknife, due to the greater difference in temperatures, higher velocities (or draughts) will be generated, as the maximum induced velocity is 0.16 m/s, compared to 0.12 m/s in Vancouver.
  - Colder temperatures also occur in Yellowknife, where the average room operative temperature is approximately 17 to 18°C versus 19°C in Vancouver. Similarly, the minimum operative temperature occurring in Yellowknife is 12.3°C versus 15.6°C in Vancouver.
  - Window W15 outperforms window W2 in both locations:
    - In Yellowknife, the estimated average room temperature is 17.5°C with window type W2, and 18°C with window type W15.
    - In Vancouver, the average room temperature for window W2 is 19°C with window type W2, and 19.5°C with window type W15.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Yellowknife, Window W2: Coldest Hours Analysis, February 11th, 2am (Outdoor Air Temp = -41.7°C)

Average room temperature = (estimated) 17.5°C



Yellowknife, Window W15: Coldest Hours Analysis, February 11th, 2am (Outdoor Air Temp = -41.7°C)

Average room temperature = (estimated) 18°C

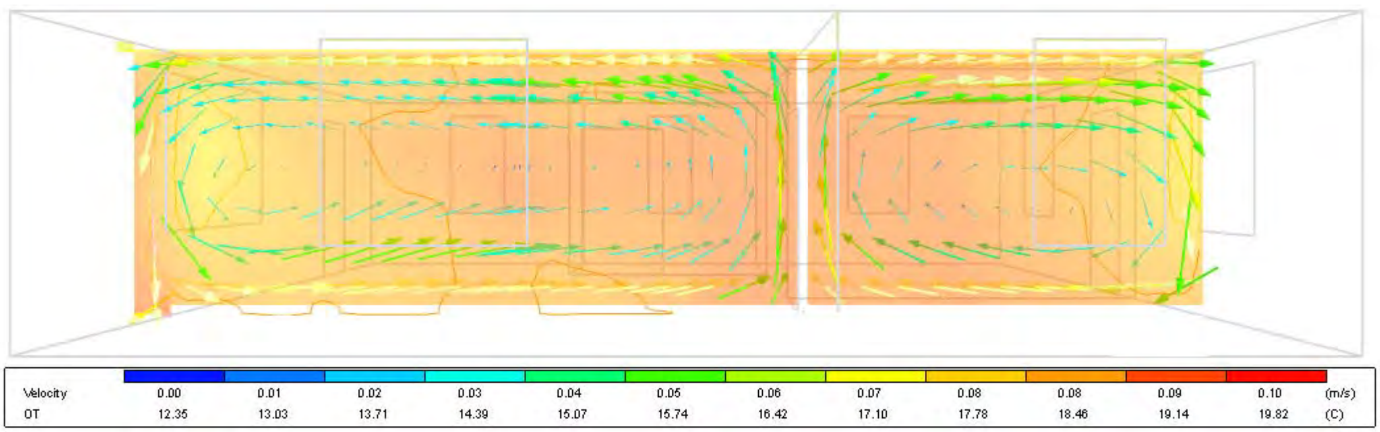
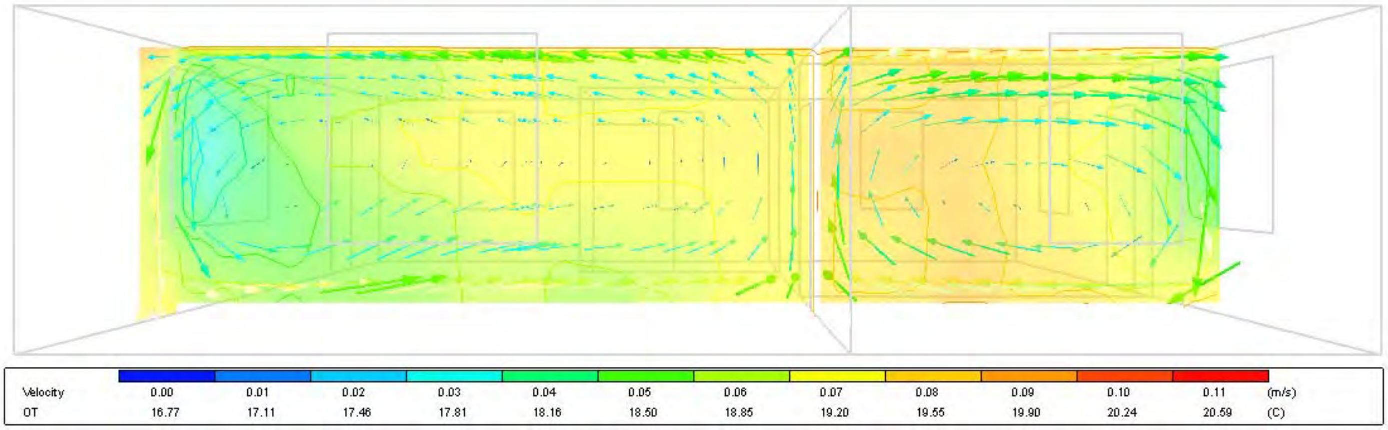


Fig. 9.6.4 CFD Results: Operative temperature distribution in Yellowknife, W2 and W15

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Vancouver, Window W2: November 22nd, 3am (Outdoor Air Temp = -6.0°C)

Average room temperature approximately 19°C



Vancouver, Window W15: November 22nd, 3am (Outdoor Air Temp = -6.0°C)

Average room temperature approximately 19.5°C

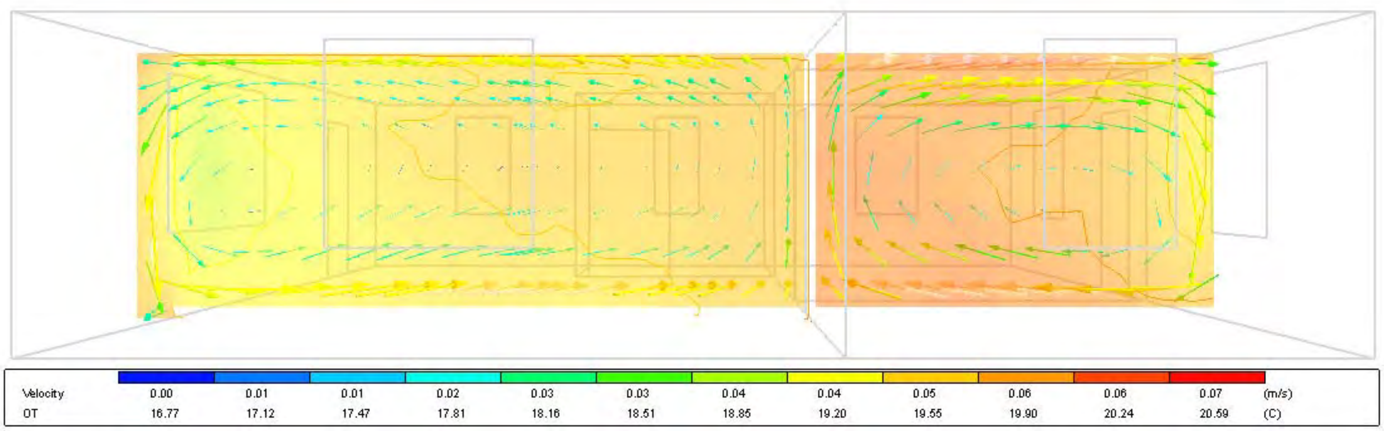
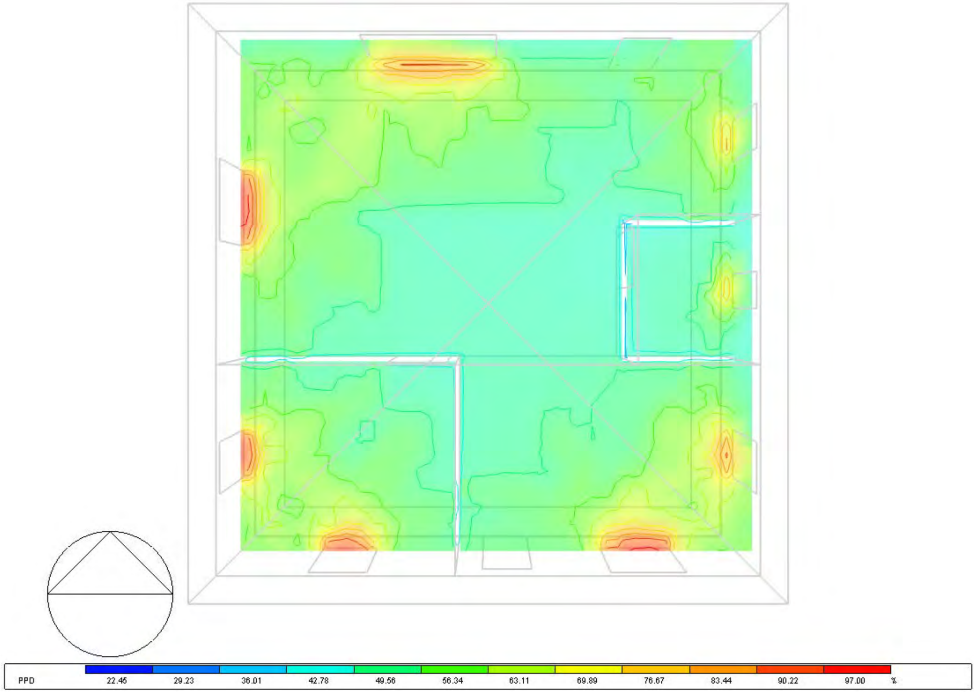


Fig. 9.6.5 CFD Results: Operative temperature distribution in Vancouver, W2 and W15

- Horizontal Percent People Dissatisfied (PPD) distribution:
  - The PPD, as described by ASHRAE-55 2010 is “an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people …” A higher PPD indicates that more people would be thermally uncomfortable, and is therefore less desirable than a lower PPD.
  - Comparing the results between the two cities predicts that more people will be thermally uncomfortable in Yellowknife than Vancouver, at the coldest hour experienced in each of those locations.
  - On average, within the room in Yellowknife, approximately 45% of people will feel uncomfortable, whereas only 25% of people will express thermal discomfort in Vancouver.
  - The PPD results also show that window W15 outperforms W2 in both locations:
    - In Yellowknife, the average PPD improves from 45% to 35% when the windows are upgraded from W2 to W15.
    - In Vancouver, the average PPD improves from 30% to 25% when the windows are upgraded from W2 to W15.

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Yellowknife, Window W2: Coldest Hours Analysis, February 11th, 2am
Average PPD = (estimated) 45%



Yellowknife, Window W15: Coldest Hours Analysis, February 11th, 2am
Average PPD = (estimated) 35%

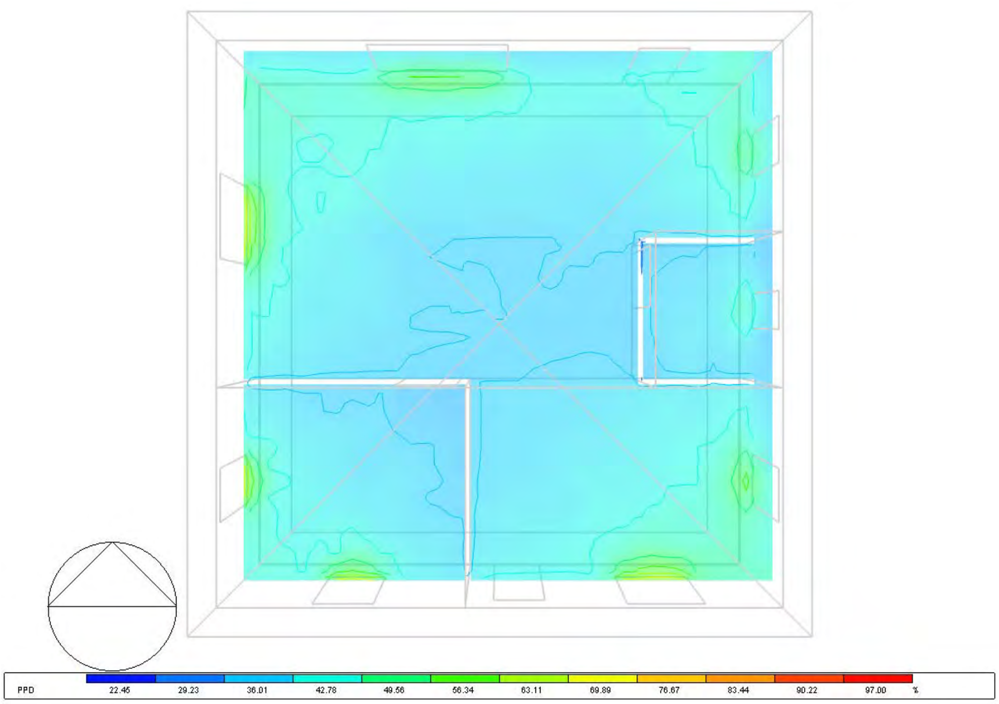
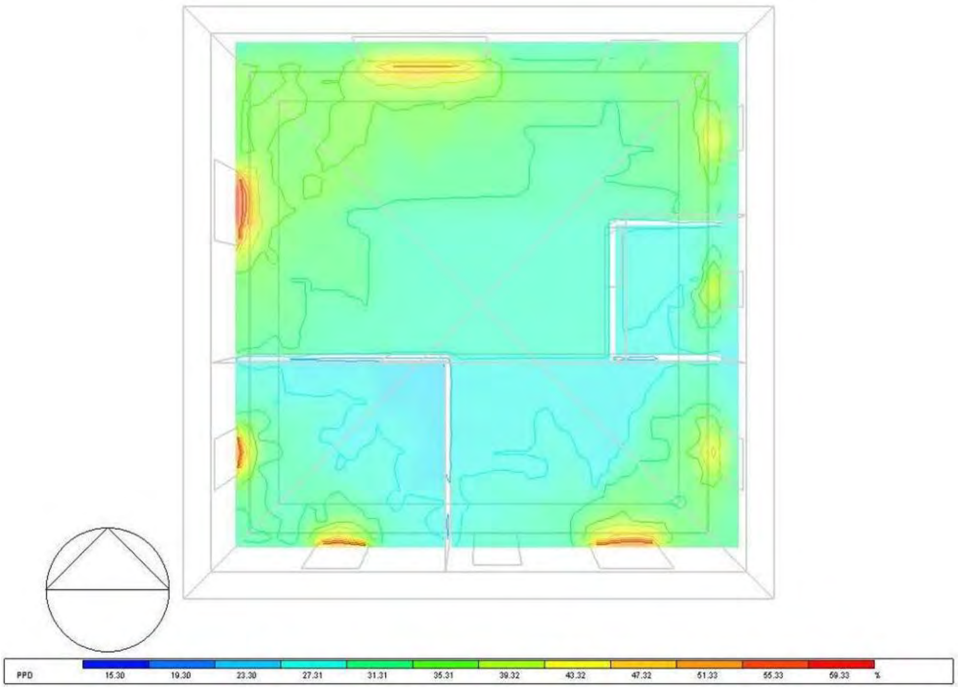


Fig. 9.6.6 CFD Results: Percent People Dissatisfied in Yellowknife, W2 and W15

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

Vancouver, Window W2: November 22nd, 3am

Average PPD = (estimated) 30%



Vancouver, Window W15: November 22nd, 3am
Average PPD = (estimated) 25%

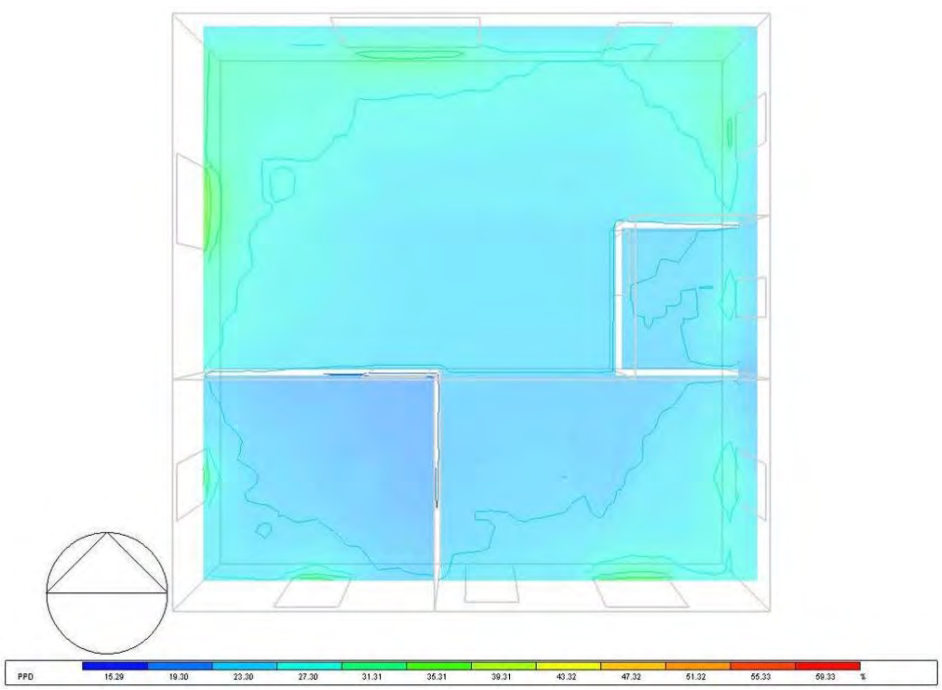


Fig. 9.6.7 CFD Results: Percent People Dissatisfied in Vancouver, W2 and W15

	W02	W05	W11	W15	W19
U-value	2.83	2	2	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2
ER	14	26	8	49	32

9.7. Summary and Conclusions

The purpose of this analysis was to evaluate whether thermal comfort considerations are consistent with those of the ER for fenestration. This review was undertaken with the understanding that the ER was originally developed to provide guidance on window selection for heating energy considerations, and was not initially intended to evaluate thermal comfort performance.

Examining the baseline situation, the mechanical system was seen to perform as anticipated, maintaining the temperature setpoints throughout the year. The operative temperature, a calculated mean of the dry-bulb and surface temperatures, varied within a larger range suggesting that the surface temperatures experienced greater swings. This was further corroborated by examining the window surface temperatures, which had the largest range out of the three parameters. Assessing the rooms individually based on geometry, there was no clear relationship between thermal comfort and the exterior surface-to-floor area ratio. However, there was a general trend where higher ERs had better overall comfort (winter and summer combined). The results were not consistent across all window types, and two windows (W11 and W15) often did not follow the trend.

- Although ER was not originally intended for thermal comfort, some correlation exists between ER and thermal comfort.
- Correlation exists between thermal comfort & U-value (lower U results in lower cool hours).
- Correlation exists between thermal comfort & SHGC (lower SHGC results in lower warm hours).

Many of the trends in the baseline simulations in Vancouver were similar in other locations, generally varying based on HDDs and CDDs. Cities with more HDDs experienced more cool discomfort hours and cities with more CDDs experienced more warm discomfort hours, as expected. However, the relationship between window performance in various locations remained fairly constant with the exception of Prince Rupert and St John's, where both experience low annual solar radiation due to increased cloud cover. Note that other locations (not studied) with similar low solar gains would likely follow these results as well.

All iterations, analysed by changing a single input parameter, typically followed the same trends when compared in a single location across the five window types. Both operative and window surface temperature results showed some correlation between a higher ER and improved thermal comfort, however, the highest and lowest ER windows (W11 and W19) again were exceptions. A final summary of the variables is presented in Table 9.7.1 and Table 9.7.2, and displays the trends described between the various iterations. Recall that the hours presented in the table represent the hours per year outside the comfort range for four rooms within a house (out of 8,760 hours/room/year x 4 rooms = 35,040 hours/year).

Table 9.7.1 Operative Temperature Discomfort Hours compared between iterations

	W2 ER-14	W5 ER-26	W11 ER-8	W15 ER-49	W19 ER-32	W2 ER-14	W5 ER-26	W11 ER-8	W15 ER-49	W19 ER-32
U-Value	2.83	2.0	2.0	0.9	0.9	2.83	2.0	2.0	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2	0.64	0.5	0.2	0.5	0.2
	D1 Baseline					D2 Natural Ventilation				
Vancouver	3,103	2,260	502	2,585	665	2,397	1,744	659	1,853	707
Toronto	3,321	2,385	628	2,583	666	10,337	9,730	7,642	10,434	8,417
Montreal	4,039	2,863	963	2,997	782	11,541	10,777	8,546	11,367	9,021
Winnipeg	2,255	1,571	438	1,749	374	12,215	10,980	9,092	10,638	8,631
Yellowknife	5,040	3,042	1,910	2,105	359	4,829	3,015	2,561	1,831	889
	D3 Electric Baseboard					D4 Thermal Mass				
Vancouver	3,333	2,460	526	2,811	728	2,397	1,369	61	1,729	121
Toronto	2,792	1,864	389	1,989	413	429	89	5	82	3
Montreal	3,585	2,310	723	2,414	514	770	223	4	216	2
Winnipeg	5,073	3,541	2,427	2,699	1,140	898	294	3	249	2
Yellowknife	12,338	11,627	12,104	11,179	11,400	947	344	0	411	0

Table 9.7.2 Window Surface Temperature Discomfort Hours compared between iterations

	W2 ER-14	W5 ER-26	W11 ER-8	W15 ER-49	W19 ER-32	W2 ER-14	W5 ER-26	W11 ER-8	W15 ER-49	W19 ER-32
U-Value	2.83	2.0	2.0	0.9	0.9	2.83	2.0	2.0	0.9	0.9
SHGC	0.64	0.5	0.2	0.5	0.2	0.64	0.5	0.2	0.5	0.2
	D1 Baseline					D2 Natural Ventilation				
Vancouver	10,768	4,398	4,684	366	554	10,960	4,382	4,628	290	427
Toronto	14,999	10,882	11,300	974	1,034	17,044	13,014	12,500	3,979	3,071
Montreal	14,902	11,407	11,851	2,115	2,424	17,024	13,584	12,882	5,842	4,528
Winnipeg	14,501	9,402	10,015	768	952	19,187	16,440	15,804	9,210	8,077
Yellowknife	21,178	18,130	18,656	9,549	9,856	21,830	18,268	18,663	9,514	9,701
	D3 Electric Baseboard					D4 Thermal Mass				
Vancouver	10,799	4,484	4,757	394	589	9,844	3,432	3,697	366	546
Toronto	14,925	10,848	11,293	772	1,037	15,180	10,919	11,115	971	1,076
Montreal	14,856	11,406	11,869	2,096	2,423	14,739	10,507	10,723	1,002	1,252
Winnipeg	16,938	14,078	14,524	5,625	5,830	16,977	13,544	13,859	4,010	4,110
Yellowknife	21,757	18,808	19,296	11,503	11,727	21,357	17,766	18,046	8,817	8,875

The natural ventilation simulations generally saw an increase in warm discomfort hours, more visible in the operative temperature analysis in locations with higher CDDs. This would be expected since the mechanical cooling was turned off. The impact on thermal comfort varied between cities; however, the ranking of the windows examined remained the same as the baseline case. In the five locations examined, there was a direct relationship between the ER and the level of thermal comfort, where a higher ER indicated more thermal discomfort hours.

With electric baseboard heaters, the operative temperature discomfort hours were similar to the baseline case except in Yellowknife, where this type of mechanical system would be less common. The window surface temperature discomfort hours were also similar to the baseline results in all locations. Again, the trends between the ER scale and the level of thermal comfort generally remained the same as the baseline case.

Including thermally massive construction elements improved the thermal comfort when evaluated by operative temperature, though little effect was noticed in the window surface temperature results. This is mostly due to the effect of the thermal mass dampening out temperature swings. Although thermal comfort was only improved when evaluated based on operative temperature, the trends visible in the both sets of results (operative and window surface) were comparable with those in the baseline simulations.

Rotating the building had the most significant impact on thermal comfort when evaluating either warm or cool hours of a specific room, since the orientation of that room would change. As expected, when a room was located on a south and/or west exposure, it experienced the most solar gain and therefore the highest number of warm hours, and the fewest number of cool discomfort hours. The correlation between ER and thermal comfort remained the same as the baseline simulation.

The two-storey house simulations, with the baseline mechanical system and with natural ventilation, both showed the same trends as the single-storey houses. When the rooms were compared individually, there were slightly more warm discomfort hours on the upper floor, likely due to the effect of heat rising. However, in general, any correlation between the ER and thermal comfort followed the trends previously distinguished in the baseline and single-storey simulations.

Across most of the simulations, the objectives of the Energy Rating appeared to align with those of thermal comfort, though not consistently across all windows in all locations. A higher ER generally correlated with fewer cool discomfort hours, seen predominantly in window surface temperature results, and more warm discomfort hours, which were more visible in the operative temperature results. Opportunities exist for improving thermal comfort through design parameters such as window selection, appropriately designed overhangs, inclusion of thermal mass or combinations thereof.

10. Other Fenestration Systems

This section investigates how the current ER calculation rates energy consumption of residential doors and skylights. Several doors and skylights are selected for simulation based on product data from the ENERGY STAR® database (NRCan). Energy simulations are run using the archetype house developed through the previous sections. Heating, cooling and total energy consumption is examined for products with different ER values to determine how the ER applies to doors and skylights.

10.1. Doors

10.1.1 Selection of Doors

The ENERGY STAR® standard defines a door as "A sliding or swinging entry door system designed for and installed in a vertical wall separating conditioned and unconditioned space in a residential building. The primary function of a door is to allow for egress." Two types of doors are defined, sliding doors and swinging doors.

- Sliding Door: "A door that contains one or more manually operated panels that slide horizontally within a common frame. Sliding doors are included under the door criteria and definition."
- Swinging Door: "A door system having, at a minimum, a hinge attachment of any type between a leaf and jamb, mullion, or edge of another leaf or having a single, fixed vertical axis about which the leaf rotates between open and closed positions. Swinging entry doors are included under the door criteria and definition."

The ENERGY STAR® database also contains transoms, sidelites, and tilt and turn doors. A transom is defined by A440 as "an operable or non-operable product that is designed to be a companion product installed above a fenestration product." A sidelite is defined by A440 as "an operable or non-operable product that is designed to be a companion product installed on one or both sides of an operable door or a fixed door." A tilt and turn door, also called a dual-action door, is defined as "a door system consisting of one or more leaves contained within an overall frame and designed such that one of the leaves is operable in a swing mode and can be tilted inward from the top for ventilation."

The ENERGY STAR® requirements for doors are shown in Table 10.1. There are two possible compliance paths to certify doors, by minimum ER or by maximum U-value. The ER path also requires a maximum U-value of 2.0 W/m^2-K (0.35 Btu/h-ft^2-F). However, unlike the ENERGY STAR® requirements for windows, the U-value path does not have a minimum ER requirement. The ER only applies to sliding glass doors, and not to opaque swing entry doors.

Table 10.1 ENERGY STAR® requirements for doors.

Zone	Heating Degree Day Range	Compliance Paths			
		Energy Rating (ER)	Or	U-Factor	
		Minimum ER (Maximum U-Factor 2.0 W/m^2-K or 0.35 Btu/h-ft^2-F)		Maximum U-Factor, W/m^2-K (Btu/h-ft^2-F)	Minimum ER
A	≤3500	21	Or	1.80 (0.32)	N/A
B	>3500 to ≤5500	25	Or	1.60 (0.28)	N/A
C	>5500 to ≤8000	29	Or	1.40 (0.25)	N/A
D	>8000	34	Or	1.20 (0.21)	N/A

There are currently 565,352 door products in the ENERGY STAR® database. This includes sliding glass doors, hinged doors, dual action (tilt-turn), sidelites and transoms. The glazing size for each door is also recorded, either full lite, ¾ lite, ½ lite, ¼ lite, or no lite. The ER is available for all sliding glass doors, but only select products from the other door types.

Fig.10.1 shows the percent distribution of each door type in the ENERGY STAR® database. The majority of ENERGY STAR® door products are hinged (single) and sidelites, with a significant portion of sliding glass doors as well.

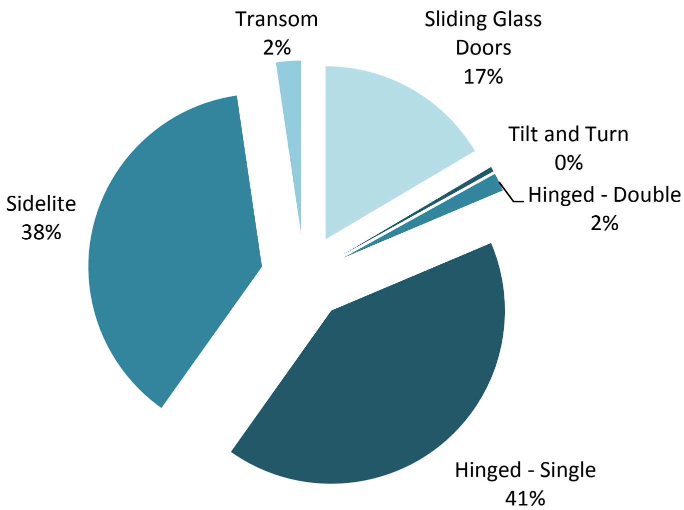


Fig.10.1 Percentage of doors by type.

The U-value, SHGC and ER parameters will vary greatly between different door types with different amounts of glazing. Table 10.2 shows the average, median, minimum and maximum U-values for each door product type in the database. Fig.10.2 shows the distribution of U-values by product type.

Table 10.2 Average U-values of ENERGY STAR® door products, W/m^2-K (Btu/hr-ft^2-F).

	Sliding Glass Door	Tilt and Turn	Hinged - Double	Hinged - Single	Sidelite	Transom
Average	1.70 (0.30)	1.51 (0.27)	1.72 (0.30)	1.35 (0.24)	1.43 (0.25)	1.58 (0.28)
Median	1.70 (0.30)	1.59 (0.28)	1.76 (0.31)	1.36 (0.24)	1.42 (0.25)	1.65 (0.29)
Minimum	0.85 (0.15)	0.97 (0.17)	0.85 (0.15)	0.66 (0.12)	0.68 (0.12)	0.85 (0.15)
Maximum	2.01 (0.35)	1.99 (0.35)	1.93 (0.34)	1.99 (0.35)	1.99 (0.35)	1.99 (0.35)

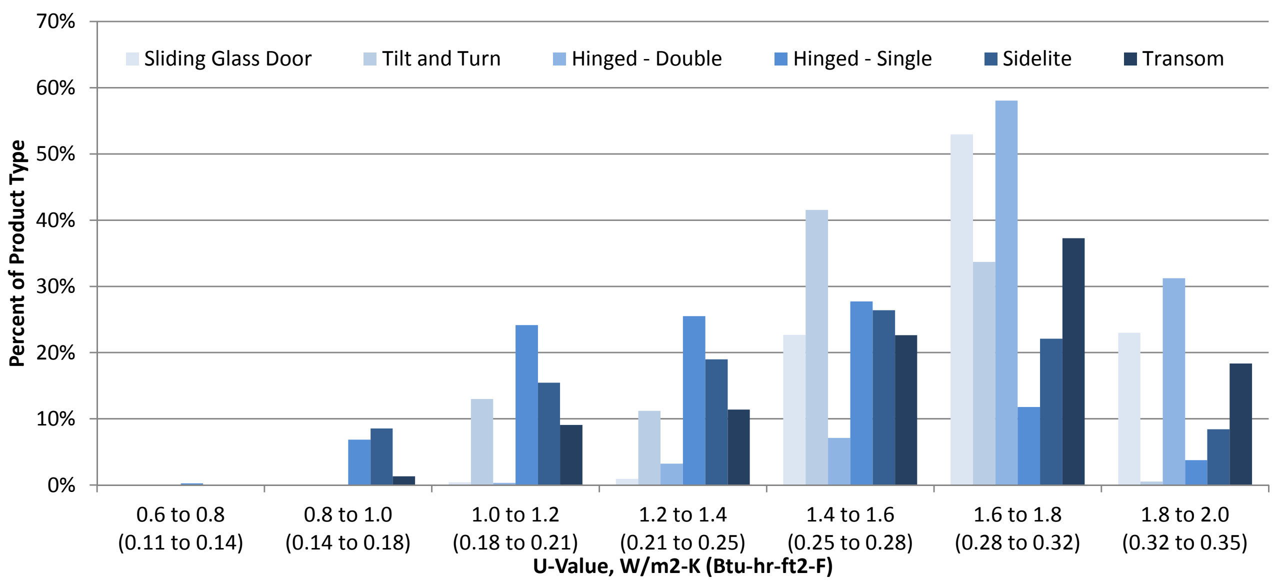


Fig.10.2 Distribution of U-values for ENERGY STAR® door products.

Table 10.3 shows the average, median, minimum and maximum SHGCs for each door product type in the database. Fig.10.3 shows the distribution of SHGCs by product type. Note that the SHGCs are for the whole door area, not just the glazed area.

Table 10.3 Average SHGC of ENERGY STAR® door products.

	Sliding Glass Door	Tilt and Turn	Hinged - Double	Hinged - Single	Sidelite	Transom
Average	0.23	0.19	0.19	0.15	0.13	0.28
Median	0.22	0.16	0.16	0.15	0.12	0.26
Minimum	0.06	0.06	0.01	0.00	0.00	0.07
Maximum	0.62	0.48	0.47	0.70	0.67	0.68

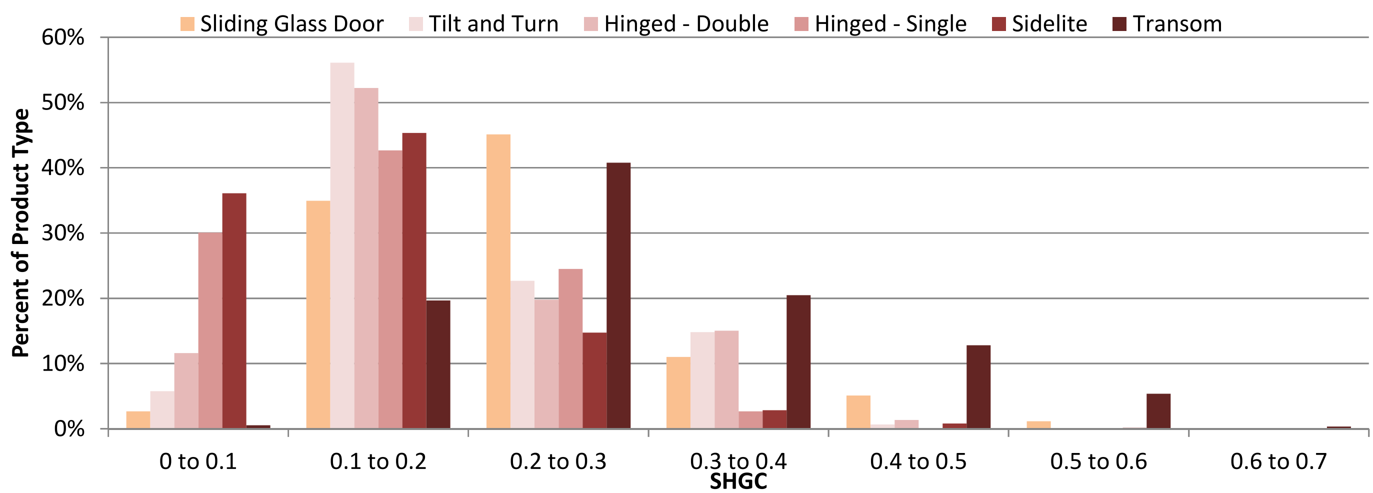


Fig.10.3 Distribution of SHGCs for ENERGY STAR® door products.

Sliding glass doors, swing doors, sidelites and transoms that are fully glazed have U-value and SHGC properties similar to the windows simulated in the previous sections, therefore, the results from the window energy simulations also apply to door products with full glazing. Doors with partial glazing and fully opaque doors need to be investigated in this section. Fully glazed swing doors tend to have thicker frames than most windows, and would also be useful to include for comparison to opaque doors. Therefore, swing doors with a full lite, half lite and with no lite (fully opaque) will be simulated. To determine appropriate U-value and SHGC properties for these doors, the ENERGY STAR® database was further analyzed for these specific amounts of glazing.

Fig.10.4 shows the distribution of U-values for ENERGY STAR® doors with a full lite, half lite and no lite. Doors with a full lite range from U_{SI}-0.85 (U-0.15) to U_{SI}-1.99 (U-0.35), with an overall average of U_{SI}-1.59 (U-0.28). A high and low U-value of U_{SI}-1.4 (U-0.25) and U_{SI}-1.8 (0.32) will therefore be simulated Doors with a half lite range from U_{SI}-0.91 (U-0.16) to U_{SI}-1.82 (U-0.32), with an average of U_{SI}-1.30 (U-0.23). A range of low, medium and high U-values will therefore be simulated, with values of U_{SI}-1.1 (U-0.19), U_{SI}-1.4 (U-0.25), U_{SI}-1.7 (U-0.30). Doors with no glazing have U-values that range from U_{SI}-0.66 (U-0.12) to U_{SI}-1.82 (U-0.32), with an average of U_{SI}-1.03 (U-0.18). A range of low, medium and high values will therefore be simulated, with values of U_{SI}-0.7 (U-0.12), U_{SI}-1.0 (U-0.18) and U_{SI}-1.5 (U-0.26).

For reference, the opaque swing doors in the database with low U-values around U_{SI}-0.7 (U-0.12) (there are 54 of these doors with U_{SI}-0.7 to U_{SI}-0.66, or U-0.12) all have the following characteristics:

- Frame material: Wood
- Slab skin material: Mostly steel, few vinyl and fibreglass
- Slab core material: Polyurethane
- Slab edge: Wood

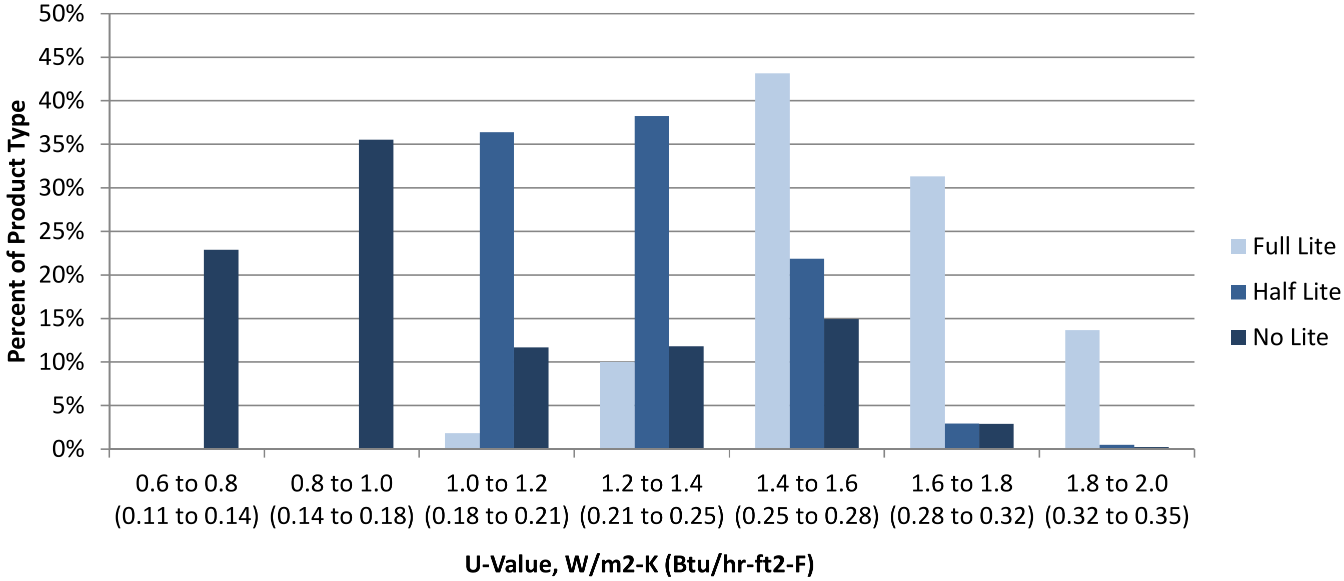


Fig.10.4 Distribution of U-Values for ENERGY STAR® doors with half lite and no lite.

Fig.10.5 shows the distribution of SHGC values for ENERGY STAR® doors with a full lite, half lite and opaque doors. For doors with a full lite, the SHGCs range from 0 to 0.55, with an average of 0.21. In general, the SHGCs for the full lite doors are lower than the window SHGCs. This is typical since the doors tend to have larger frames than most windows. Based on this data, full lite doors with high and low SHGC values of 0.15 and 0.3 will be simulated.

For doors with a half lite, the SHGCs range from 0.01 to 0.41, with an average of 0.13 and a median of 0.14. Half lite doors with a low and high solar heat gain glazing unit will therefore be simulated, with overall SHGC values of 0.10 and 0.20 when area-weighted to include the opaque and glazed portions.

For opaque doors, there appear to be some errors in the database as there are a significant number of products with SHGC values between 0.1 and 0.4. Doors with sidelites or transoms may have been included in these database entries. The average SHGC of all opaque doors in the database is 0.08, however, the mean value is 0.01. A SHGC is not required for input into the energy model, however, for the purpose of a “theoretical” ER calculation a SHGC value of 0.01 will be used for opaque doors.

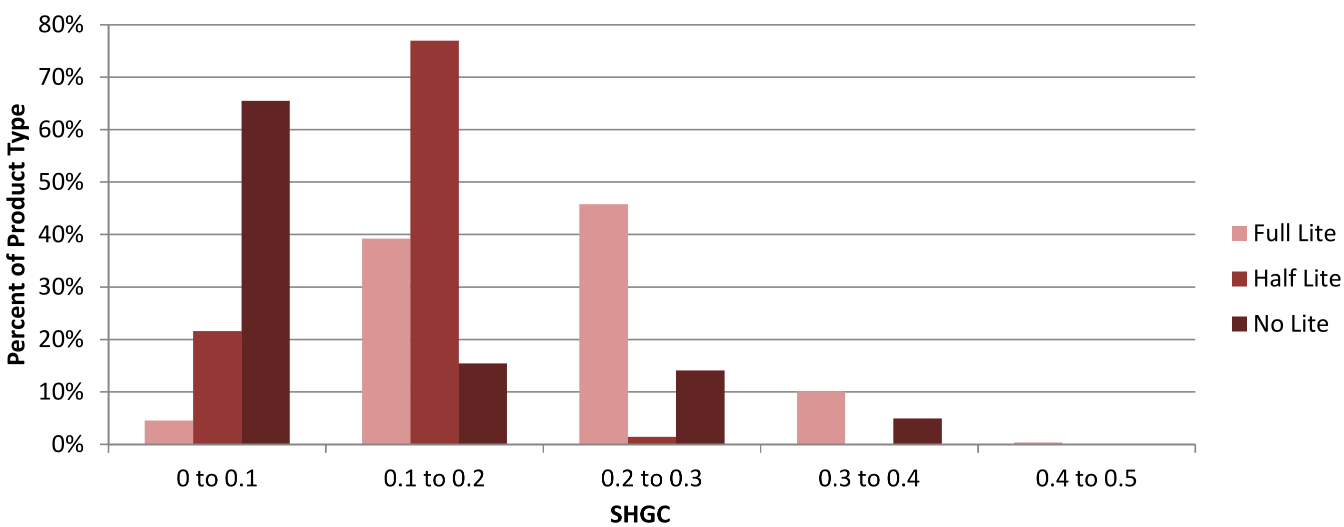


Fig.10.5 Distribution of SHGCs for ENERGY STAR® doors with half lite and no lite.

Table 10.4 shows the doors for simulation. In order to assess whether an ER is appropriate for doors, a “theoretical” ER was calculated for each door product using the CSA ER formula. Note that the ER for many doors will be lower than the ER for windows due to the lower SHGC of doors with only partial glazing.

Relatively few doors in the ENERGY STAR® database include an air leakage rate, however, a number of products do (6,664 or 3% of the single hinged doors have A440 air leakage rates). Of the single hinged doors with air leakage ratings, the average leakage rate is 0.16 $m^3/h/m$, with a range from 0.05 $m^3/h/m$ to 5.067 $m^3/h/m$. For reference, the A440 airtightness ratings are 8.35 $m^3/h/m$ for a storm, 2.79 $m^3/h/m$ for A1, 1.65 $m^3/h/m$ for A2, 0.55 $m^3/h/m$ for A3, and 0.25 $m^3/h/m$ for a fixed window (note this standard does not cover doors, so the A-ratings are provided for reference only). An air leakage rating of 0.55 $m^3/h/m$ (equivalent to an A3 rating) is used for all product ER calculations, recognizing that the doors in the database with air leakage rates have low ratings, and also the air leakage rate is a relatively minor component of the overall ER (as shown in the earlier sections). Also note that doors are often certified for ENERGY STAR® on the U-value path because they do not have air leakage testing performed, as required for the ER.

Table 10.4 Door products for energy simulation.

	Representative Door	U-Value, W/m^2-K ($Btu/hr\text{-}ft^2$-F)	SHGC	"Theoretical" Calculated ER	ENERGY STAR® Zone, U-Value Path	ENERGY STAR® Zone, ER Path
D01	Swing Door, Fully Glazed	1.4 (U-0.25)	0.15	18	ABC	None
D02	Swing Door, Fully Glazed	1.8 (U-0.32)	0.15	9	A	None
D03	Swing Door, Fully Glazed	1.4 (U-0.25)	0.3	26	ABC	AB
D04	Swing Door, Fully Glazed	1.8 (U-0.32)	0.3	18	A	None
D05	Swing Door, ½ Lite	1.1 (U-0.19)	0.10	19	ABCD	None
D06	Swing Door, ½ Lite	1.4 (U-0.25)	0.10	12	ABC	None
D07	Swing Door, ½ Lite	1.7 (U-0.30)	0.10	5	A	None
D08	Swing Door, ½ Lite	1.1 (U-0.19)	0.20	24	ABCD	A
D09	Swing Door, ½ Lite	1.4 (U-0.25)	0.20	18	ABC	None
D10	Swing Door, ½ Lite	1.7 (U-0.30)	0.20	11	A	None
D11	Swing Door, Opaque	0.7 (0.12)	0.01	25	ABCD	AB
D12	Swing Door, Opaque	1.0 (0.18)	0.01	18	ABCD	None
D13	Swing Door, Opaque	1.5 (0.26)	0.01	7	AB	None

To confirm that the doors for simulation represent a wide range of products that exist in the Canadian market, the U-value and SHGC combinations were compared to data in the ENERGY STAR® door database. The results of this analysis are presented in Table 10.5.

Table 10.5 Doors for simulation and the ENERGY STAR® database.

	Door Type	Number of Doors with Exact Properties	Number of Doors within +/- 1%	Number of Doors within +/- 5%
D01	Swing Door, Fully Glazed	0	1	1987
D02	Swing Door, Fully Glazed	0	544	2896
D03	Swing Door, Fully Glazed	1	2	751
D04	Swing Door, Fully Glazed	0	375	2861
D05	Swing Door, ½ Lite	1	4	2578
D06	Swing Door, ½ Lite	1	5	892
D07	Swing Door, ½ Lite	25	26	309
D08	Swing Door, ½ Lite	0	0	25
D09	Swing Door, ½ Lite	0	0	1008
D10	Swing Door, ½ Lite	6	6	218
D11	Swing Door, Opaque	2	3	253
D12	Swing Door, Opaque	1	1	55
D13	Swing Door, Opaque	0	3	7

10.1.2 Energy Analysis of Doors

The energy analysis of doors was completed using the same archetype house simulations as the previous sections in this study. The single-storey house with typical existing enclosure thermal performance (see Section 4) was simulated with the various doors in five Canadian locations (Vancouver, Toronto, Montreal, Winnipeg, Yellowknife). The house is heated by a natural gas furnace, with central air conditioning.

The archetype house energy simulations include two exterior doors, both of which were changed to reflect the door types identified in the previous section. It should be noted that the difference in energy consumption when changing only two doors in a model is relatively small, however it still identifies trends between different door types. These trends can be used to assess how the ER ranks energy consumption of doors. The following plots show a small difference in energy consumption between different door types, but the trends are still visible. Also, the difference in energy consumption for different cities is much greater than the change between different door types, and so it is sometimes necessary to plot cities separately.

Doors are often protected by overhangs, which would also result in some shading of the doors. In this analysis the doors were not simulated with additional shading in order to compare the results to the results from the window analysis. Shading was analyzed in the window analysis, and if the findings are consistent between doors and windows, then it will be possible to also extend the shading results to doors.

Fig.10.6, Fig.10.7 and Fig.10.8 show the annual heating, cooling and total energy, respectively, for the archetype house with all of the doors established in the previous section. The results show that opaque doors (D11, D12, D13) clearly stand out for both heating and cooling energy. In the heating plot, a higher ER door generally results in lower energy consumption with the exception of opaque doors. The opaque doors use less energy than the glazed doors in Yellowknife, and more energy in the other climates. The line for Vancouver is difficult to see in this plot, but a close up shows that it follows the same pattern as Toronto and Montreal, just with smaller overall differences (as seen in the windows analysis). The cooling plot shows that cooling energy generally increases as the ER increases, but with more variations than in the heating plot. The opaque doors tend to result in lower cooling energy. Since cooling energy is low relative to heating energy, the total energy consumption plot shows similar trends to the heating energy plot.

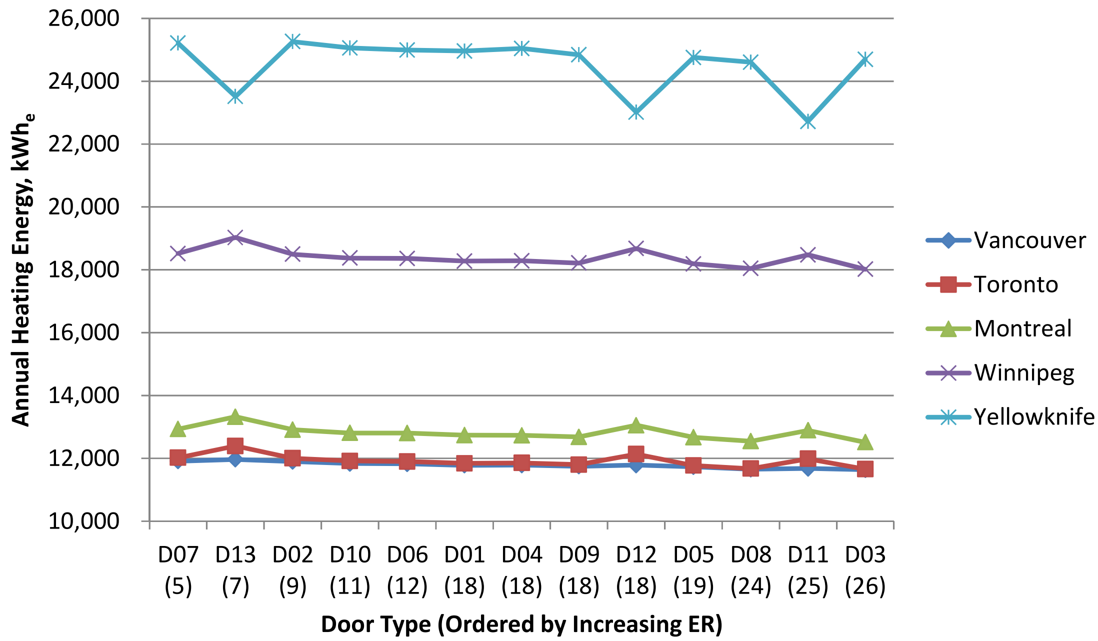


Fig.10.6 Annual heating energy consumption of doors, including all door types, kWh_e.

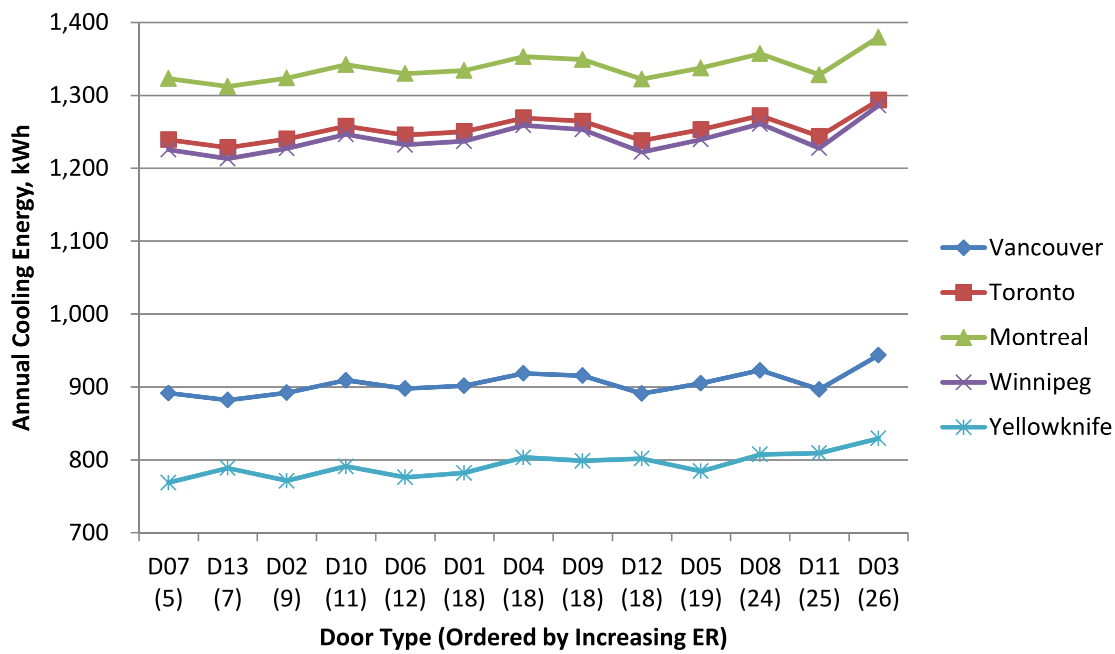


Fig.10.7 Annual cooling energy consumption of doors, including all door types, kWh.

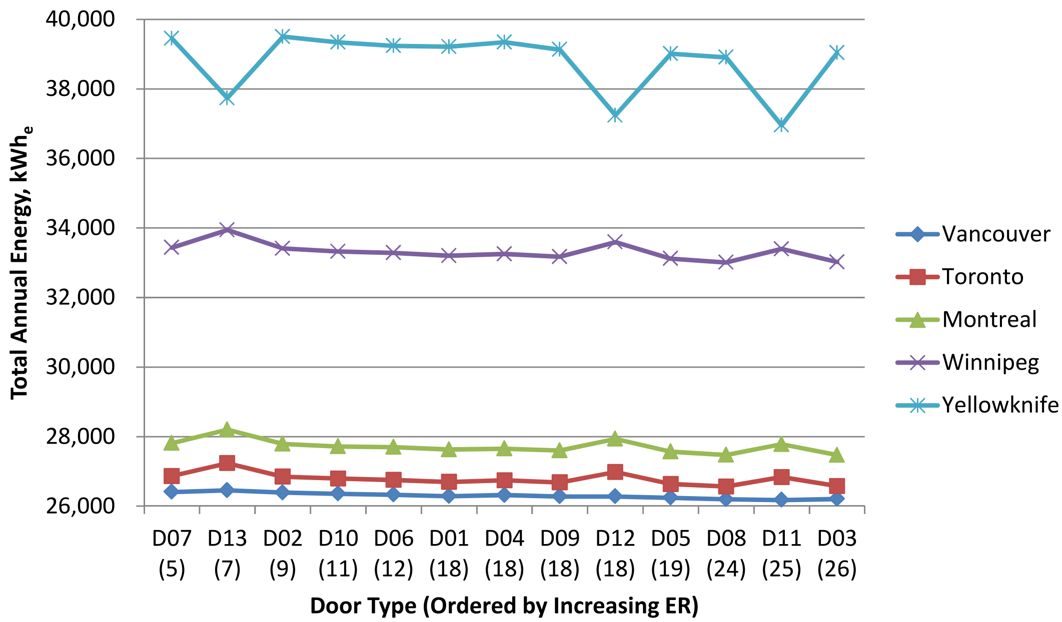


Fig.10.8 Total annual energy consumption of doors, including all door types, kWh$_e$.

Overall, the plots for all door types indicate that ordering doors by increasing ER results in lower heating energy consumption for fully glazed and half glazed doors, but the opaque doors (D11, D12, D13) do not follow this trend when compared to glazed doors. Clearly a fully glazed door versus an opaque door would be expected to perform differently; therefore, it is also important to examine the results by door type. That is, how an opaque door compares to other opaque doors.

Fig.10.9 and Fig.10.10 show the annual heating energy consumption for the fully glazed doors, Fig.10.11 shows the cooling energy consumption and Fig.10.12 shows the total energy consumption. The heating energy plots are separated to show the trends for each city, since Winnipeg and Yellowknife have a much greater energy consumption than the other locations. The results show that for all locations, a higher ER results in lower heating energy consumption. This is consistent with the window findings (Section 7), since a smaller number of doors were simulated (showing general overall trends rather than trends of door products with ER values that are close). The cooling plot shows that energy consumption increases as ER increases for the four glazed doors that were simulated. Cooling energy is much lower than heating energy, and therefore total energy consumption decreases as ER increases, like the heating energy plot.

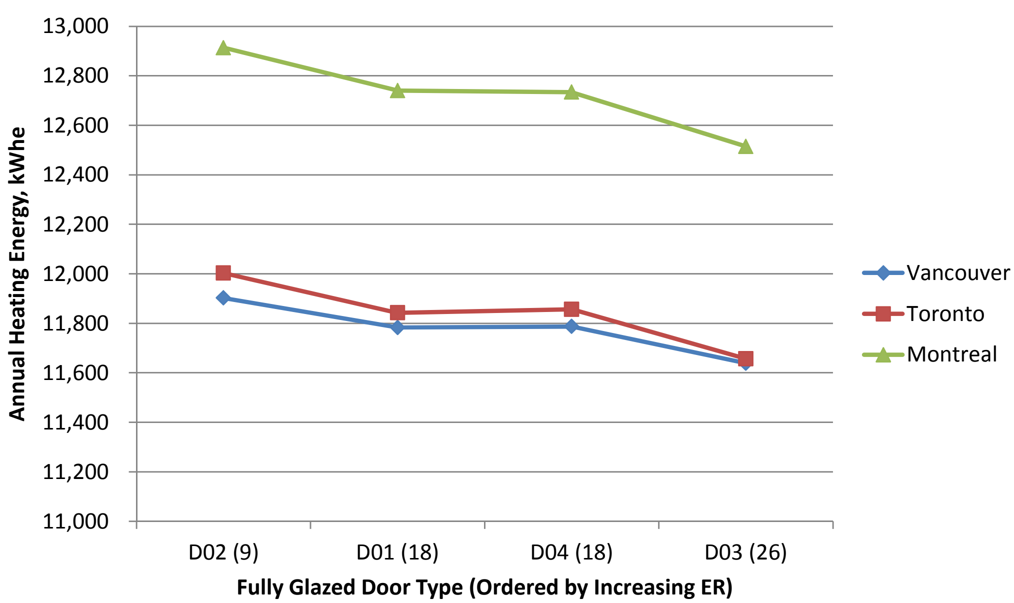


Fig.10.9 Annual heating energy consumption of fully glazed doors, Vancouver, Toronto and Montreal, kWh$_e$.

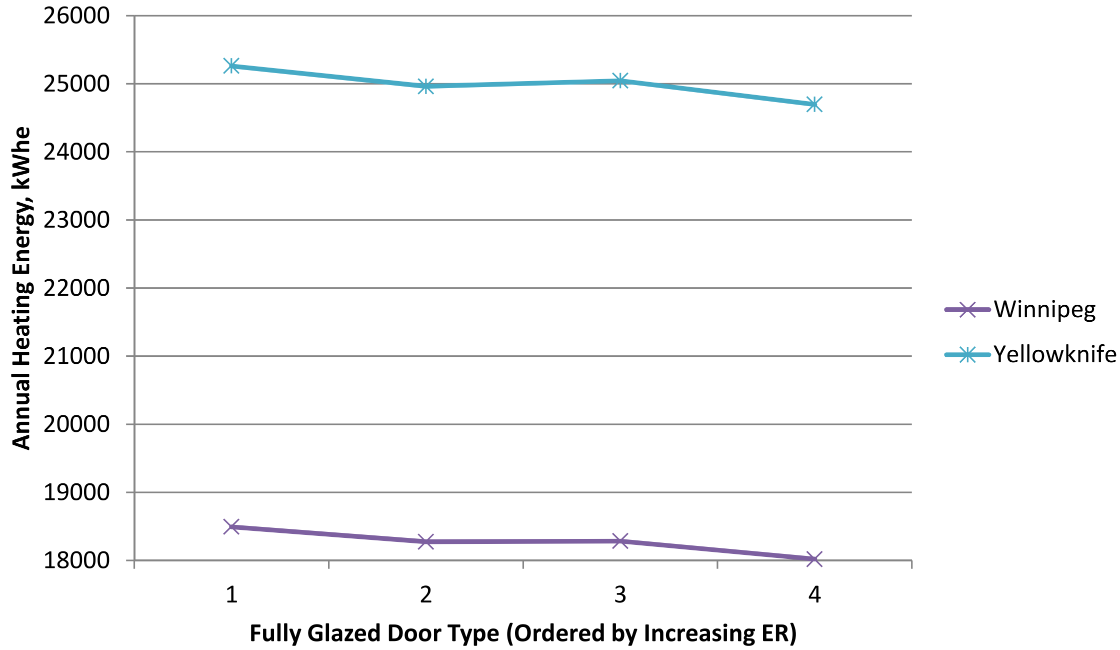


Fig.10.10 Annual heating energy consumption of fully glazed doors, Winnipeg and Yellowknife, kWh_e.

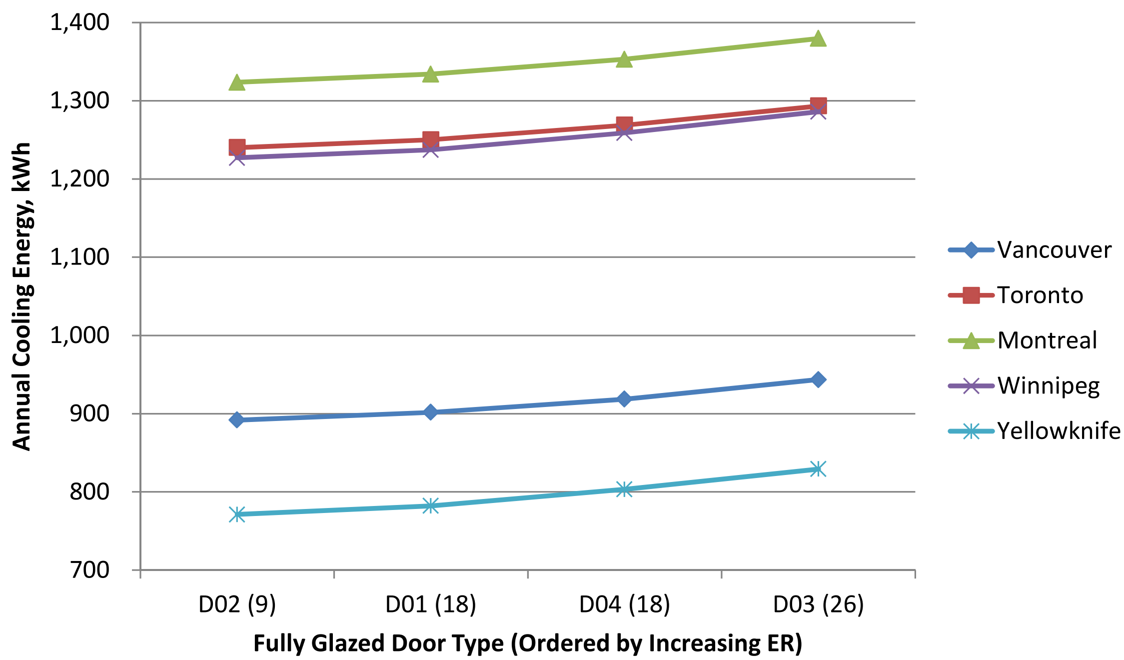


Fig.10.11 Annual cooling energy consumption of fully glazed doors, kWh.

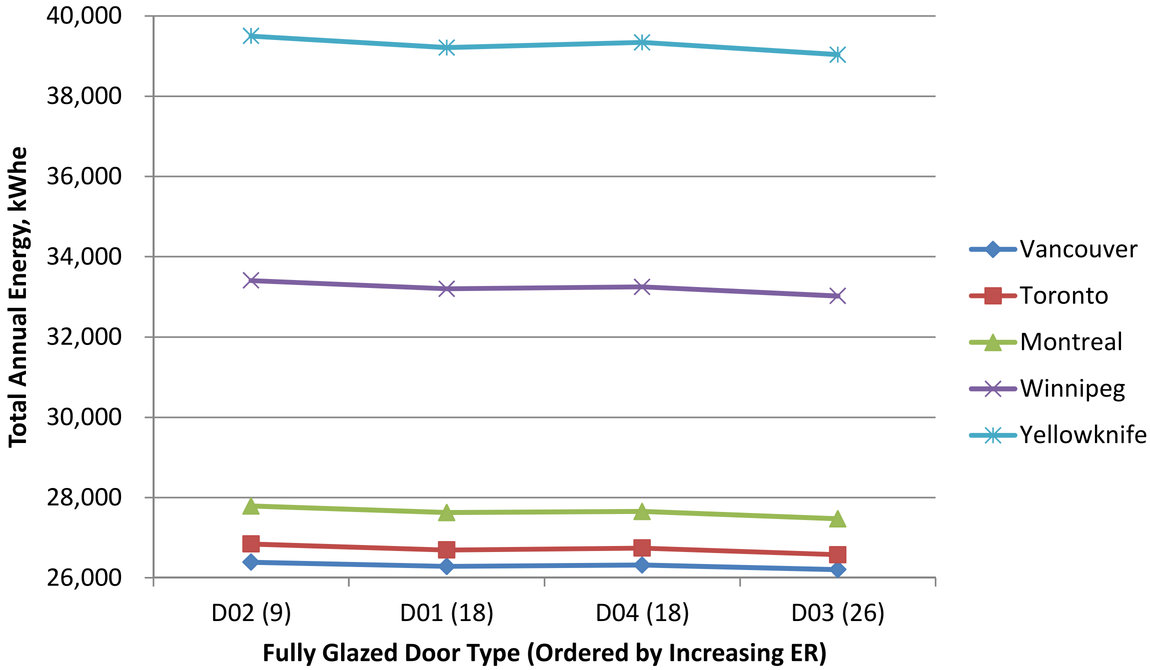


Fig.10.12 Total annual energy consumption of fully glazed doors, kWh_e.

Fig.10.13 and Fig.10.14 show the annual heating energy consumption for the fully glazed doors, Fig.10.15 shows the cooling energy consumption and Fig.10.16 shows the total energy consumption. The heating energy plots are separated to show the trends of each city, since Winnipeg and Yellowknife have a much greater energy consumption than the other locations. As with the fully glazed doors, the results show that for all locations, a higher ER results in lower heating energy consumption. The cooling plot shows that energy consumption generally increases as ER increases for the half glazed doors that were simulated, with two exceptions. Cooling energy is much lower than heating energy, and therefore total energy consumption decreases as ER increases, like the heating energy plot.

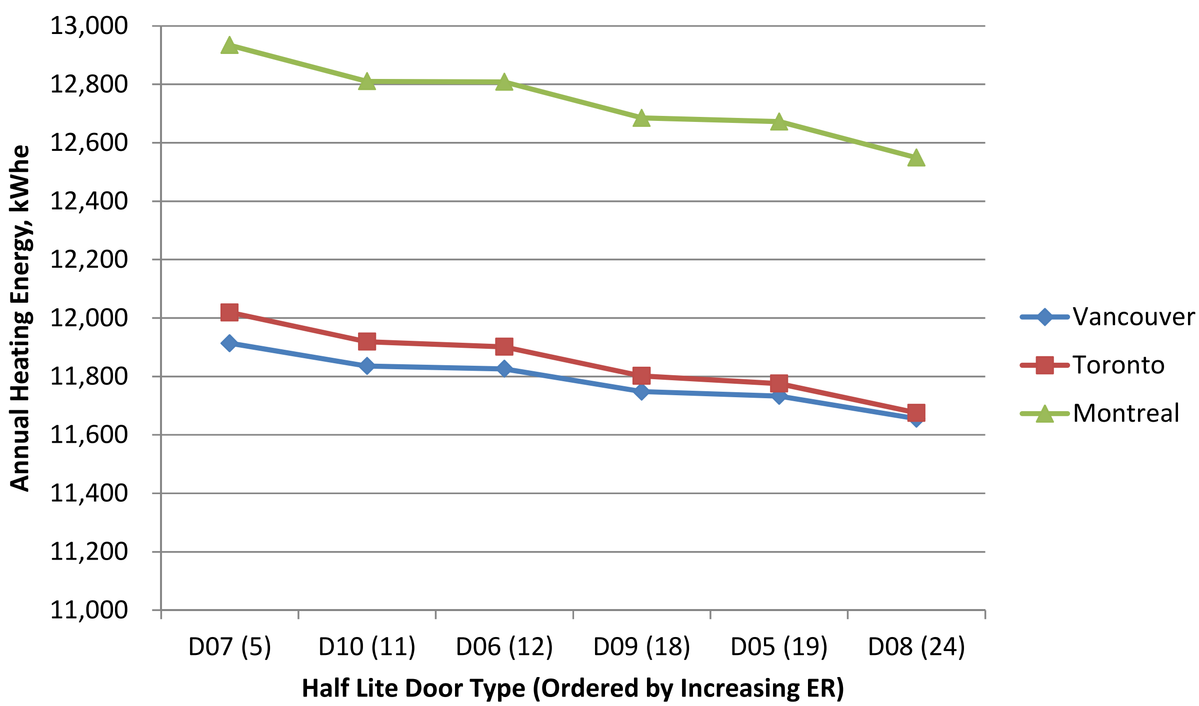


Fig.10.13 Annual heating energy consumption of half lite doors, Vancouver, Toronto and Montreal, kWh_e.

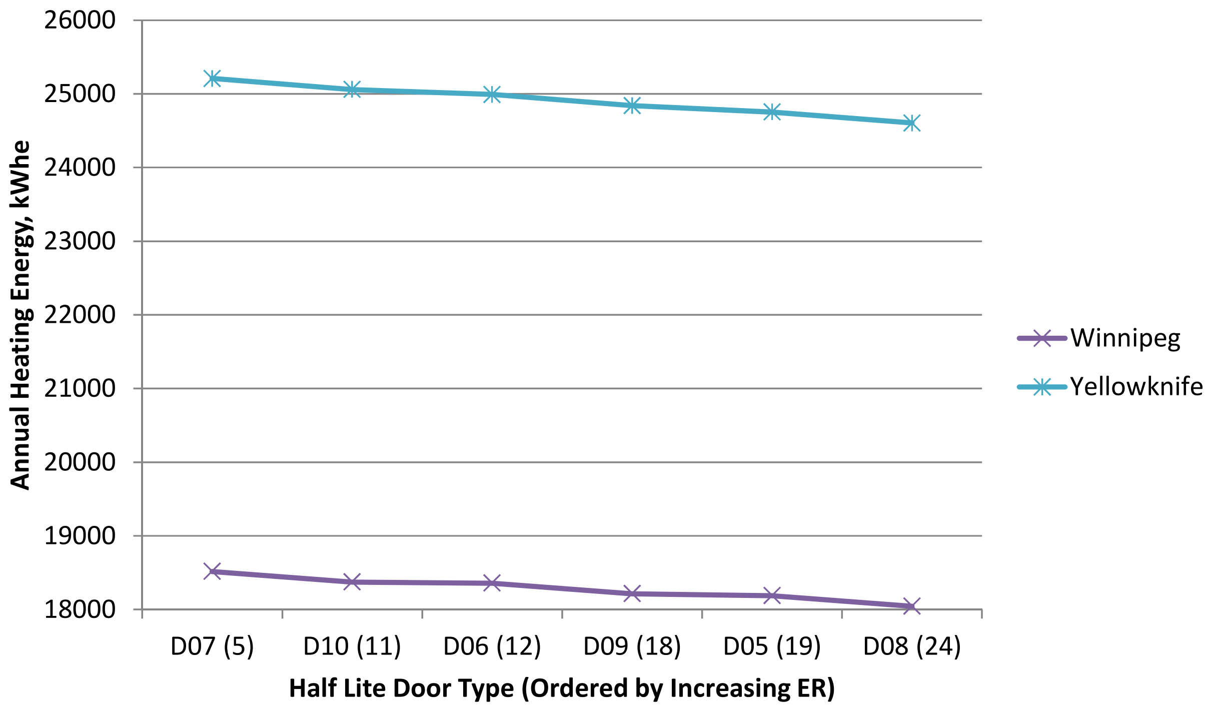


Fig.10.14 Annual heating energy consumption of half lite doors, Winnipeg and Yellowknife, kWh_e.

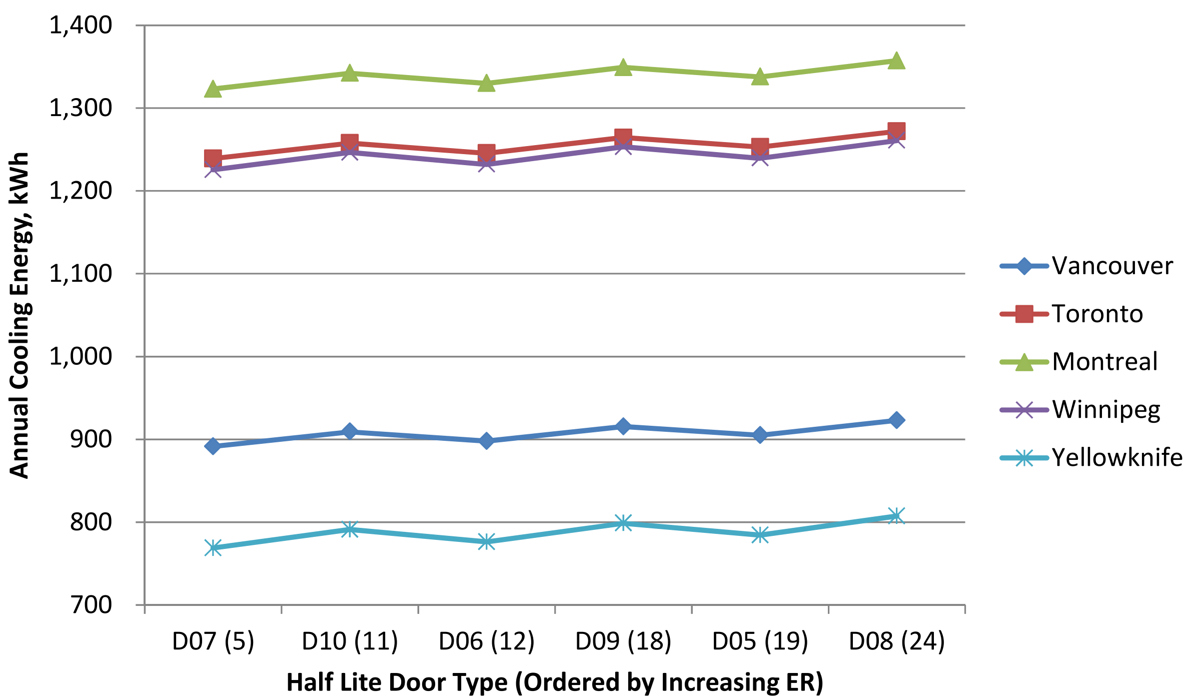


Fig.10.15 Annual cooling energy consumption of half lite doors, kWh.

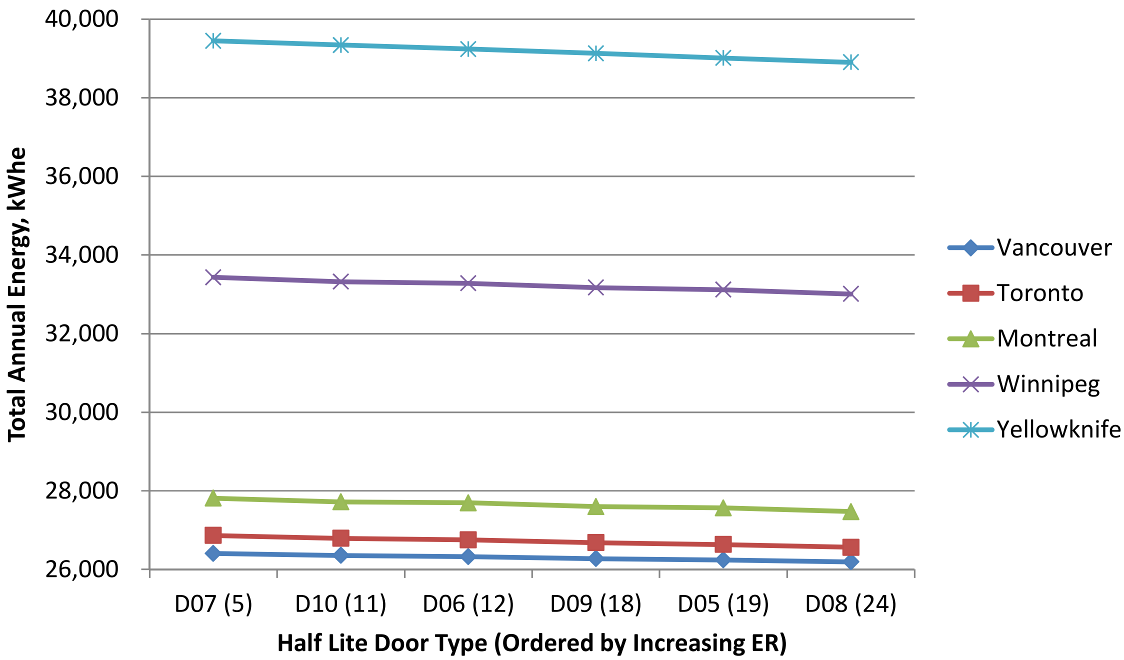


Fig.10.16 Total annual energy consumption of half lite doors, kWh_e.

Fig.10.17 and Fig.10.18 show the annual heating energy consumption for the opaque doors, Fig.10.19 shows the cooling energy consumption and Fig.10.20 shows the total energy consumption. The heating energy plots are separated to show the trends of each city, since Winnipeg and Yellowknife have a much greater energy consumption than the other locations. As with the fully glazed and half glazed doors, the results show that for all locations, a higher ER results in lower heating energy consumption. The cooling plot shows that energy consumption increases as ER increases for the opaque doors that were simulated. Cooling energy is much lower than heating energy, and therefore total energy decreases as ER increases, like the heating energy plot.

The opaque door results confirm that even though the ER does not appropriately rank them compared to glazed doors, when compared to other opaque doors the ER does predict lower energy consumption. This is expected since the SHGC is effectively zero for these doors, and so a higher U-value results in a better ER and lower energy consumption.

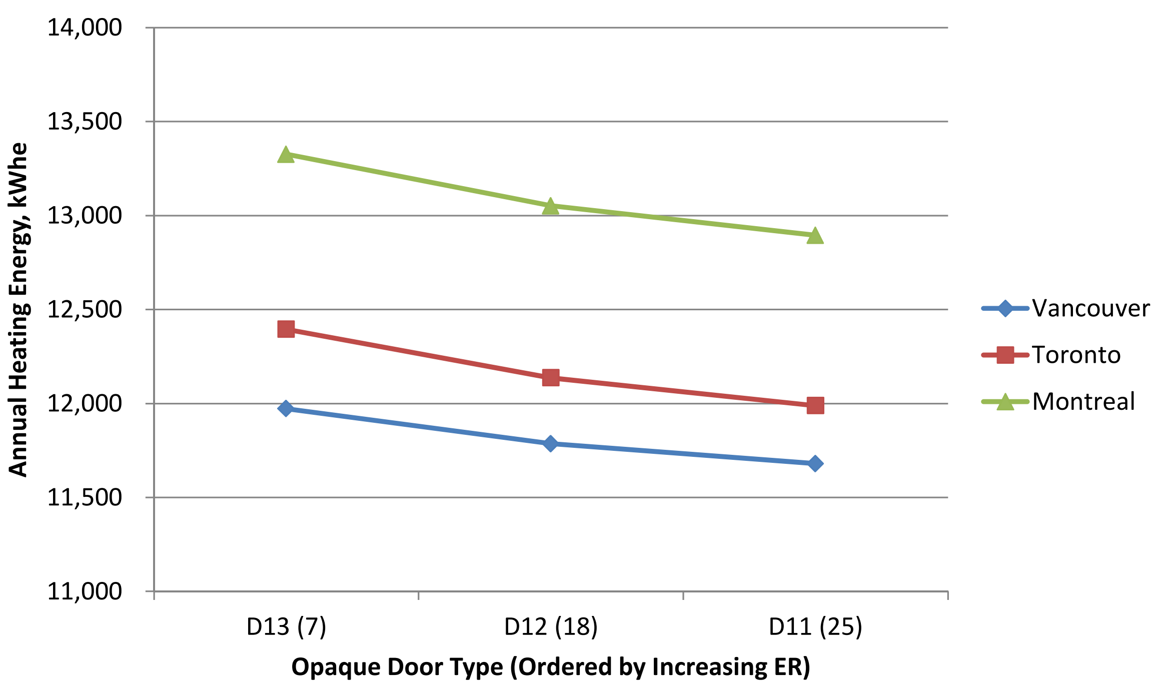


Fig.10.17 Annual heating energy consumption of half lite doors, Vancouver, Toronto and Montreal, kWh_e.

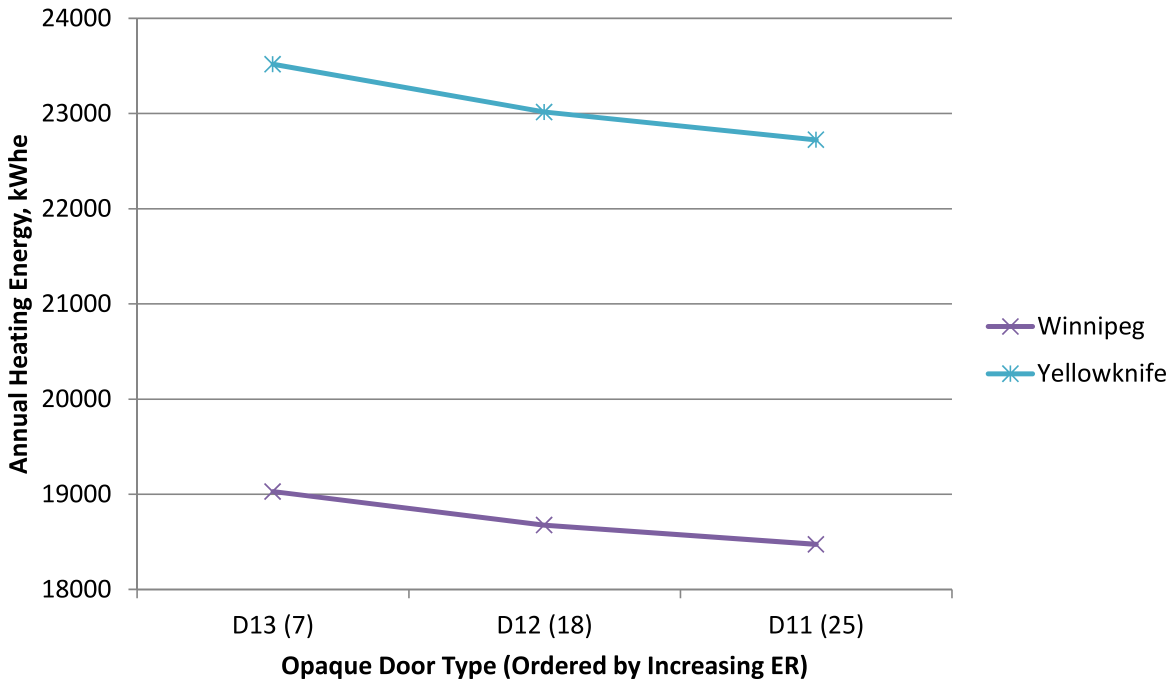


Fig.10.18 Annual heating energy consumption of half lite doors, Winnipeg and Yellowknife, kWh_e.

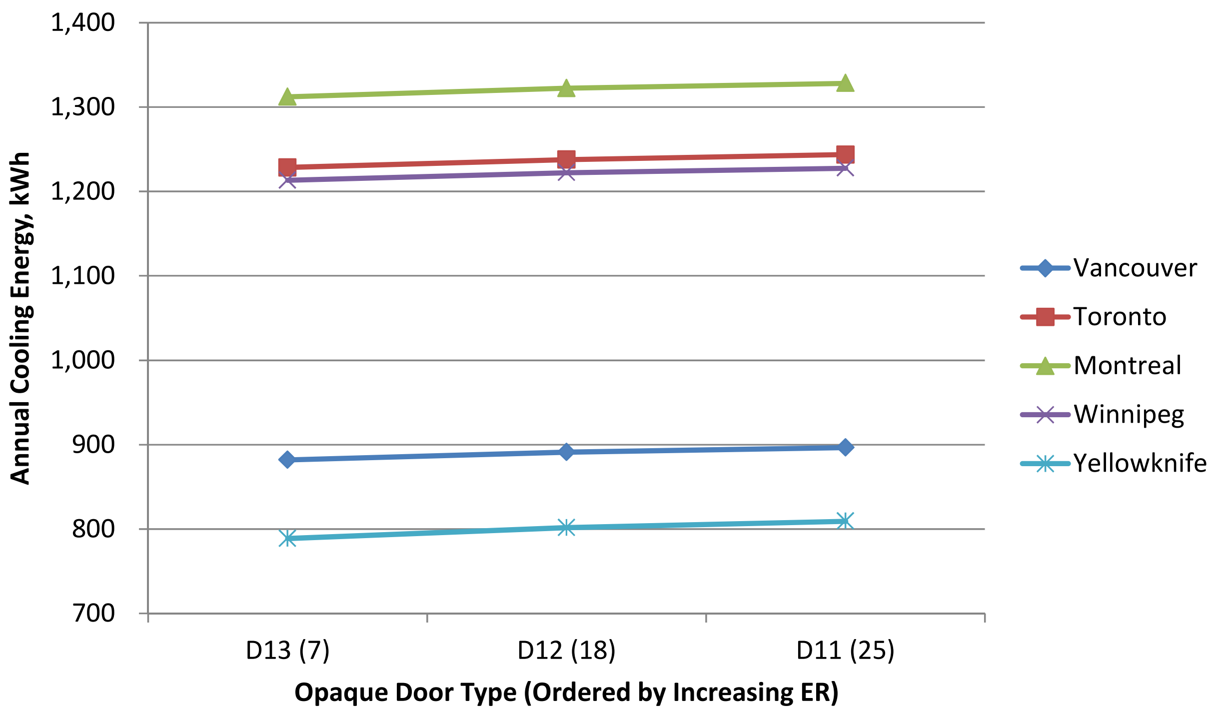


Fig.10.19 Annual cooling energy consumption of opaque doors, kWh.

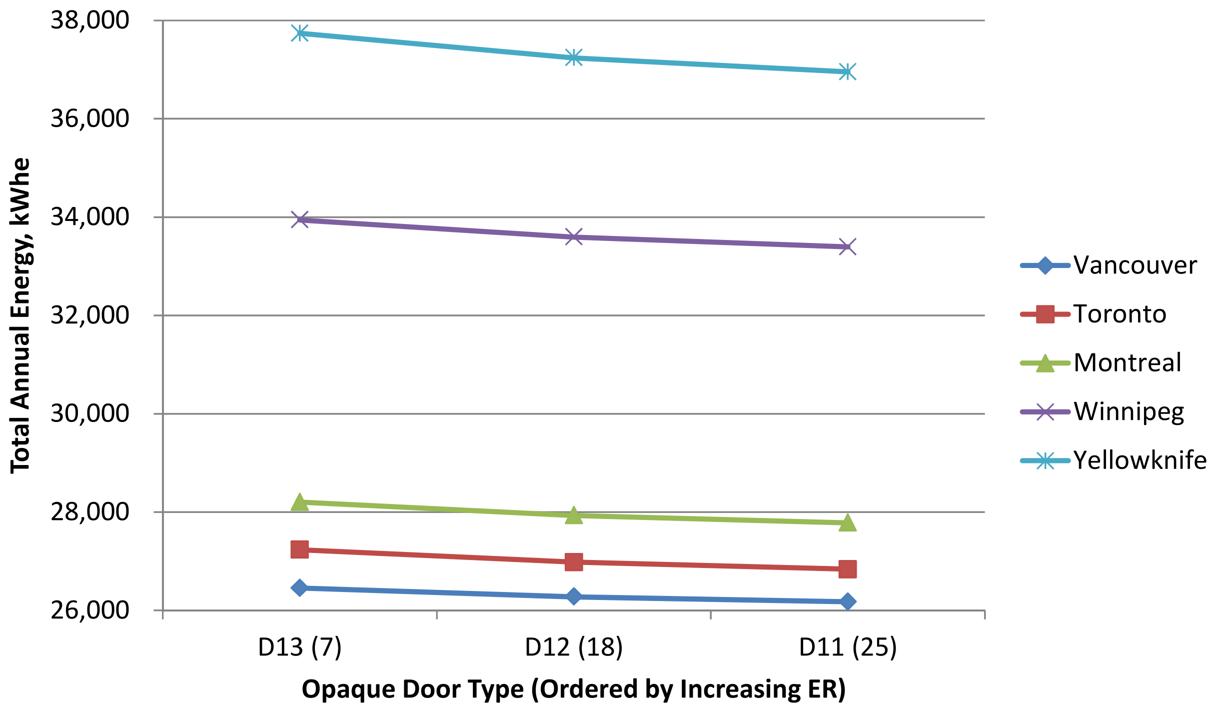


Fig.10.20 Total annual energy consumption of opaque doors, kWh_e.

A range of opaque, half glazed and fully glazed doors were simulated in order to view how the ER ranks energy consumption of doors. Even though the difference in energy consumption is small since they have a relatively low contribution to the house's heating or cooling load, the results still show trends in energy consumption between different door types. The results show that when different product types are compared (e.g. opaque doors versus doors with glazing), a higher ER does not necessarily result in lower energy consumption. However, when the same door type is compared (e.g. examining only opaque doors, or only glazed doors), a higher ER consistently results in lower energy consumption for the doors that were simulated.

A smaller number of door products were simulated to show general trends, and it was seen that a higher ER consistently results in lower energy consumption. For the window simulations, the same general trend was seen, however, within products that were close there were a number of cases where a higher ER did not result in lower energy consumption. It is anticipated that if a large number of door products were simulated this same trend would be seen.

10.2. Skylights

10.2.1 Selection of Skylights

The ENERGY STAR® standard defines skylights as "A window designed for sloped or horizontal application in the roof of a residential building, the primary purpose of which is to provide daylighting and/or ventilation. May be fixed or operable. Skylights have their own set of ENERGY STAR® criteria. Tubular daylighting devices are included under the skylight criteria." Tubular daylighting devices (TDD) are "A non-operable device primarily designed to transmit daylight from a roof surface of a residential building to an interior ceiling surface via a tubular conduit. The device consists of an exterior glazed weathering surface, a light transmitting tube with a reflective inside surface and an interior sealing device, such as a translucent ceiling panel. TDDs are included under the skylight criteria."

The ENERGY STAR® requirements for skylights are shown in Table 10.6; this includes TDDs. There is currently only one path for certifying skylights, the U-value path. The maximum U-value requirements for skylights are much higher than the window U-value requirements, largely because sloped IGUs have higher U-values due to increased convection within the glazing cavity. The CSA ER calculation does not apply to sloped glazing.

Table 10.6 ENERGY STAR® requirements for skylights.

Zone	Heating Degree-Day Range	Maximum U-Factor, W/m^2-K (Btu/h-ft^2-F)
A	≤3500	2.80 (0.50)
B	>3500 to ≤5500	2.60 (0.46)
C	>5500 to ≤8000	2.40 (0.42)
D	>8000	2.20 (0.39)

There are currently 187 skylights in the ENERGY STAR® database. Fig.10.21 shows the percentage of skylights that are certified in each climate zone. The distribution is fairly even between the four zones, with slightly greater percentages certified only in zones A and B. Table 10.7 shows the average, median, minimum and maximum U-values of skylights certified in each zone and overall. The best U-value in the ENERGY STAR® database of skylights is U_{SI}-1.14 (U-0.20). This product corresponds to a triple glazed skylight with two low-e coatings and krypton gas fill in the database.

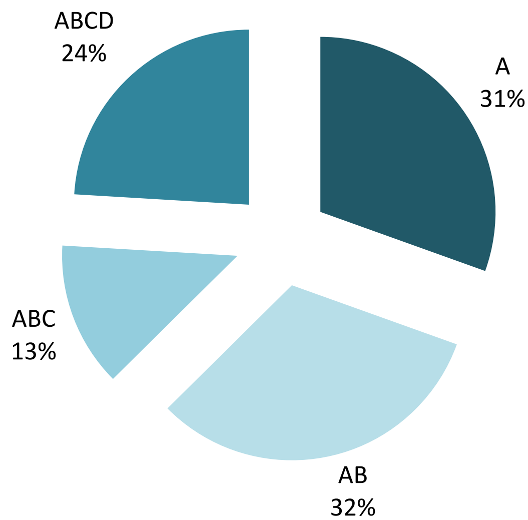


Fig.10.21 Percentage of skylights certified in each climate zone.

Table 10.7 ENERGY STAR® skylight U-value statistics, W/m^2-K (Btu/h-ft^2-F).

	A	AB	ABC	ABCD	Overall
Average	2.73 (0.48)	2.52 (0.44)	2.34 (0.41)	1.86 (0.33)	2.40 (0.42)
Median	2.73 (0.48)	2.53 (0.45)	2.33 (0.41)	1.99 (0.35)	2.48 (0.44)
Minimum	2.61 (0.46)	2.44 (0.43)	2.25 (0.40	1.14 (0.20)	1.14 (0.20)
Maximum	2.84 (0.50)	2.61 (0.46)	2.40 (0.42)	2.21 (0.39)	2.84 (0.50)

The ENERGY STAR® database contains flat-glazed skylights, domed skylights and TDDs. TDDs will be considered separately from flat glazed and domed skylights in this analysis since they have a different range of performance values for the properties being considered. Fig.10.22 shows the distribution of flat-glazed and domed ENERGY STAR® skylights in the database.

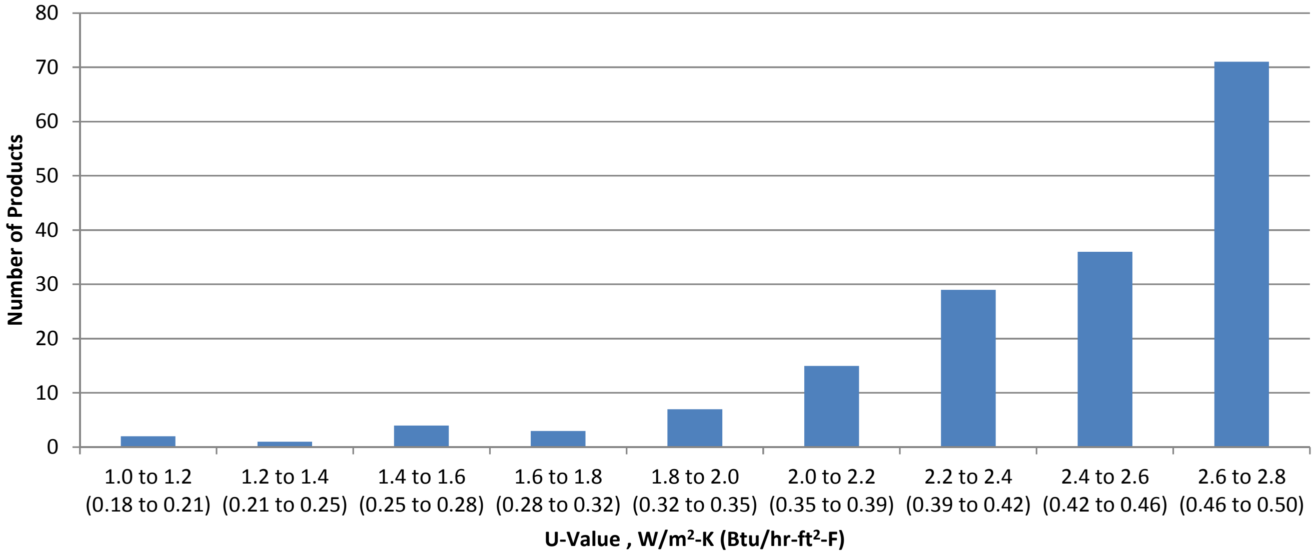


Fig.10.22 Distribution of ENERGY STAR® skylight U-values.

Fig.10.23 shows the distribution of SHGCs for products in the ENERGY STAR® database. Based on these products, three U-values and two SHGCs are chosen for a total of six skylights: U_{SI}-2.0 (U-0.35), U_{SI}- 2.4 (U-0.42), U_{SI}-2.8 (U-0.49); and SHGC-0.20, SHGC-0.35.

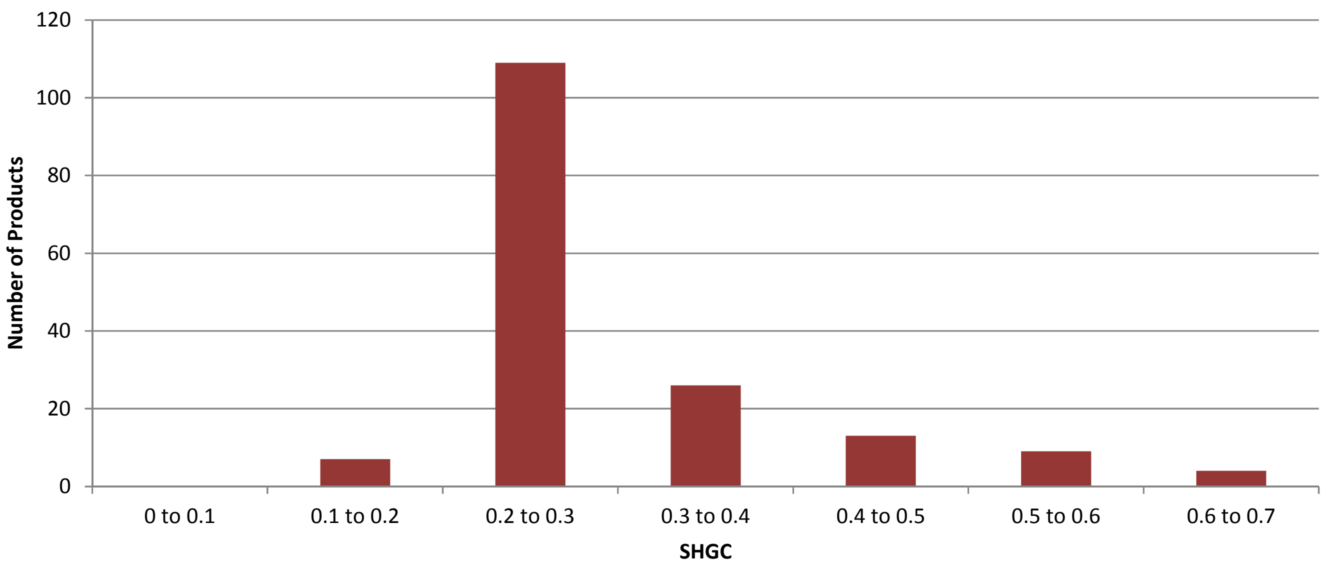


Fig.10.23 Distribution of ENERGY STAR® skylight SHGCs.

There are 19 TDD products in the ENERGY STAR® database. Of the TDDs, the average U-value is U_{SI}-2.06 (U-0.36), with a low of U_{SI}-1.48 (U-0.26) and a high of U_{SI}-2.45 (U-0.43). The SHGC values ranged from 0.15 to 0.35, with an average of 0.24. Two U-values and two SHGCs will therefore be simulated (four TDDs total): USI-1.5 (U-0.26), USI-2.4 (U-0.42), SHGC-0.15, SHGC-0.30. These values result in products similar to those found in the ENERGY STAR® database.

Table 10.8 shows the skylights for energy simulation. Although the current ER does not apply to skylights, a "theoretical" ER was calculated in order to assess the ability of the ER to rate skylights. In the database, 62 products (34%) include CSA A440 air leakage rates. Of these, the average is 0.2 m^3/m/h, with a maximum of 1.2 m^3/m/h and a minimum of 0.001 m^3/m/h. An air leakage rating of 0.55 m^3/h/m (equivalent to an A3 rating) is used for all product ER calculations. Also note that the SHGCs used in the ER calculations are from published manufacturers' data, at normal incidence angle. The SHGC varies with angle of incidence, and while the hourly energy simulations take this into account, the ER calculation using the standard rated SHGC does not account for this.

Table 10.8 Skylights for energy simulation.

	Representative Skylight	U-Value, W/m^2-K (Btu/hr-ft^2-F)	SHGC	"Theoretical" Calculated ER	ENERGY STAR® Zones	Nearest Product in the ENERGY STAR® Database
S01	Flat glazed	2.00 (0.35)	0.20	8	ABCD	U_{SI}-1.99 (U-0.35), SHGC-0.22
S02	Flat glazed	2.40 (0.42)	0.20	-2	ABC	U_{SI}-2.38 (U-0.42), SHGC-0.23
S03	Flat glazed	2.80 (0.49)	0.20	-11	A	U_{SI}-2.78 (U-0.49), SHGC-0.22
S04	Flat glazed	2.00 (0.35)	0.35	16	ABCD	U_{SI}-2.0 (U-0.35), SHGC-0.33
S05	Flat glazed	2.40 (0.42)	0.35	7	ABC	U_{SI}-2.40 (U-0.42), SHGC-0.36
S06	Flat glazed	2.80 (0.49)	0.35	-2	A	U_{SI}-2.8 (U-0.49), SHGC-0.36
T01	TDD	1.50 (0.26)	0.15	16	ABCD	U_{SI}-1.53 (U-0.27), SHGC-0.15
T02	TDD	2.40 (0.42)	0.15	-5	ABC	U_{SI}-2.44 (U-0.43), SHGC-0.24
T03	TDD	1.50 (0.26)	0.30	24	ABCD	U_{SI}-1.48 (U-0.26), SHGC-0.23
T04	TDD	2.40 (0.42)	0.30	5	ABC	U_{SI}-2.44 (U-0.43), SHGC- 0.33

10.2.2 Energy Analysis of Skylights

The skylight simulations were run using the same baseline archetype house as described in the previous sections (single-storey, typical existing enclosure, natural gas furnace and central air conditioning). Skylights were added to the house to assess the difference between various skylight parameters and their calculated ER value. Two types of skylights were simulated: flat glazed skylights and Tubular Daylighting Devices (TDDs). The skylights and TDDs were simulated using standard NFRC sizes, however multiple skylights had to be added to the model in order to view changes in energy consumption, particularly for the TDDs which have a small surface area. The flat glazed skylights and TDDs are assessed separately since these are different products.

Two flat glazed skylights were added to the baseline archetype house simulation. For each skylight type identified in the previous section, the simulations were run with skylights facing each cardinal direction, plus north-south, east-west, and with an equal area of skylights facing each direction. Skylights were simulated in different directions since houses would often have skylights facing only one direction, though multiple directions were also simulated for comparison. In all cases the model contained the same area of skylights. The skylights were placed on the roof, sloped at the same angle as the roof pitch (30 degrees). The roof construction was changed to a cathedral ceiling so that the skylights look into the interior space (no attic).

The difference in total household energy consumption between different skylight types is very low, even smaller than the door simulations, however the results can still be used to view trends between the different products and their ER's.

A primary factor in the difference between the performance of windows and skylights is that skylights are typically positioned at an angle (or horizontal), whereas windows are vertical. The angle of incidence, and hence the angle of the glazing, is an important factor in the amount of solar radiation incident on the window, and the solar heat gain to the space. In Canada, glazing that is at a higher slope (i.e. closer to vertical) results in more solar heat gain in the winter when the sun is lower in the sky. Glazing that is at a lower slope (i.e. closer to horizontal) results in more solar heat gain in the summer when the sun is higher in the sky. The SHGC of a glazing product varies with the angle of incidence, and this is modeled in the hourly energy simulation program. It is recognized that the ER was not intended for sloped glazing, however the following analysis is completed to determine how the existing ER calculation relates to skylights that are at a slope.

Fig.10.24, Fig.10.25 and Fig.10.26 show the heating, cooling and total annual energy consumption, respectively, for the different skylight simulations in Vancouver. The results show that the skylights follow the same trend of increasing and decreasing energy consumption for different orientations in the heating and cooling plots. For total energy, there is one anomaly where the south and north-south orientations differ from the other orientations between two skylights with the same ER. It is interesting that the trends do not change for different orientations, unlike the results for windows. It is likely that this occurs because the skylight is at a slope, and a north-facing skylight receives more incident direct solar radiation than a window.

The heating plot shows that energy consumption generally decreases as the ER increases, with the exception of skylight S01 (U_{SI}-2.0 or U-0.35, SHGC-0.20), which has a higher energy consumption than S05 (U_{SI}-2.4 or U-0.49, SHGC-0.35) and S06 (U_{SI}-2.8 or U-0.49, SHGC-0.35). This shows that, in this case, the low U-value provides a better thermal performance than a higher SHGC.

The cooling energy plot shows that cooling energy generally increases with ER, though S01 is again an anomaly. The total energy plot generally follows the trend of the heating energy plot, however the large anomaly seen at S01 in the heating plot only occurs at south and north-south elevations in the total energy plot.

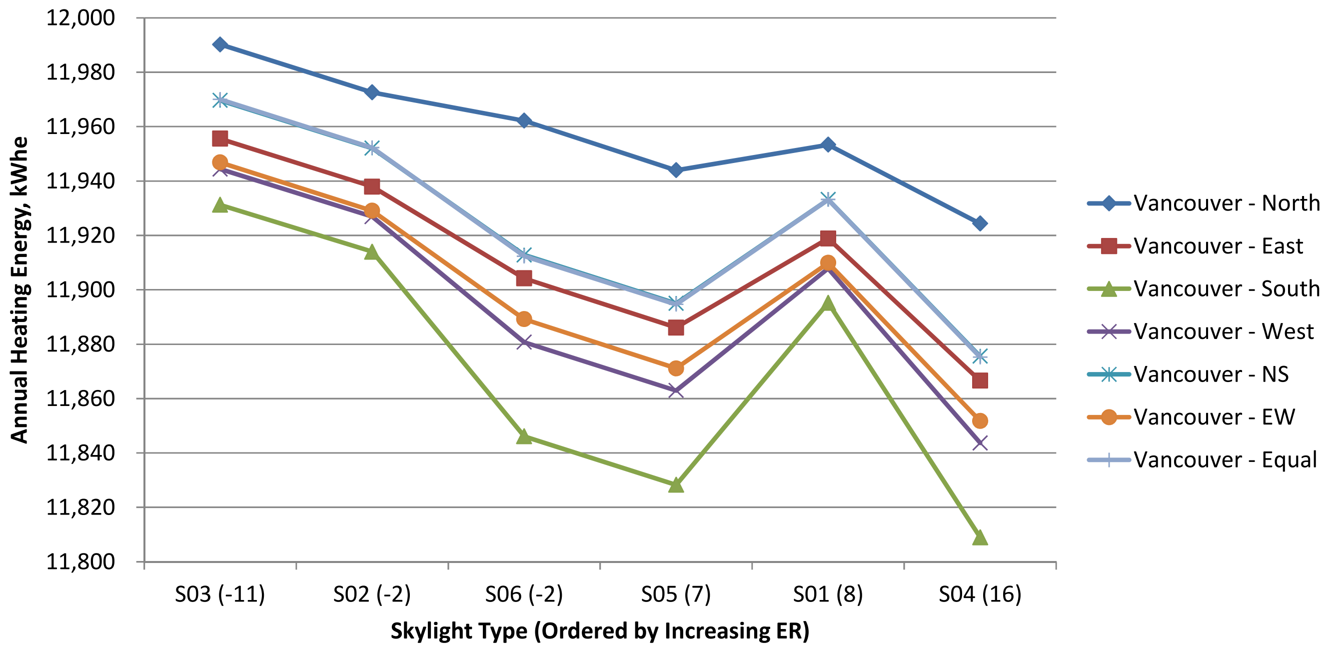


Fig.10.24 Annual heating energy consumption, Vancouver, kWh_e.

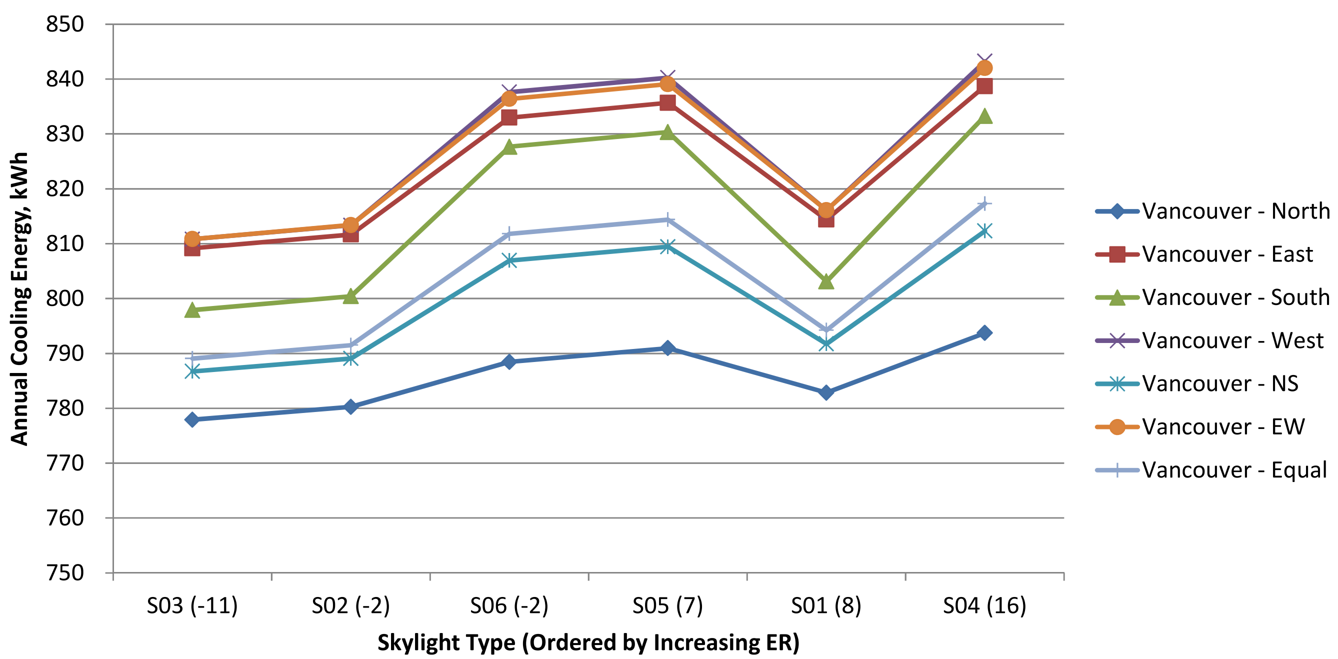


Fig.10.25 Annual cooling energy consumption, Vancouver, kWh.

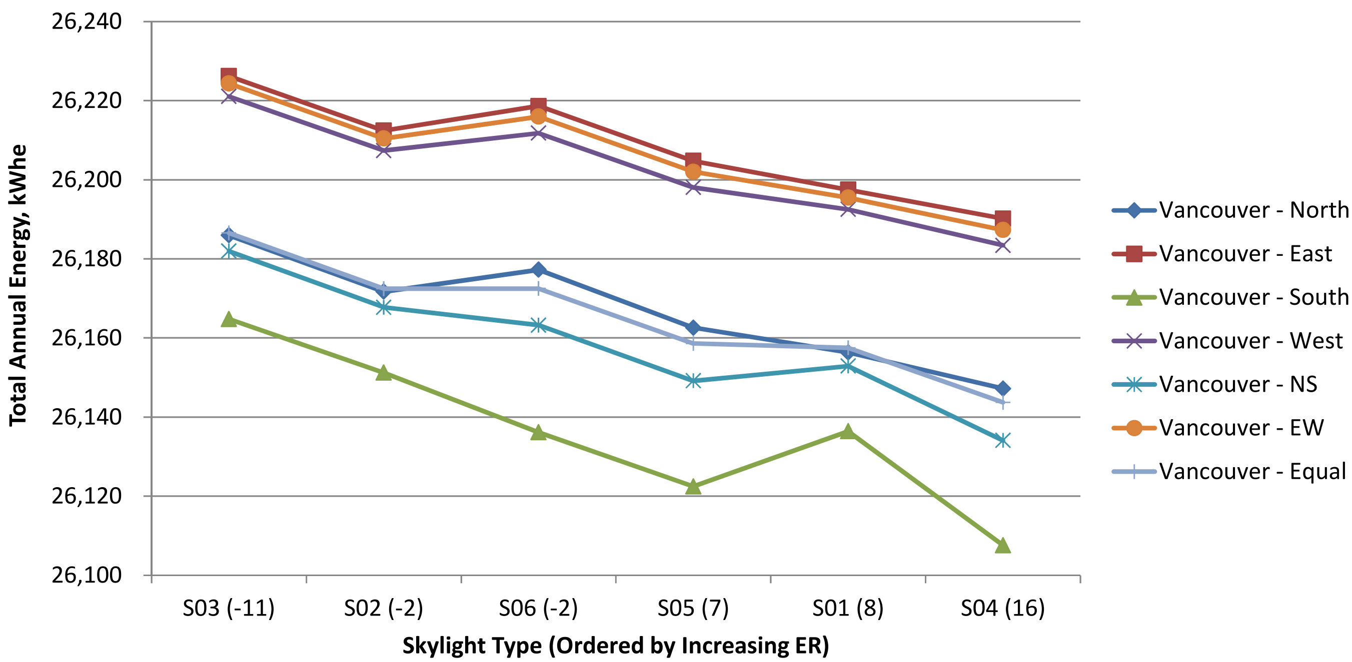


Fig.10.26 Total annual energy consumption, Vancouver, kWh_e.

The skylight simulations were also run for Toronto, Montreal, Winnipeg, and Yellowknife. The majority of the plots for these locations follow the same trend as the Vancouver plots shown in this section, and are therefore provided in Appendix E. The only exception is in Winnipeg and Yellowknife, where the heating energy plot shows an increase in energy consumption from S02 to S06 for the north orientation, and a decrease in energy for the other orientations. This is shown in Fig.10.27. This occurs because of the lower amount of solar heat gain at the north elevation at locations that are further north. A similar trend was seen in the window analysis, where a lower U-value provides better performance than a high SHGC in far north locations that do not receive as much solar radiation in the winter.

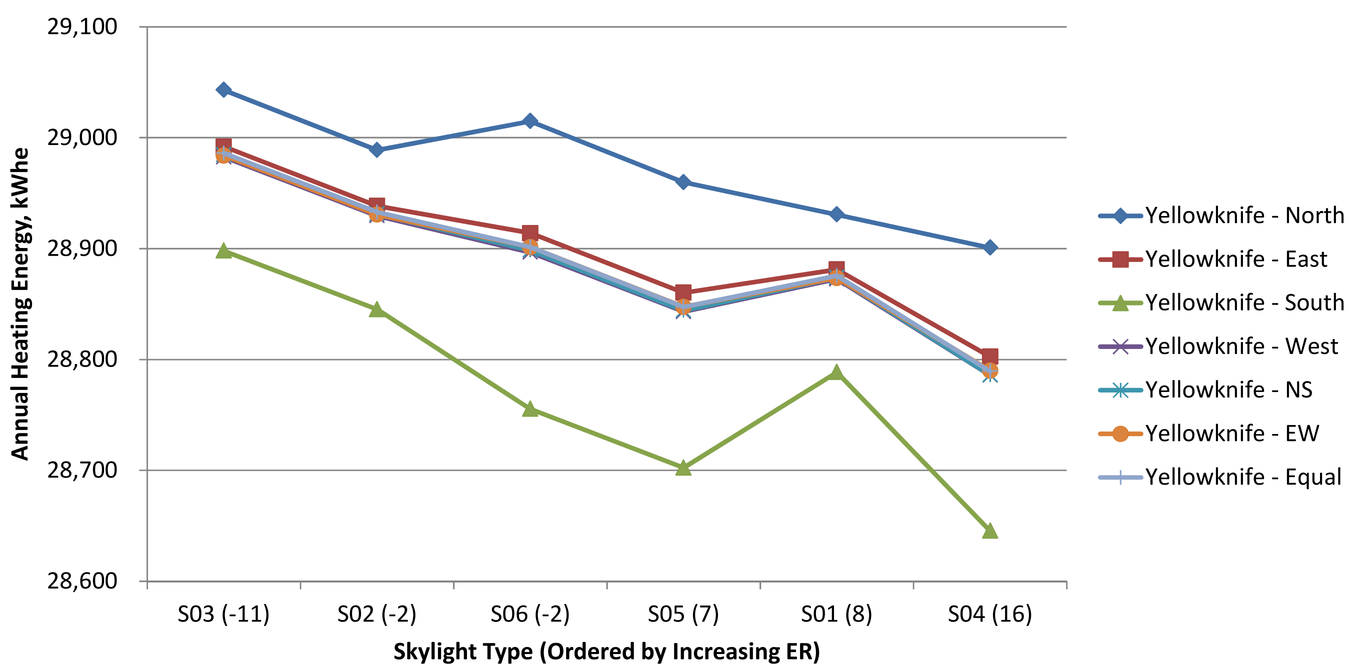


Fig.10.27 Total annual energy consumption, Vancouver, kWh_e.

The second set of skylight simulations were performed for TDDs. Since TDDs are very small relative to the overall building enclosure of the house, eight TDDs had to be added to the model in order to view trends in changing energy consumption between different product types. As with the flat glazed skylights, simulations were run with all TDDs facing each cardinal direction, north-south, east-west, and equally distributed in all four directions. Each simulation included the same area of TDDs in the model.

Fig.10.28, Fig.10.29 and Fig.10.30 show the annual heating, cooling and total energy consumption for the TDD simulations in Vancouver. The results show that the skylights generally follow the same trend of increasing and decreasing energy consumption for different orientations in the heating and cooling plots. In the heating plot there is one occurrence where the north orientation energy increases while the other orientations decrease (T04 to T01). In this case, T01 (U_{SI}-1.5 or U-0.26, SHGC-0.15) has a better ER but a higher energy consumption than T04 (U_{SI}-2.4 or U-0.42, SHGC-0.30) for all elevations except the north, which receives less solar radiation.

The cooling energy plot shows that all orientations follow the same trend of increasing or decreasing energy consumption. In the total energy plot, it is interesting that each orientation plot shows a trend of decreasing total energy consumption as the ER improves. It appears that the differences in heating and cooling balance out such that the result is always a decrease in energy for a better ER.

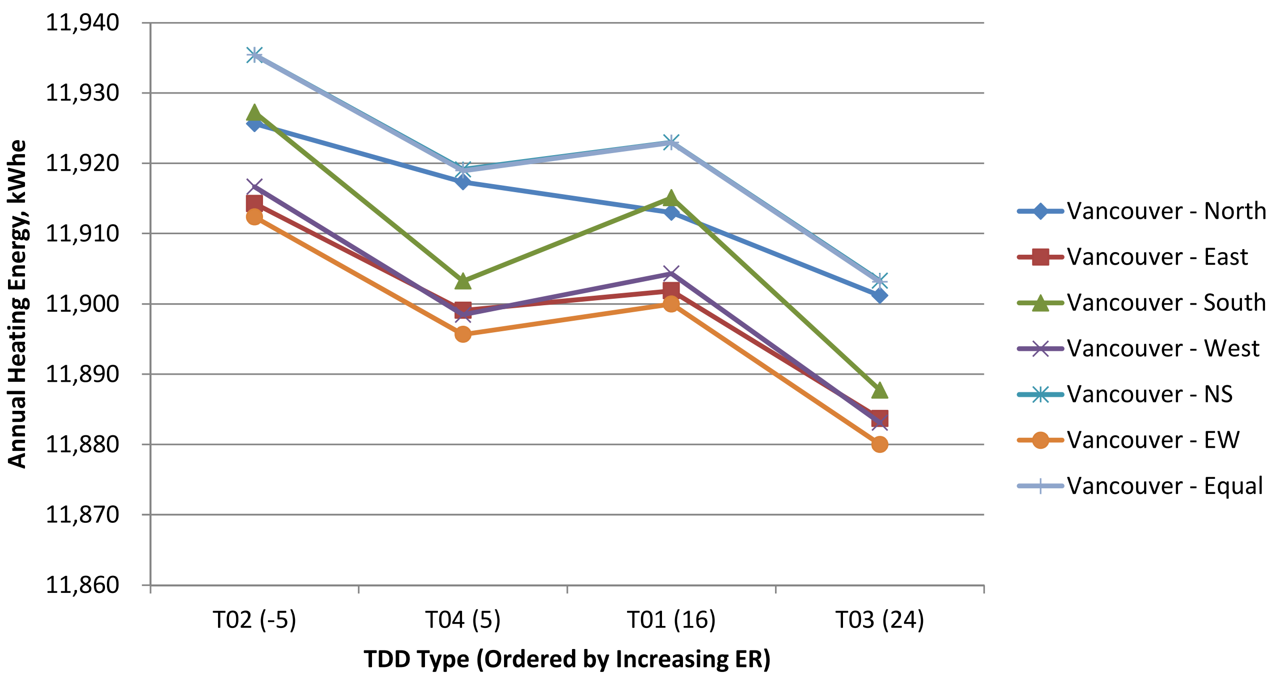


Fig.10.28 Annual heating energy consumption, Vancouver, kWh_e.

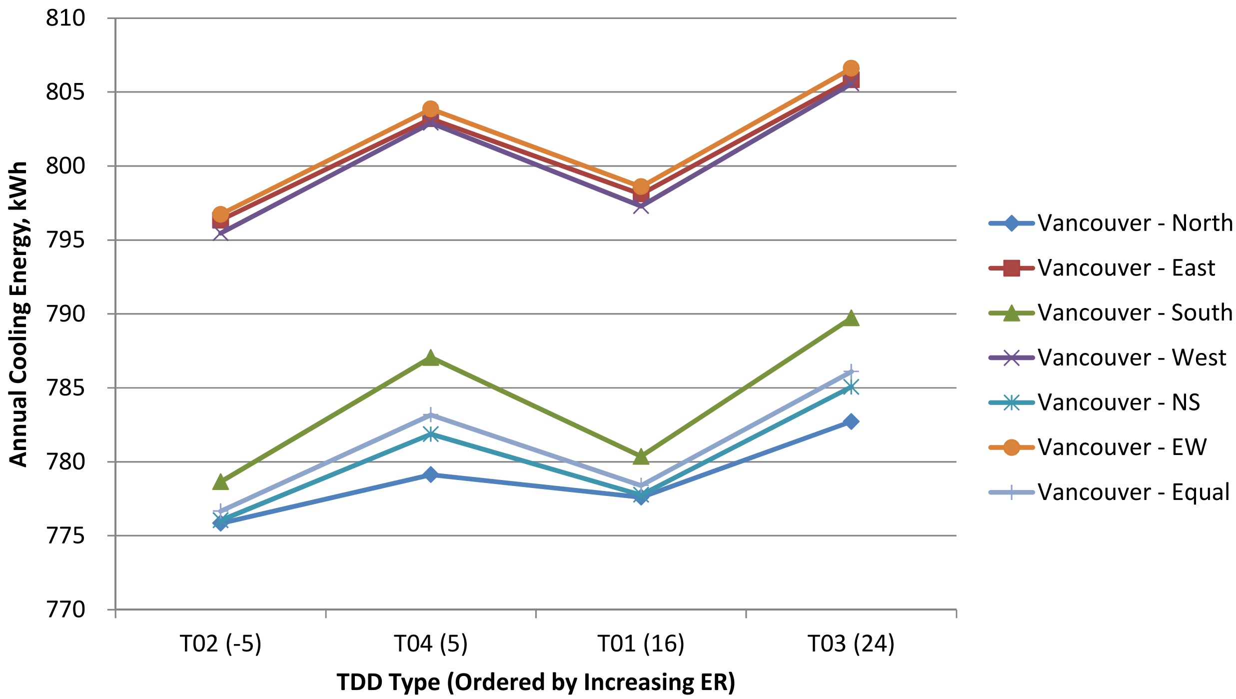


Fig.10.29 Annual cooling energy consumption, Vancouver, kWh.

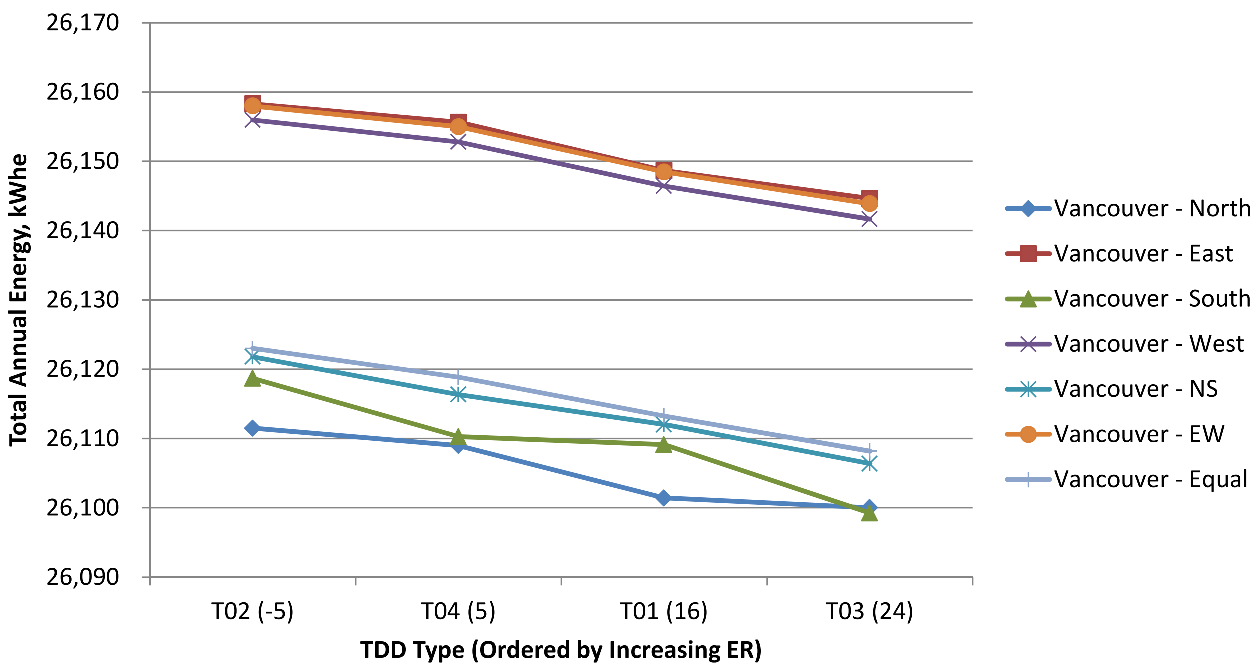


Fig.10.30 Total annual energy consumption, Vancouver, kWh_e.

The TDD simulations were completed for four additional cities, including Toronto, Montreal, Winnipeg and Yellowknife. The trends seen in the simulations of the other cities are generally the same as the trends in the Vancouver plots and, therefore, plots for the remaining locations are provided in Appendix E. The one exception to this is the plot of heating energy in Yellowknife, shown in Fig.10.31. In this case, heating energy decreases as the ER increases for T04 (U_{SI}-2.4 or U-0.42, SHGC-0.30) to T01 (U_{SI}-1.5 or U-0.26, SHGC-0.15) for all orientations except south. This occurs because of the lower solar radiation in the far north, meaning a low U-value provides better performance than a high SHGC.

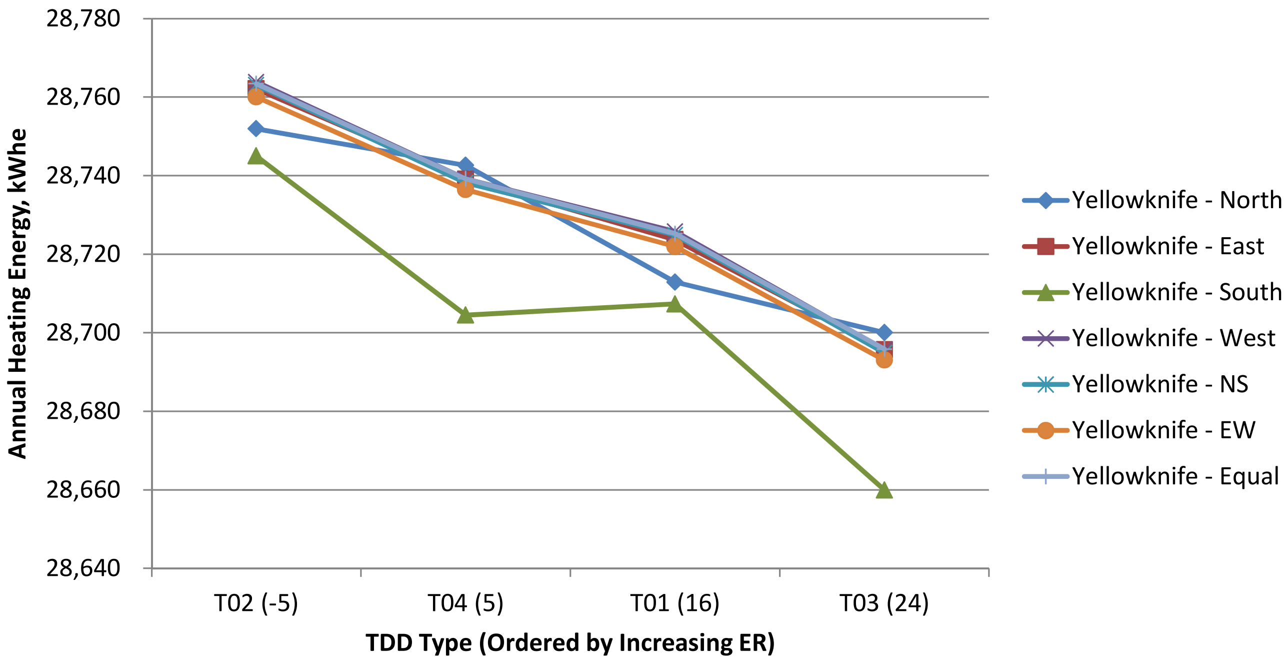


Fig.10.31 Annual heating energy consumption, Yellowknife, kWh_e.

A range of flat glazed skylights and TDDs were simulated in order to view how the ER calculated for these products ranks energy consumption. The difference in energy consumption between different skylight products is small since they have a relatively low contribution to the house's heating or cooling load, however, the results still show trends in energy consumption between different products.

The energy simulation results for skylights showed that heating energy generally decreased with improved ER, though there were several areas where this was not the case even for products with very different ER's. For flat glazed skylights, S01 (ER of 8) had a higher energy consumption than S05 (ER of 7) and S06 (ER of -2). For TDDs, T01 (ER-16) had a higher energy consumption than T04 (ER of 5). For the window energy simulations it was found that anomalies occurred between windows with an ER that are close. However, this does not appear to be the case for the skylights that were simulated, where several anomalies occur between products with significantly different ER values.

10.3. Summary

This analysis was completed to investigate the application of the current ER calculation to doors and skylights. Several door and skylight products were selected for energy analysis using the NRCan ENERGY STAR® database of doors and skylights. For doors, it was seen that the ER does not appropriately compare opaque doors to glazed doors. However, when comparing door products that are the same type (e.g. opaque doors to opaque doors, or fully glazed doors to fully glazed doors), products with a higher ER generally have a lower heating and total energy consumption. This is consistent with the findings for windows. It is anticipated that if a larger number of doors were simulated, with ER values that are close together, some small anomalies would be seen as with the window findings.

For skylights, within the flat glazed and TDD products that were simulated, a number of anomalies were seen where a product with a much higher ER value resulted in greater heating energy consumption than a product with a lower ER value.

11. Multi-Unit Residential Buildings

Multi-unit residential buildings perform differently than houses since these buildings can have higher glazing ratios and less shading. The purpose of this section is to perform a preliminary investigation of the extension of the ER to multi-unit residential buildings. Three archetypes are developed for analysis in this section: a row house (both end unit and middle unit are investigated), a four-storey low-rise building of combustible construction, and a 20-storey high-rise building of non-combustible construction. Energy simulations were completed for each archetype, similar to the analysis completed in Section 7. The following sections discuss the results for each of the three archetypes.

11.1. Row House

11.1.1 Model Set-Up

The energy model for the row house archetype was established based on an archetype house developed through a previous project[17]. Row houses are different from the single- and two-storey house used for the previous sections in that they tend to have a rectangular floor plate, and one or two of the elevations are adjacent to another dwelling unit and are therefore adiabatic (i.e. no heat transfer). Two row house archetypes are simulated, an end unit and a middle unit. Each unit was simulated for two orientations, with the long axis facing north-south and east-west. A complete set of inputs is shown in Appendix F, however, the following is a brief summary of the row house archetype model.

- Two-storeys plus basement
- Sloped roof
- 6m by 10m floor plate for a total floor area of 120 m^2 (1,300 sf) excluding the basement, or 180 m^2 (1,900 sf), including the basement
- Same enclosure construction as the previous archetypes (typical “existing” enclosure thermal performance)
- 15% window to wall ratio at the front and back, 5% window to wall ratio at the exposed side (for the end unit)
- Same HVAC system as the previous archetypes for houses (gas furnace, central air conditioning, intermittent exhaust fans)
- Shading provided by 0.5m roof overhang only
- No natural ventilation (assumed windows are closed throughout the summer)
- Same window types as simulated with the pervious archetypes

The energy consumption of the row house archetype was examined to ensure the results are representative of typical household energy consumption in Canada. Fig.11.1 shows the distribution of household energy consumption for the end unit facing north-south in Vancouver. This simulation has a total annual energy consumption of 201 kWh/m^2 (not including basement area), with 42% heating energy. By comparison, the single-storey house had an energy consumption of 268 kWh/m^2 (not including basement area), with 46% heating energy. The row house archetype would be expected to have a lower heating energy intensity since it has less enclosure area (one adiabatic wall, in this case) and less window area (5% window to wall ratio on the exposed side). Otherwise, the energy distribution plots are similar for the two archetypes.

[17] Near Net Zero Building Enclosure Retrofits for Houses, 2011, by RDH Building Engineering Ltd. for Canada Mortgage and Housing Corporation (CMHC).

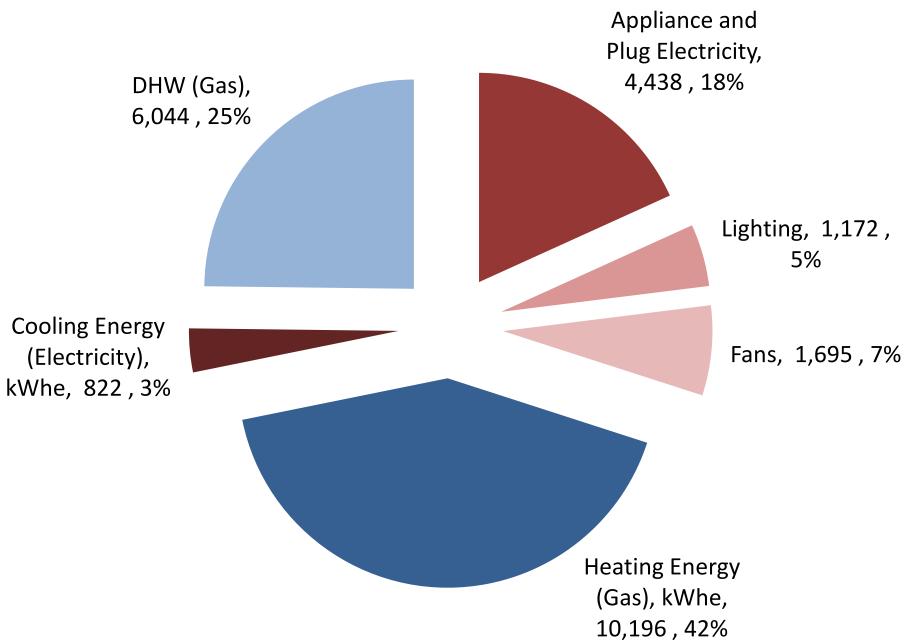


Fig.11.1 Distribution of row house end unit (north-south) household energy consumption in Vancouver, kWh_e and percent of total.

Fig.11.2 shows the distribution of household energy consumption for the middle unit facing north-south in Vancouver. The total annual energy consumption of this archetype is 180 kWh/m^2 (excluding basement floor area), of which 38% is for heating. As expected, this unit has a lower energy intensity and a lower proportion of space heating since it has less exterior enclosure area (two adiabatic walls adjacent to other units).

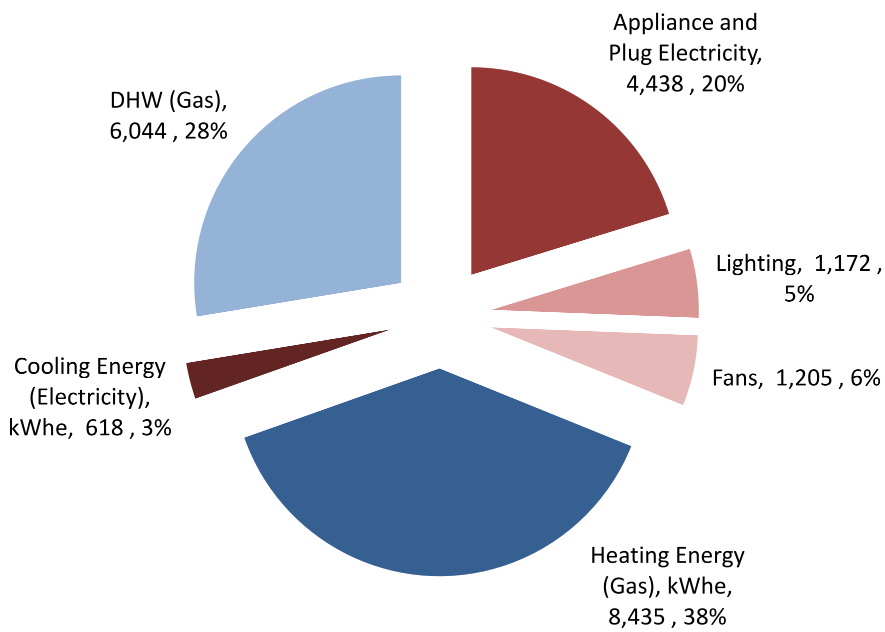


Fig.11.2 Distribution of row house middle unit (north-south) household energy consumption in Vancouver, kWh_e and percent of total.

Fig.11.3 shows the distribution of household energy consumption for the end unit facing north-south in Toronto. This simulation has a total annual energy consumption of 210 kWh/m^2 (not including basement floor area), with 42% heating energy. By comparison, the single-storey archetype house in Toronto had an energy consumption of 277 kWh/m^2, with 46% heating. As with the Vancouver simulations, it is expected that the row house would have a lower energy intensity and a lower percentage of energy for heating due to the lower enclosure area. The energy distribution plots are otherwise similar.

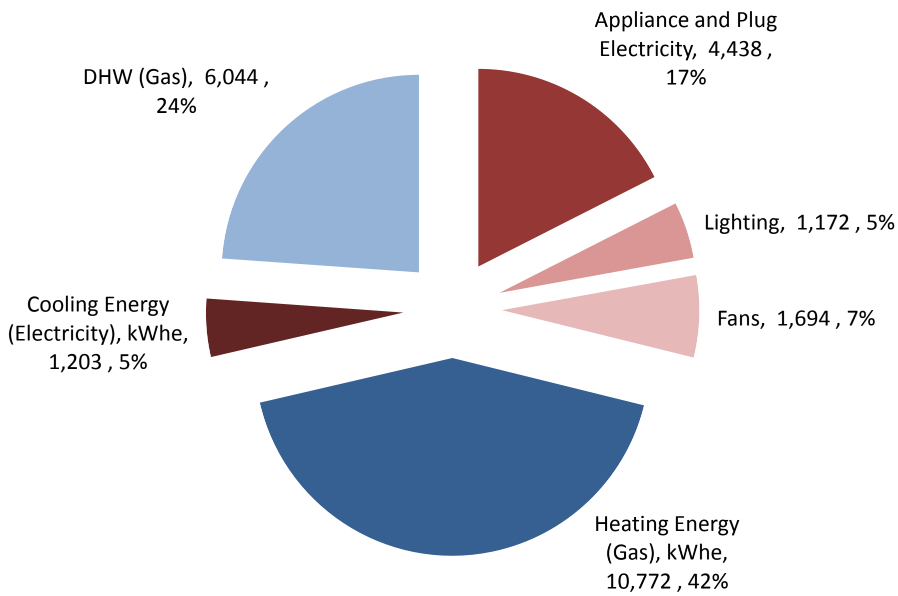


Fig.11.3 Distribution of row house end unit (north-south) household energy consumption in Toronto, kWh_e and percent of total.

11.1.2 Energy Simulations

Energy simulations were run for the row house end unit and middle unit, oriented both north-south and east-west, for each of the 23 window types. Energy simulations were completed for five locations: Vancouver, Toronto, Montreal, Winnipeg, and Yellowknife. A selection of plots are shown for analysis in this section, while complete simulation results are in Appendix G.

Fig.11.4, Fig.11.5 and Fig.11.6 show the annual heating, cooling and total energy consumption, respectively, for the end unit row house facing north-south. For all three plots, the different locations follow the same pattern of increasing or decreasing energy consumption with the exception of Yellowknife, which was also identified as an anomaly in Section 7. The far north has some differences likely due to the lower solar radiation seen in the winter months, where a high SHGC would not provide as much benefit in the winter.

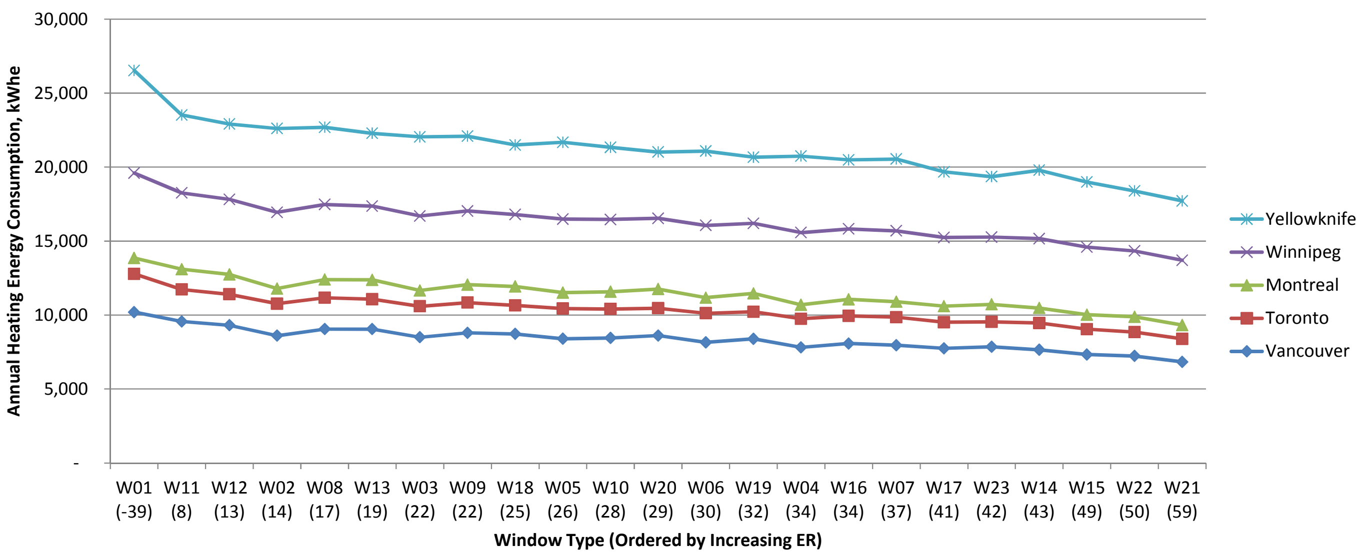


Fig.11.4 Annual heating energy consumption, end unit archetype facing north-south, kWh_e.

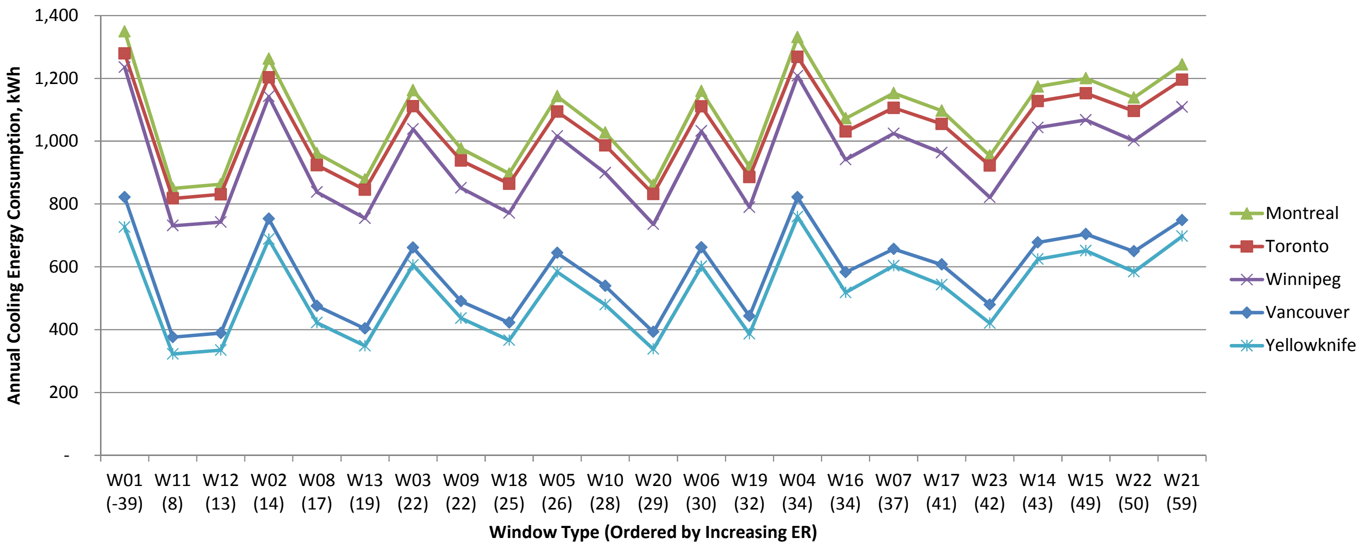


Fig.11.5 Annual cooling energy consumption, end unit archetype facing north-south, kWh.

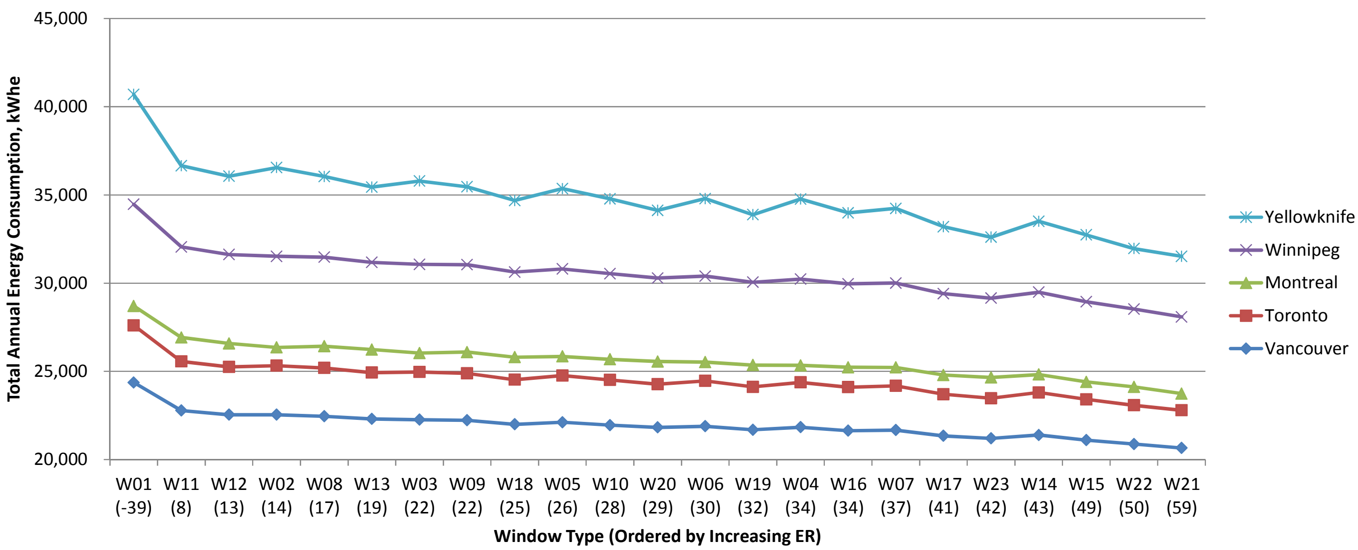


Fig.11.6 Total annual energy consumption, end unit archetype facing north-south, kWh_e.

Fig.11.7, Fig.11.8 and Fig.11.9 show the annual heating, cooling and total energy consumption, respectively, for the four archetype variations in Toronto. All three plots show that each archetype follows the same pattern of increasing or decreasing energy consumption across the various window types. The different cases have a different relative impact, for example in the cooling plot the east-west oriented houses have a greater range of cooling energy consumption than the north-south orientations, though the same pattern or trend occurs for each case. Likewise, in the plot of total energy consumption, comparing the middle unit n-south versus east-west orientations shows that the middle unit has a greater change in energy consumption between different window types, however a careful examination shows that both lines follow the same trend of increasing or decreasing energy consumption.

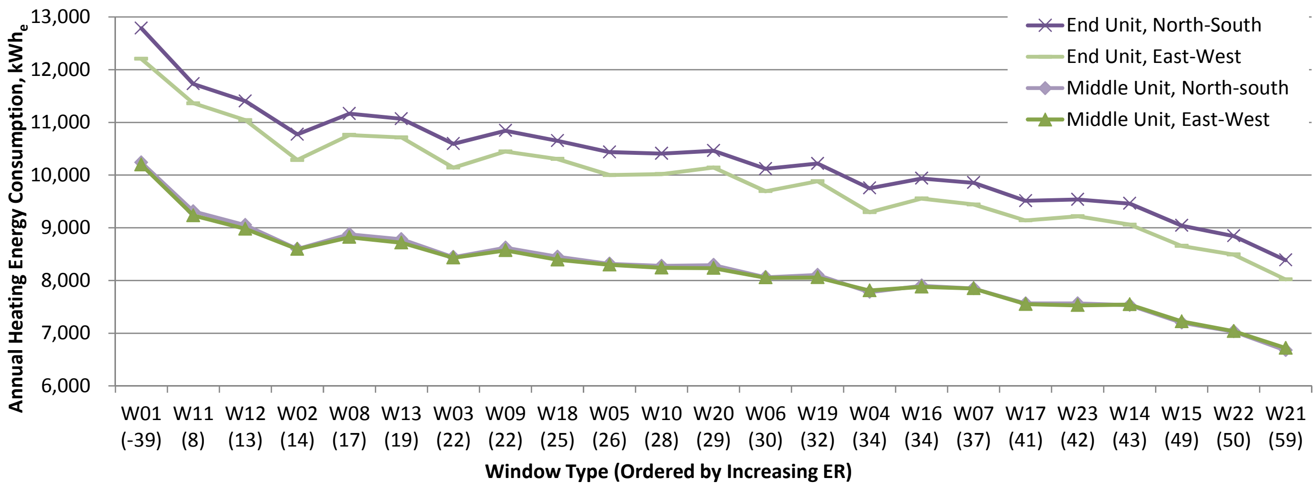


Fig.11.7 Annual heating energy consumption, row house archetypes in Toronto, kWh$_e$.

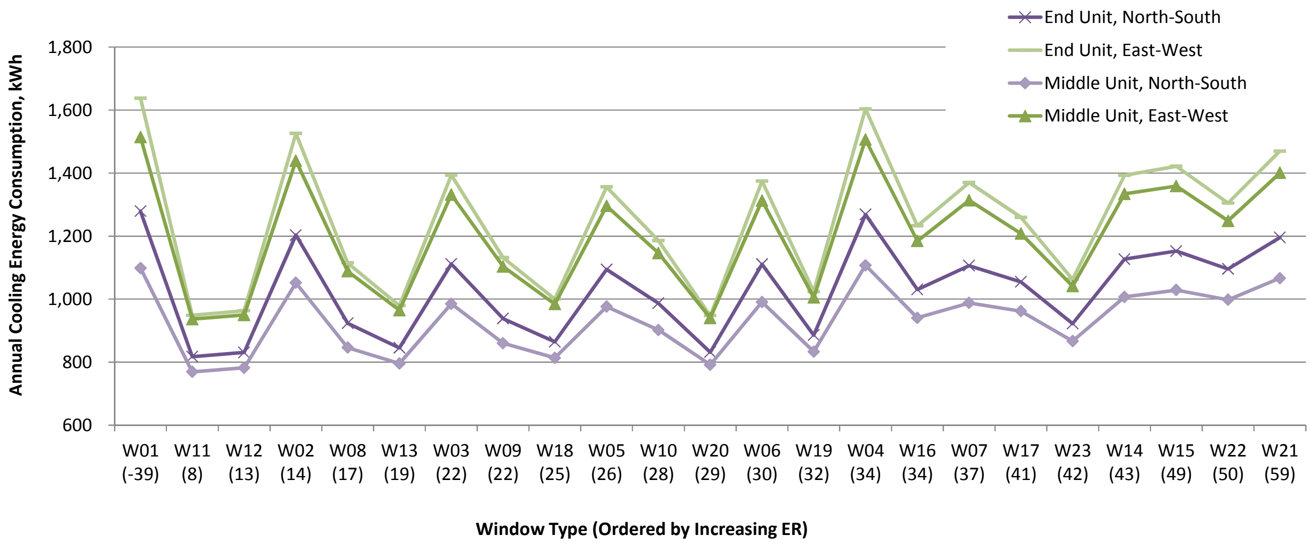


Fig.11.8 Annual cooling energy consumption, row house archetypes in Toronto, kWh.

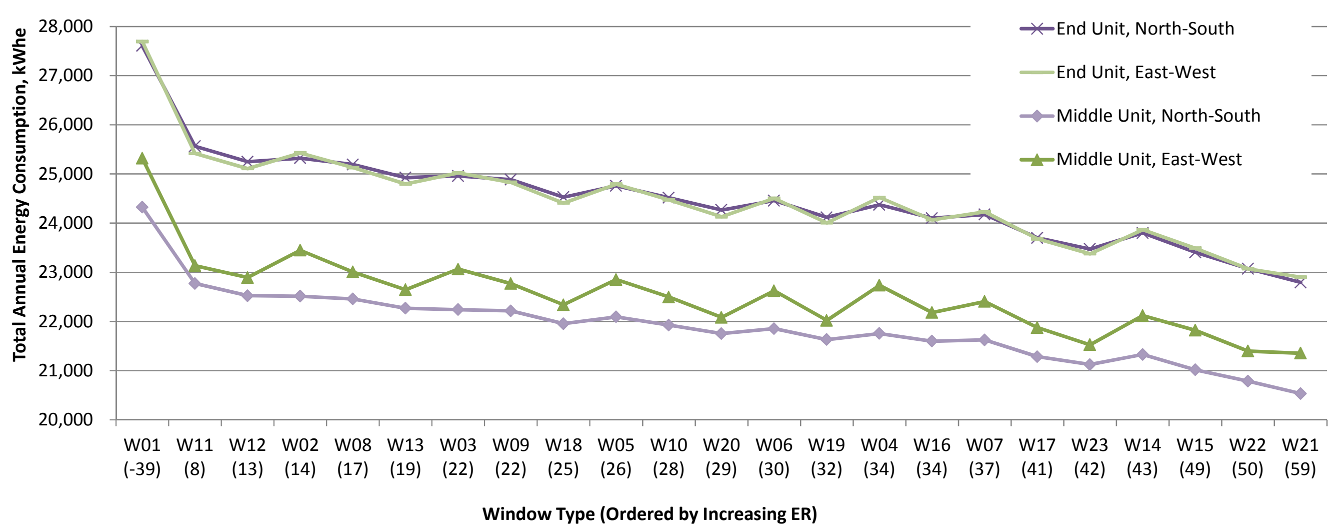


Fig.11.9 Total annual energy consumption, row house archetypes in Toronto, kWh$_e$.

Fig.11.10, Fig.11.11 and Fig.11.12 show the annual heating, cooling and total energy consumption, respectively, for the row house and the single-storey house (results from Section 7). The results show that for all three plots, the two archetypes follow the same pattern of increasing or decreasing energy consumption. The row house archetype appears to perform similarly to the single-storey archetype. This is consistent with the Section 7 findings, where the archetype house parameters did not affect the ranking of energy consumption by ER. Based on this analysis, the ER appears to be as appropriate for row houses as it is for single detached houses.

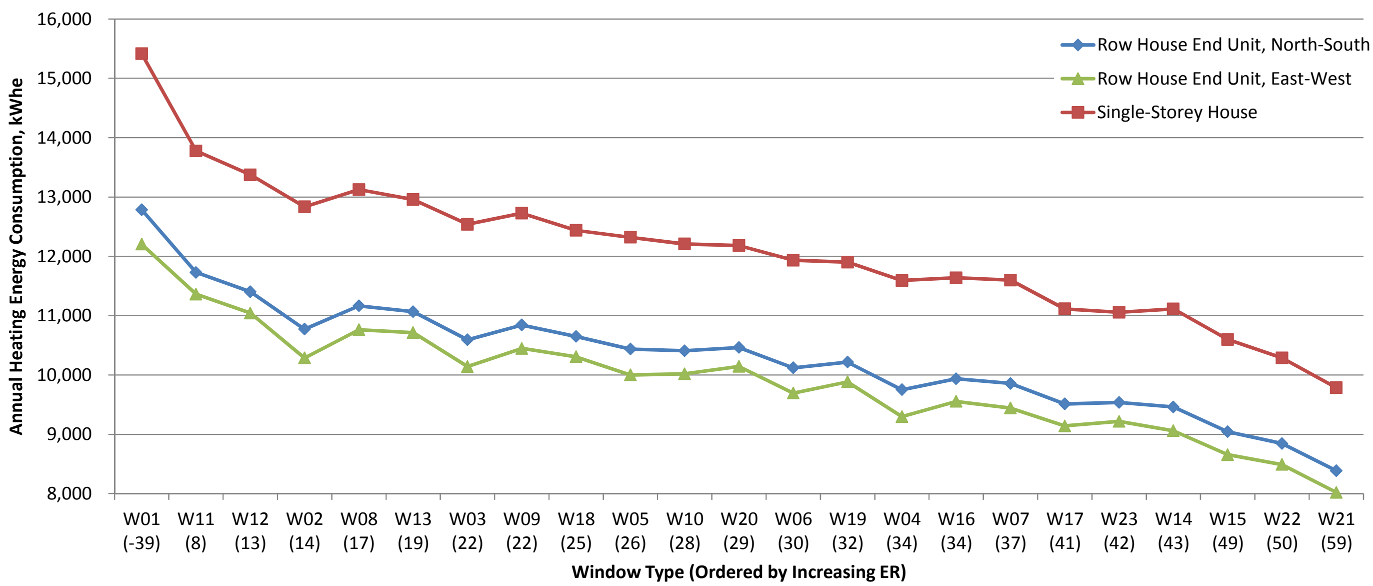


Fig.11.10 Annual heating energy consumption, row house and single-storey archetypes in Toronto, kWh_e.

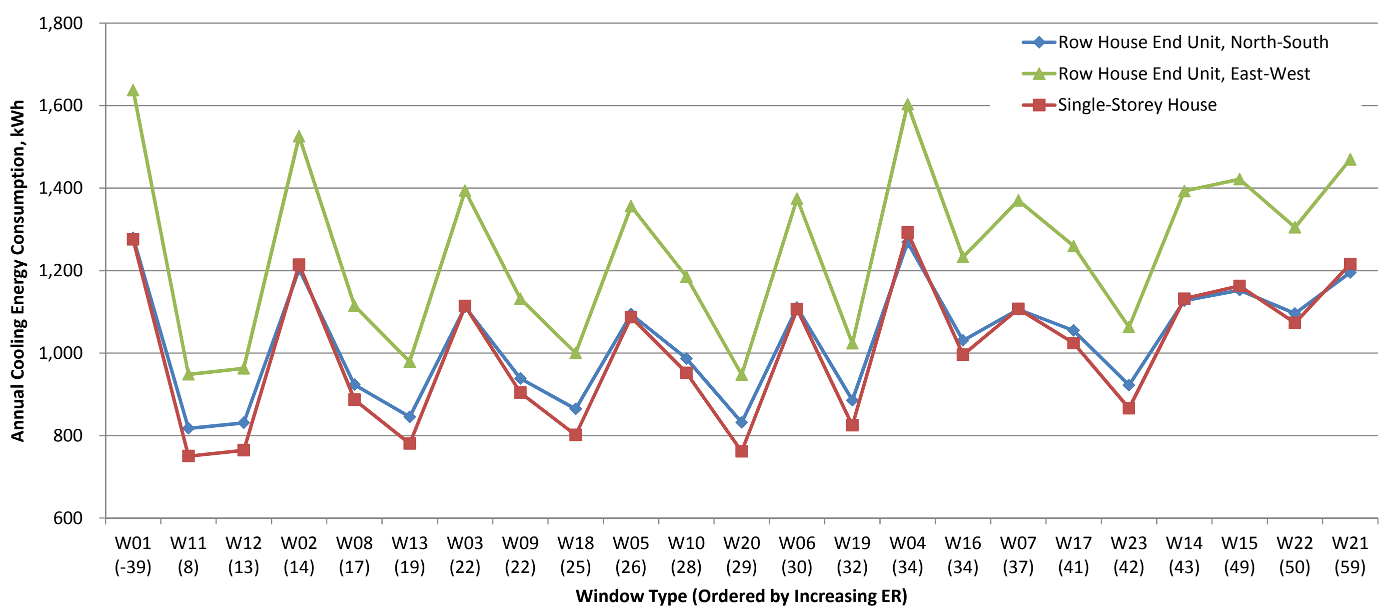


Fig.11.11 Annual cooling energy consumption, row house and single-storey archetypes in Toronto, kWh.

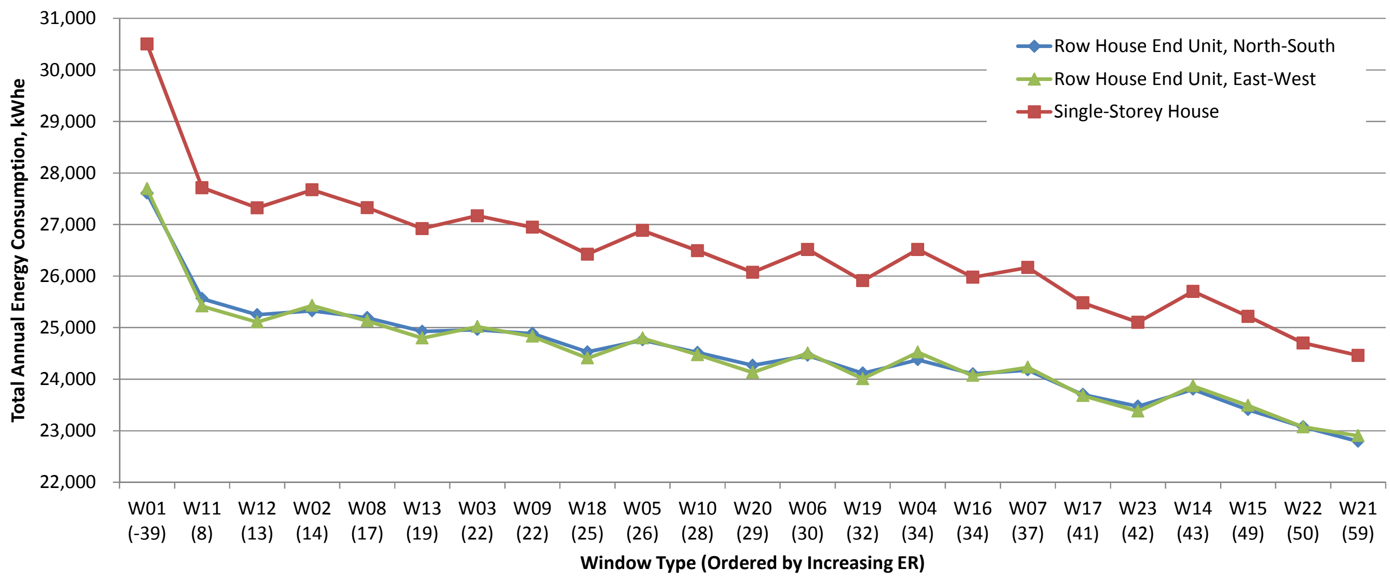


Fig.11.12 Total annual energy consumption, row house and single-storey archetypes in Toronto, kWh_e.

11.2. Four Storey Low-Rise Building

CSA A440.2 notes that the ER applies only to "low-rise residential buildings." A low-rise residential building is defined as "a building of three storeys or less, having a building area not exceeding 600 m^2 (6,460 ft^2) and used for residential occupancies." This represents a fairly small multi-unit residential building. This analysis is completed to investigate a building that is still considered low-rise (combustible construction) but would fall under Part 3 of the Building Code.

Many Part 3 buildings have greater window to wall ratios than typical single family dwellings. In some jurisdictions, WWRs greater than 40% require energy modeling to show compliance with energy code or standard requirements. However, WWRs greater than 40% are still common in practice, as modeling can be used to show compliance by "trading off' energy savings with other building systems (e.g. other enclosure components, mechanical systems or electrical systems). For example, the 2012 proposed NBCC changes include a provision that a reference house may have a maximum WWR of 40%; therefore a proposed building will be penalized for going above 40% WWR, but can make up the savings in another area of the building.

11.2.1 Model Set-Up

The energy model for the low-rise multi-unit residential building archetype was established based on typical buildings from RDH project experience. A complete set of inputs is shown in Appendix F, however, the following is a brief summary of the low-rise archetype model.

- Rectangular floor plate
- Four storeys, 40 units with a total floor area of 2,900 m^2 (31,200 sf)
- Enclosure: 2x4 wood stud walls with batt insulation
- Window to wall ratios of 20%, 40% and 60% were investigated
- No shading
- HVAC: split system with heat pumps for heating and cooling, intermittent exhaust fans in suites, supply air to pressurize corridors

Simulations were run with the long axis oriented north-south since this is the preferred orientation for winter and summer design.

The energy consumption of the low-rise archetype was examined to ensure the results are representative of typical building energy consumption in Canada. Fig.11.13 shows the distribution of household energy consumption for the building with a 20% window to wall ratio in Vancouver. This simulation has a total annual energy consumption of 147 kWh/m^2, with 46% heating energy. The overall energy is below that of an average Vancouver building[18], however the simulation did not include miscellaneous common area electrical loads that are typically included in building statistics (e.g. amenity rooms, elevators, parkade lighting, etc.). This could account for an additional 40 to 50 kWh/m^2 per year or more depending on the amenities in the building. Based on this, the energy intensity and energy distribution plot appears reasonable for a typical wood-frame multi-unit residential building in Vancouver.

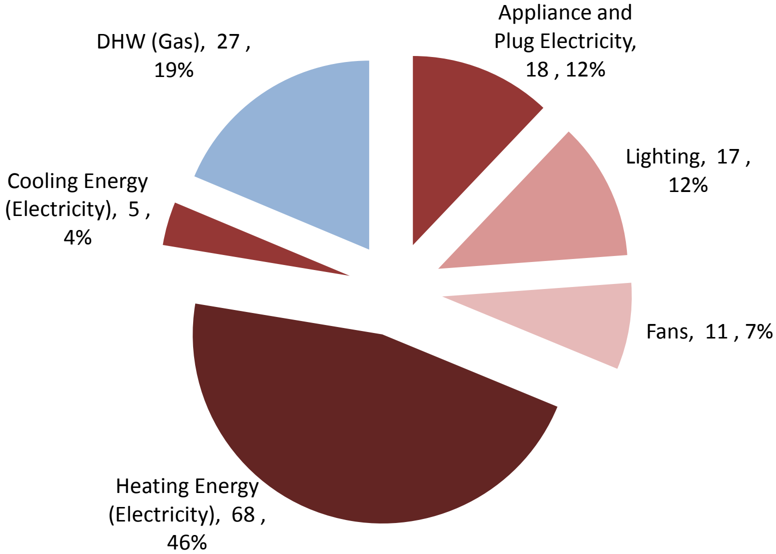


Fig.11.13 Distribution of low-rise building energy consumption in Vancouver, 20% WWR, kWh$_e$/m^2 and percent of total.

Fig.11.14 shows the distribution of household energy consumption for the building with a 20% window to wall ratio in Toronto. This simulation has a total annual energy consumption of 169 kWh/m^2, with 52% heating energy. Again, the overall energy is below that of an average Toronto building; however, the simulation does not include miscellaneous common area electrical loads. The energy intensity and energy distribution plot appears reasonable for a typical wood-frame multi-unit residential building in Toronto.

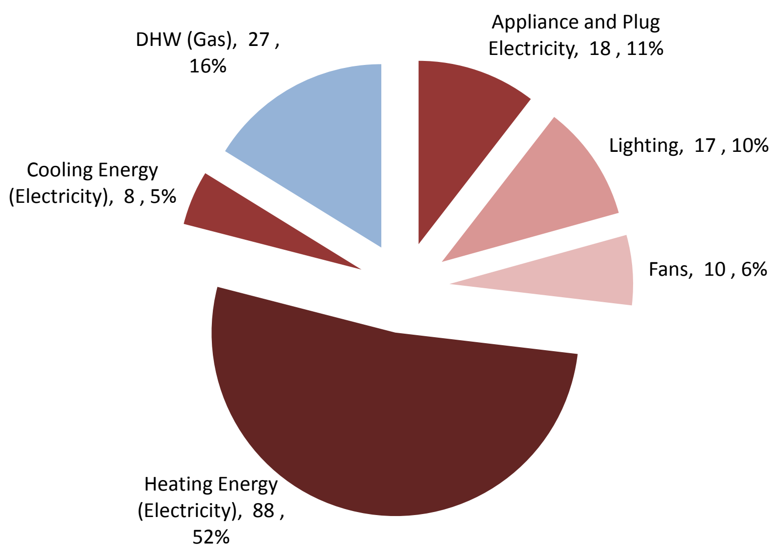


Fig.11.14 Distribution of low-rise building energy consumption in Toronto, 20% WWR, kWh$_e$/m^2 and percent of total.

[18] "Energy Consumption and Conservation in Mid and High Rise Residential Buildings in British Columbia", 2011, RDH Building Engineering Ltd.

11.2.2 Energy Simulations

Energy simulations were run for the four-storey low-rise building, for each of the 23 window types. Energy simulations were completed for five locations: Vancouver, Toronto, Montreal, Winnipeg, and Yellowknife. A selection of plots are shown for analysis in this section, while complete simulation results are given in Appendix G.

Fig.11.15, Fig.11.16 and Fig.11.17 show the annual heating, cooling and total energy consumption, respectively, for low-rise building with a 40% window to wall ratio. For all three plots, the different locations follow the same pattern of increasing or decreasing energy consumption with the exception of Yellowknife, which was also identified as an anomaly in Section 7. The far north has some additional differences likely due to the lower solar radiation seen in the winter months, where a high SHGC would not provide as much benefit in the winter.

The heating plot shows a similar trend to the previous findings, where a higher ER generally results in lower energy consumption, with a few small anomalies where the opposite is true. The cooling plot shows that the ER is not related to cooling energy, as expected. Both of these findings are consistent with the simulation results for the single detached house. The plot of total energy consumption, however, shows a greater number of cases where a higher ER results in higher energy consumption. This is evident when comparing the total energy plot to the heating energy plot; for heating energy the trend is nearly linear, however, for total energy consumption there are many more increases and decreases. This likely occurs because cooling energy is much more significant with a higher window to wall ratio, and therefore has a greater impact on the total energy consumption of the building.

Plots for the building with 20% and 60% window to wall ratios showed the same trends as the 40% case discussed here, and are given in Appendix G.

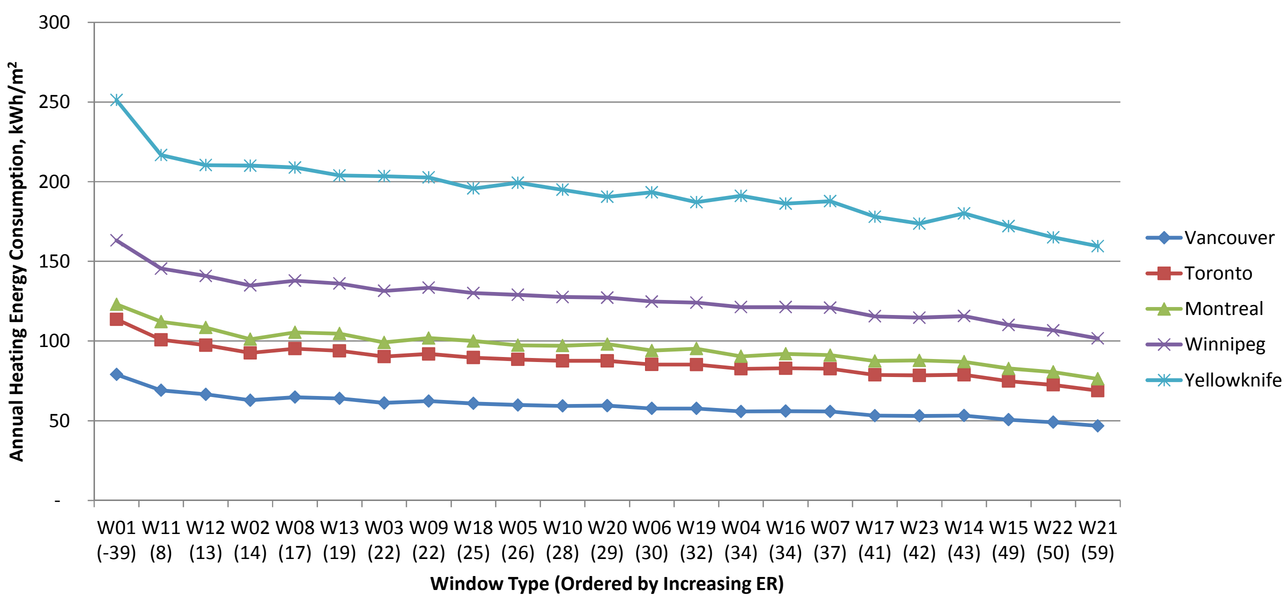


Fig.11.15 Annual heating energy consumption for low-rise building with 40% WWR, kWh/m^2.

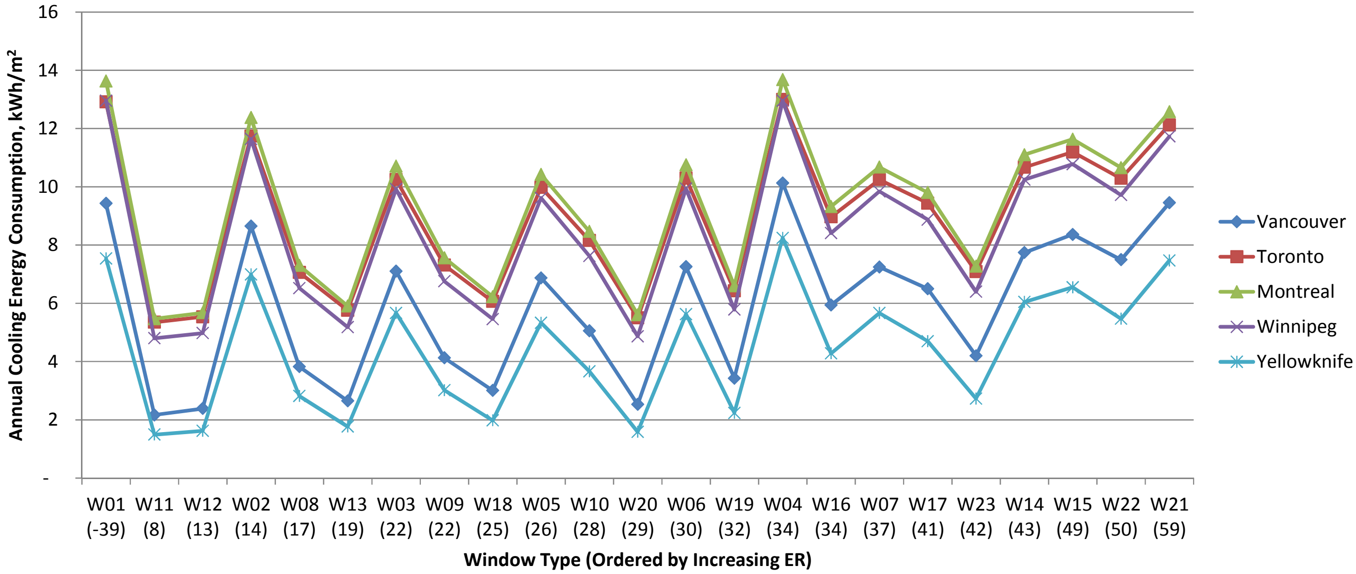


Fig.11.16 Annual cooling energy consumption for low-rise building with 40% WWR, kWh/m^2.

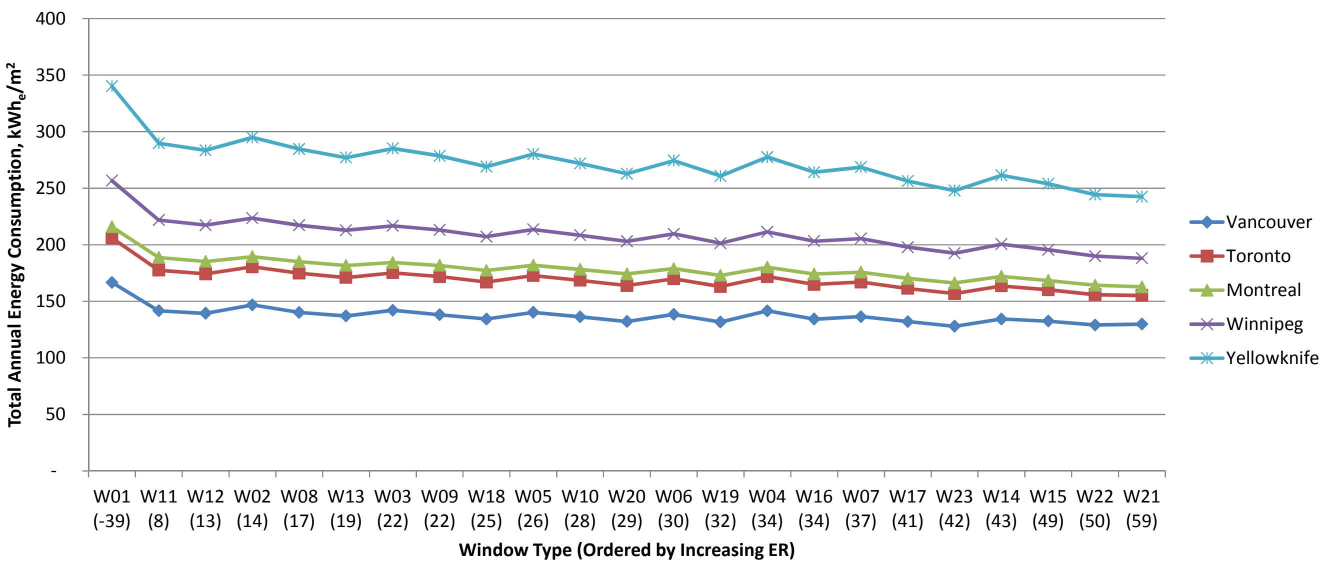


Fig.11.17 Total annual energy consumption for low-rise building with 40% WWR, kWh$_e$/m^2.

Fig.11.18, Fig.11.19 and Fig.11.20 show the annual heating, cooling and total energy consumption, respectively, for the low-rise building in Toronto with three different WWRs. The heating energy plot shows a similar trend to the results seen in Section 7 for the house, where higher WWRs use more heating energy for lower ER windows and less heating for higher ER windows. In this case, windows with an ER of around 30 to 37 have approximately the same heating consumption for all three WWRs. The three WWR cases still follow the same trend of increasing or decreasing heating energy, and therefore the same comparison between windows can be made for a given WWR. For example, W09 uses less energy than W08 for all three WWRs.

The cooling energy plot shows that, as expected, the cooling energy does not increase or decrease with the ER, although the lines do follow the same trend for each WWR case. The difference in cooling energy is much greater for higher WWRs, as would be expected; that is, buildings with a higher WWR experience a greater increase in cooling energy for high SHGC windows.

As seen in the set of plots for all five cities, the total energy plot shows a greater number of anomalies than the heating energy plot, where a window with a higher ER has a greater total energy consumption. The variations are greatest for the building with the highest WWR. This is likely due to the larger impact of cooling in buildings with a higher WWR. Plots for the other locations showed similar trends as the case for Toronto discussed here, and are given in Appendix G.

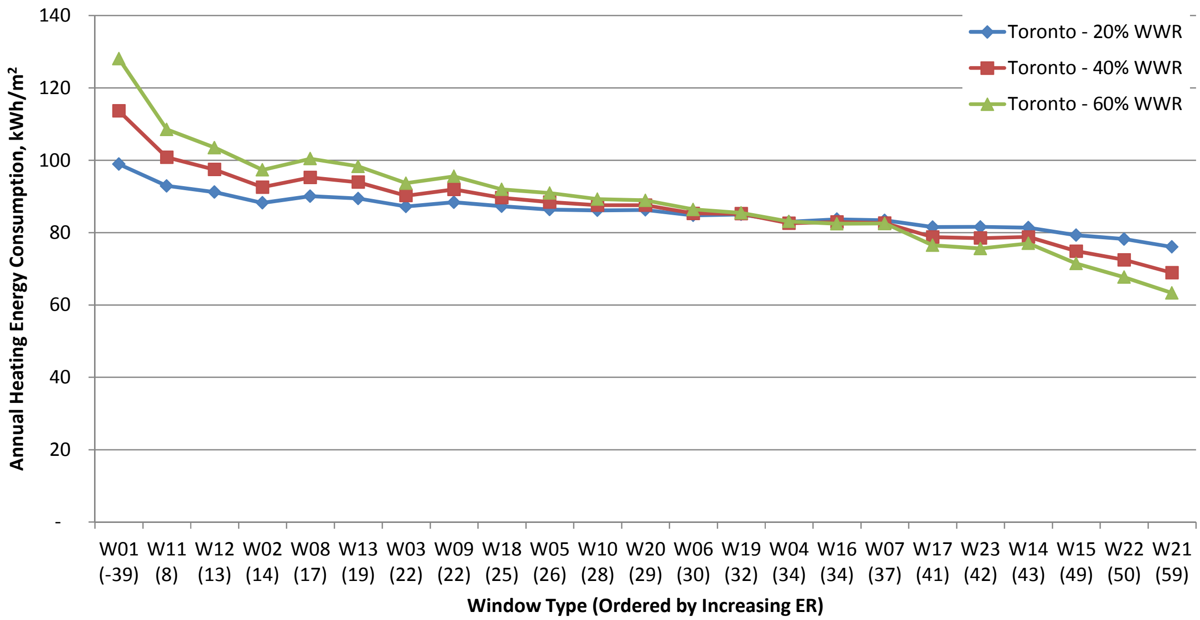


Fig.11.18 Annual heating energy consumption for low-rise building in Toronto, kWh/m^2.

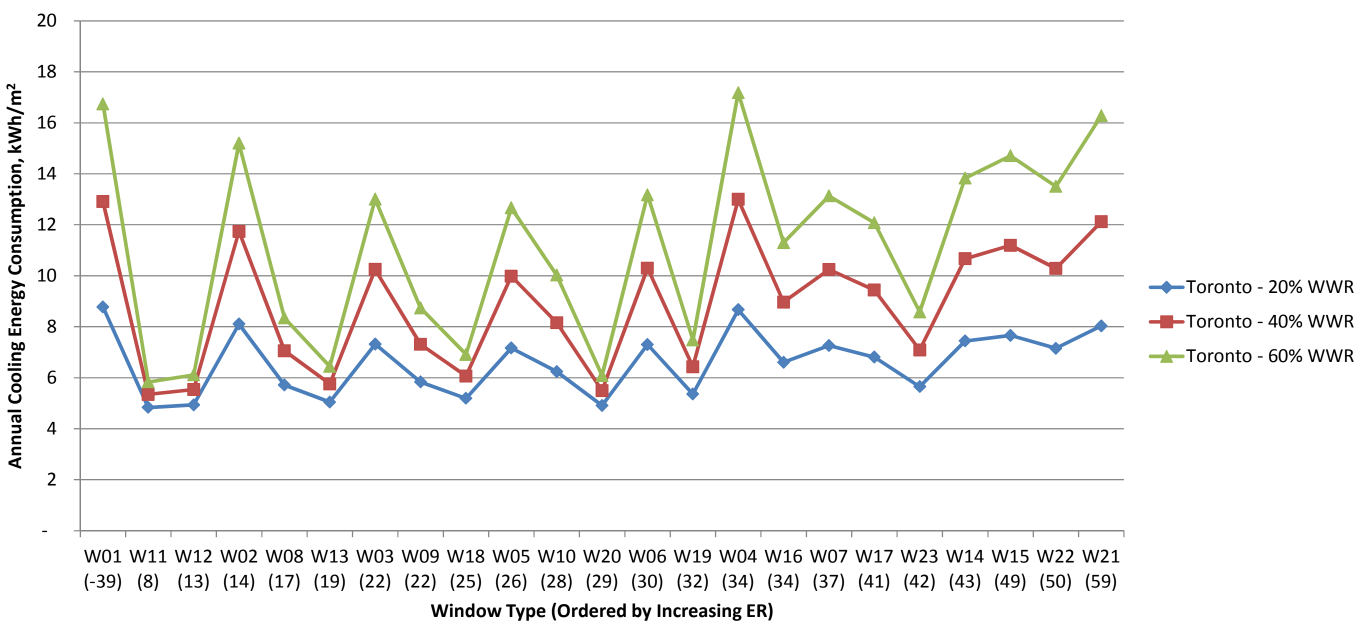


Fig.11.19 Annual cooling energy consumption for low-rise building in Toronto, kWh/m^2.

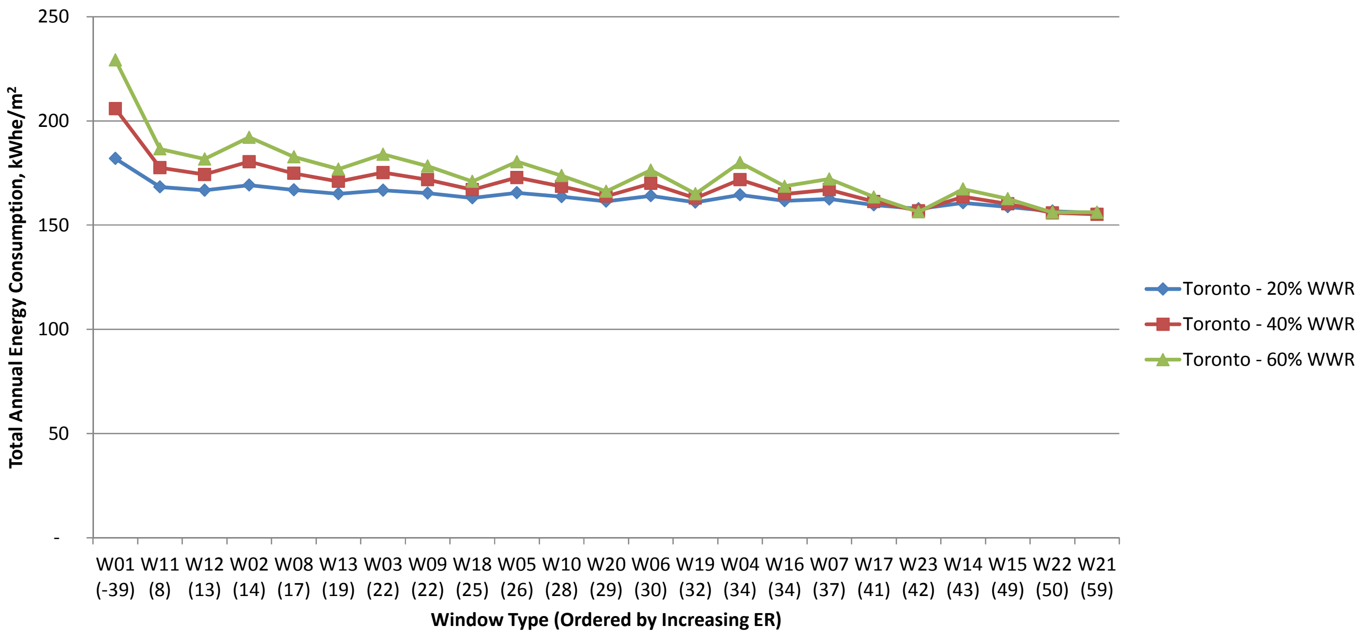


Fig.11.20 Total annual energy consumption for low-rise building in Toronto, kWh_e/m^2.

To view the correlation between ER and heating energy, and the difference in ranking by U-value and ER, heating energy and total energy were plotted versus U-value and ER. Plots are shown here for the four-storey building with 40% window to wall ratio, while the 20% and 60% WWR cases are included in Appendix G.

Fig.11.21 and Fig.11.22 show the heating energy and total energy, respectively, plotted versus the ER. These plots show a better correlation for heating energy than for total energy. Fig.11.23 and Fig.11.24 show the heating energy and total energy, respectively, plotted versus the U-value. These plots show a better correlation for total energy than for heating energy, opposite to the plots versus ER. Interestingly, the plot of total energy vs. U-value has lower R^2 values than the plot of total energy vs. ER. This highlights the greater impact of cooling energy in this building with a higher WWR.

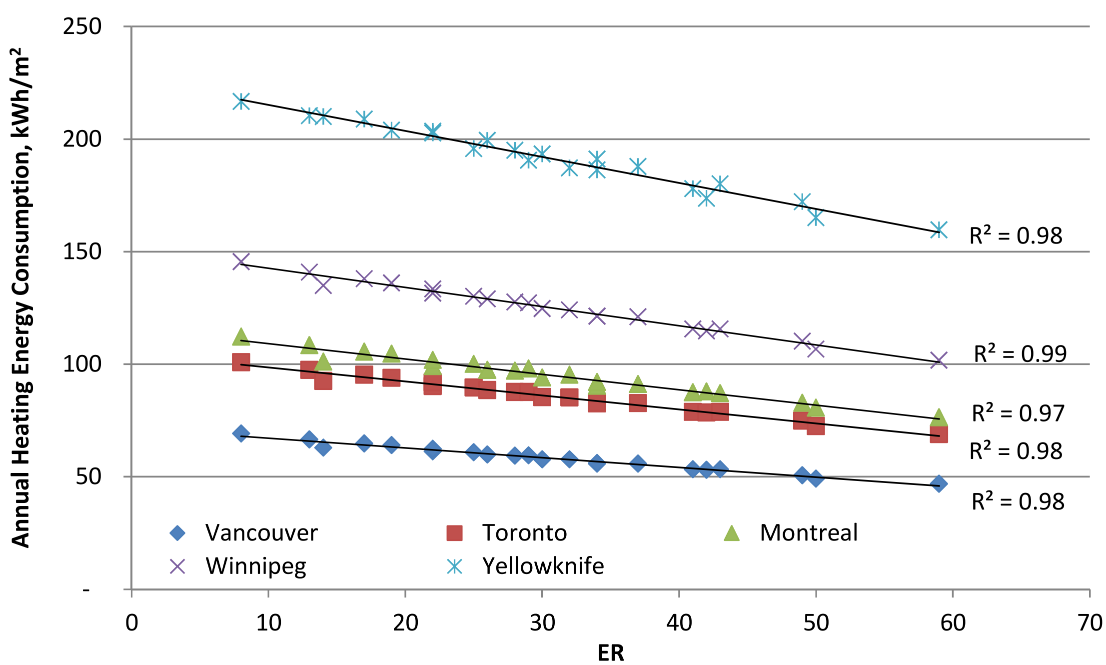


Fig.11.21 Annual heating energy consumption versus ER, 40% WWR, kWh/m^2.

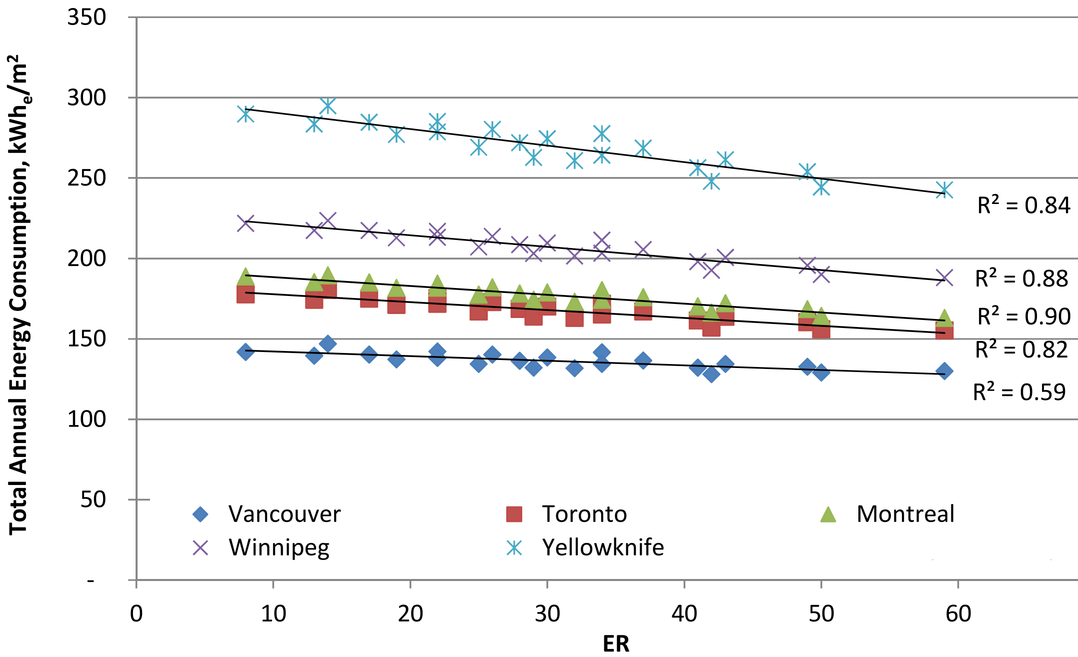


Fig.11.22 Total annual energy consumption versus ER, 40% WWR, kWh$_e$/m^2.

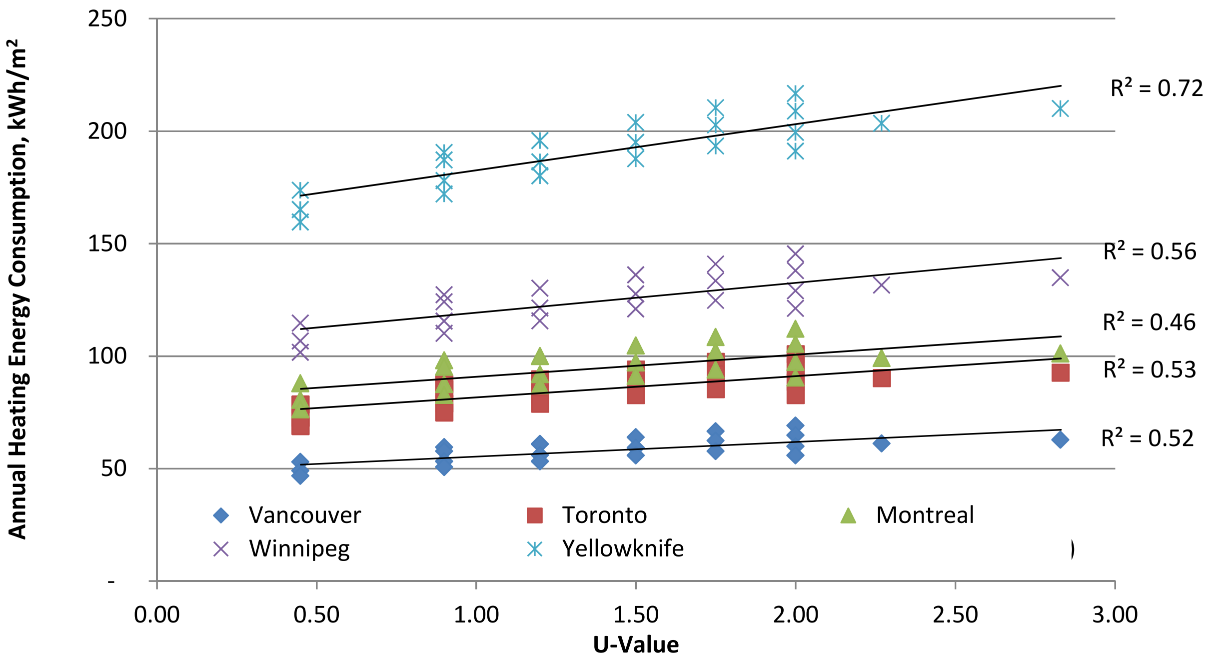


Fig.11.23 Annual heating energy consumption versus U-value, 40% WWR, kWh/m^2.

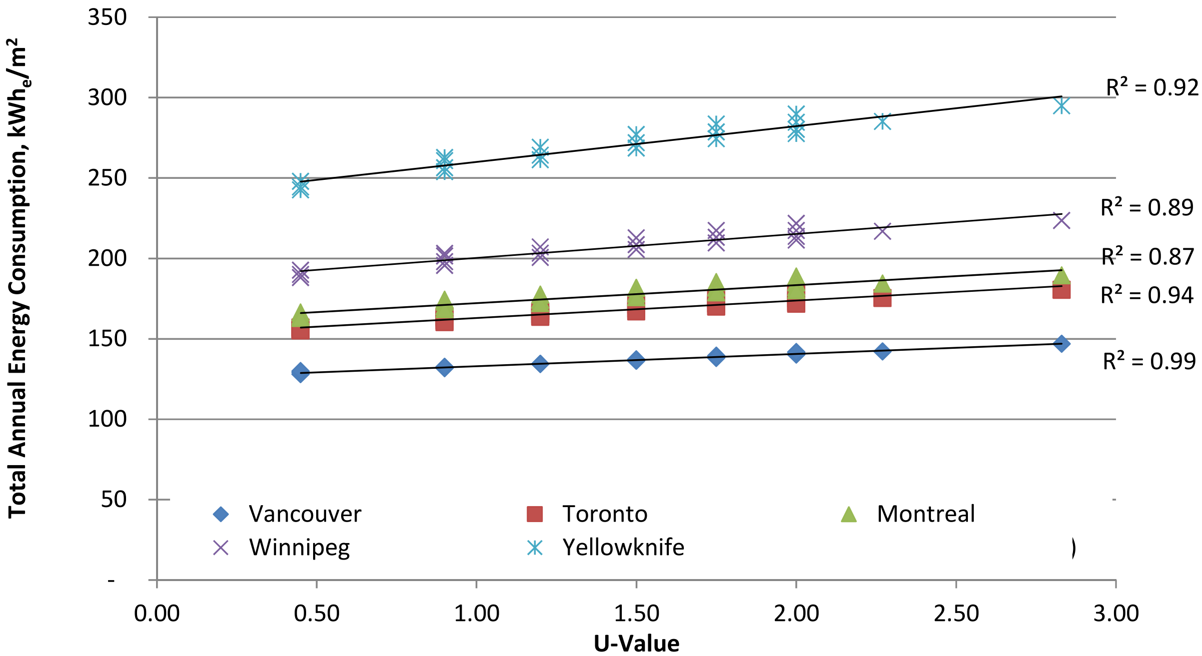


Fig.11.24 Total annual energy consumption versus U-value, 40% WWR, kWh$_e$/m^2.

11.3. High-Rise Building

The ER does not apply to high-rise buildings, however, this analysis was undertaken to see whether it could also be used to rate windows for high-rises. As with the low-rise building analyzed in the previous section, many high-rise buildings have greater window to wall ratios than typical single family dwellings. Where codes or standards discourage this, higher WWRs are achieved by "trading off" energy savings through computer energy modeling.

11.3.1 Model Set-Up

The energy model for the high-rise multi-unit residential building archetype was established based on typical buildings from the authors' project experience. A complete set of inputs is shown in Appendix F, however the following is a brief summary of the high-rise archetype model:

- Square floor plate
- 20 storeys, eight units per floor with a total gross floor area of 13,100 m^2 (141,100 sf)
- Enclosure: Exposed concrete with insulation at the interior surface (overall effective wall R_{SI}-1.4 or R-8)
- Window to wall ratios of 40%, 60% and 80% were investigated
- No shading
- HVAC: split system with heat pumps for heating and cooling, intermittent exhaust fans for ventilation, supply air to pressurize corridors

This building was simulated in five climates: Vancouver, Toronto, Montreal, Winnipeg and Yellowknife. The high-rise building with higher WWRs would be most commonly found in populous Canadian cities with more mild climates, such as Vancouver and Toronto. This building would not be found in Yellowknife, however, it is still simulated in the northern location for comparison.

This building would also have very different windows than a house and even a low-rise, combustible construction building. The high-rise would mostly have aluminum frame windows with lower U-values, though a large range of SHGC values are still possible. Despite this, for the preliminary analysis performed in this section, the same set of windows are simulated with the high-rise building so that it may be more easily compared to the previous analysis. This will allow an initial investigation into the use of the ER for high-rise residential buildings, and will determine whether further investigation is warranted.

The energy consumption of the high-rise archetype was examined to ensure the results are representative of typical building energy consumption in Canada. Fig.11.25 shows the distribution of household energy consumption for the building with a 40% window to wall ratio in Vancouver. This simulation has a total annual energy consumption of 155 kWh/m^2, with 46% heating energy. The overall energy is below that of an average Vancouver building, however, the simulation did not include miscellaneous common area electrical loads that are typically included in building statistics (e.g. amenity rooms, elevators, parkade lighting, etc.). This could account for an additional 40 to 50 kWh/m^2 per year or more depending on the amenities in the building. Based on this, the energy intensity and energy distribution plot appears reasonable for a typical high-rise residential building in Vancouver.

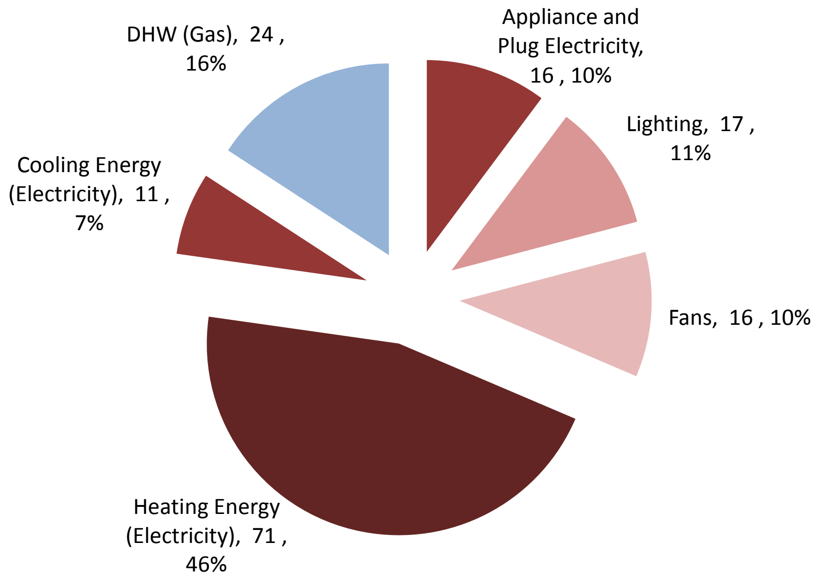


Fig.11.25 Distribution of high-rise building energy consumption in Vancouver, 40% WWR, kWh$_e$/m^2 and percent of total.

Fig.11.26 shows the distribution of household energy consumption for the building with a 60% window to wall ratio in Vancouver. This simulation has a total annual energy consumption of 176 kWh/m^2, with 47% heating energy. As expected, the higher window to wall ratio results in a higher energy density and greater proportion of space heating.

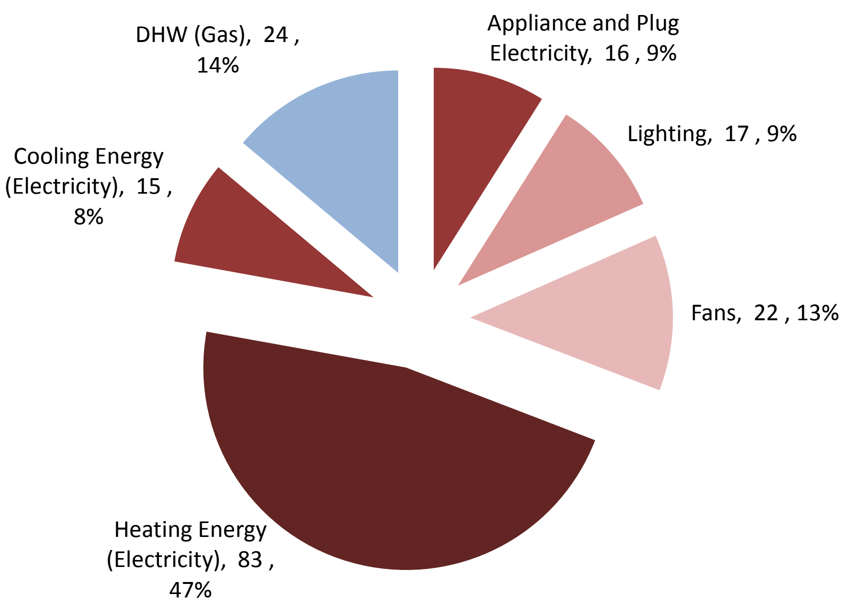


Fig.11.26 Distribution of high-rise building energy consumption in Vancouver, 60% WWR, kWh$_e$/m^2 and percent of total.

Fig.11.27 shows the distribution of household energy consumption for the building with a 40% window to wall ratio in Toronto. This simulation has a total annual energy consumption of 164 kWh/m^2, with 49% heating energy. As expected, the building in Toronto has a higher energy intensity and greater proportion of heating than in Vancouver.

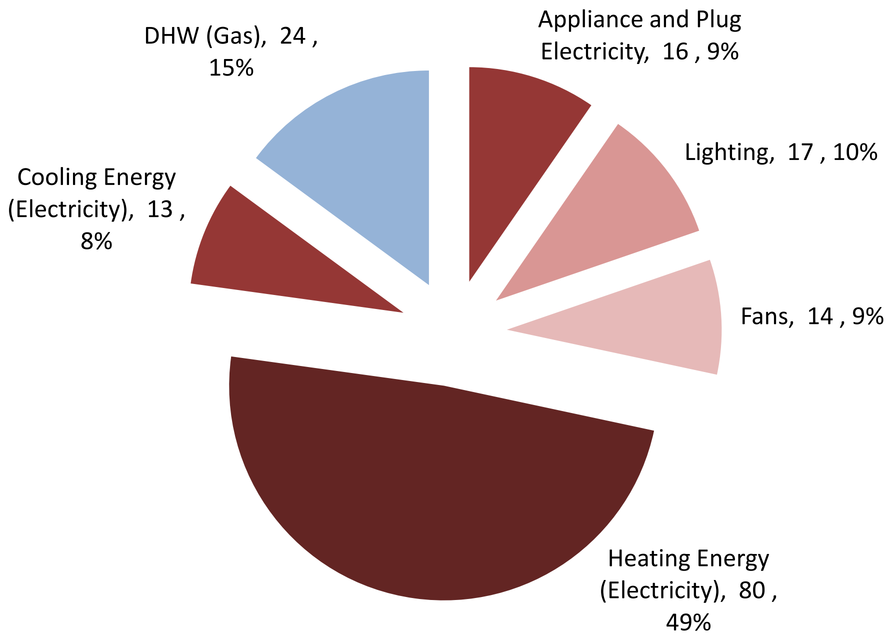


Fig.11.27 Distribution of high-rise building energy consumption in Toronto, 40% WWR, kWh$_e$/m^2 and percent of total.

11.3.2 Energy Simulations

Energy simulations were run for the 20-storey high-rise building, for each of the 23 window types. Energy simulations were completed for five locations: Vancouver, Toronto, Montreal, Winnipeg, and Yellowknife. A selection of plots are shown for analysis in this section, while complete simulation results are given in Appendix G.

Fig.11.28, Fig.11.29 and Fig.11.30 show the annual heating, cooling and total energy consumption, respectively, for the high-rise building with a 60% window to wall ratio. For all three plots, the different locations follow the same pattern of increasing or decreasing energy consumption with the exception of Yellowknife, which was also identified as an anomaly in Section 7. The far north has some additional differences likely due to the lower solar radiation seen in the winter months, where a high SHGC would not provide as much benefit in the winter.

The results for the high-rise building are similar to the results for the low-rise building. The heating plot shows a similar trend to the previous findings (Section 7), where a higher ER generally results in lower energy consumption, with a few small anomalies where the opposite is true. The cooling plot shows that the ER is not related to cooling energy, as expected. Both of these findings are consistent with the simulation results for the single detached house. The plot of total energy consumption, however, shows a greater number of cases where a higher ER results in higher energy consumption. This is evident when comparing the total energy plot to the heating energy plot; for heating energy the trend is nearly linear, however for total energy consumption there are many more increases and decreases. This likely occurs because cooling energy is much more significant with a higher window to wall ratio and, therefore, has a greater impact on the total energy consumption of the building. Plots for the building with 40% and 80% window to wall ratios showed the same trends as the 40% case discussed here, and are given in Appendix G.

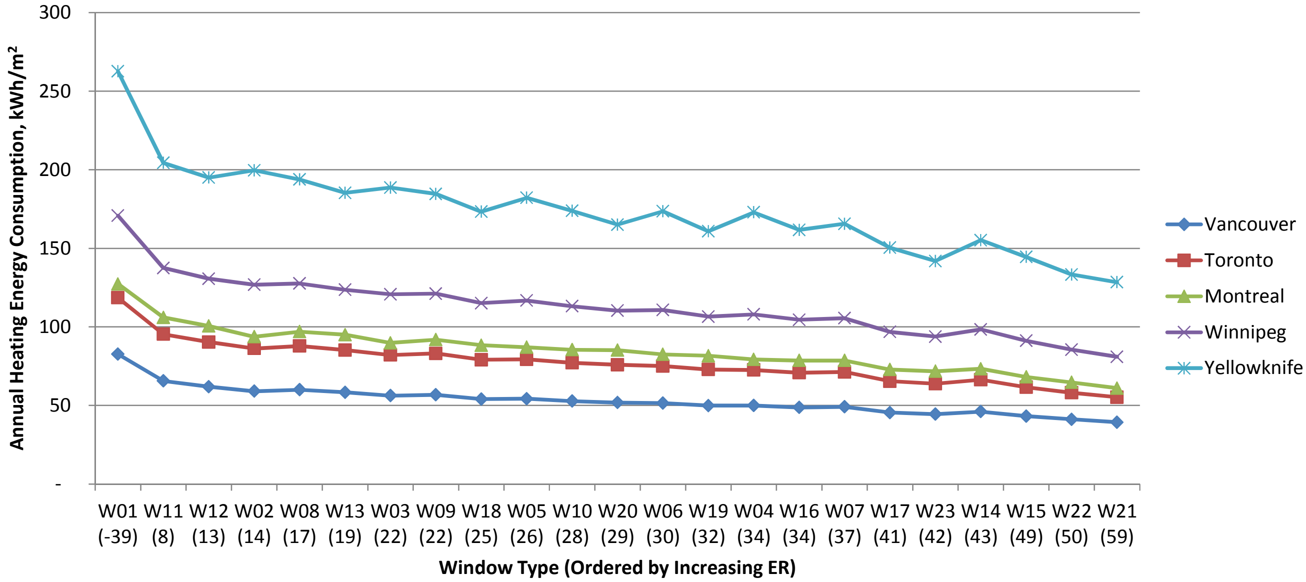


Fig.11.28 Annual heating energy consumption for high-rise building with 60% WWR, kWh/m^2.

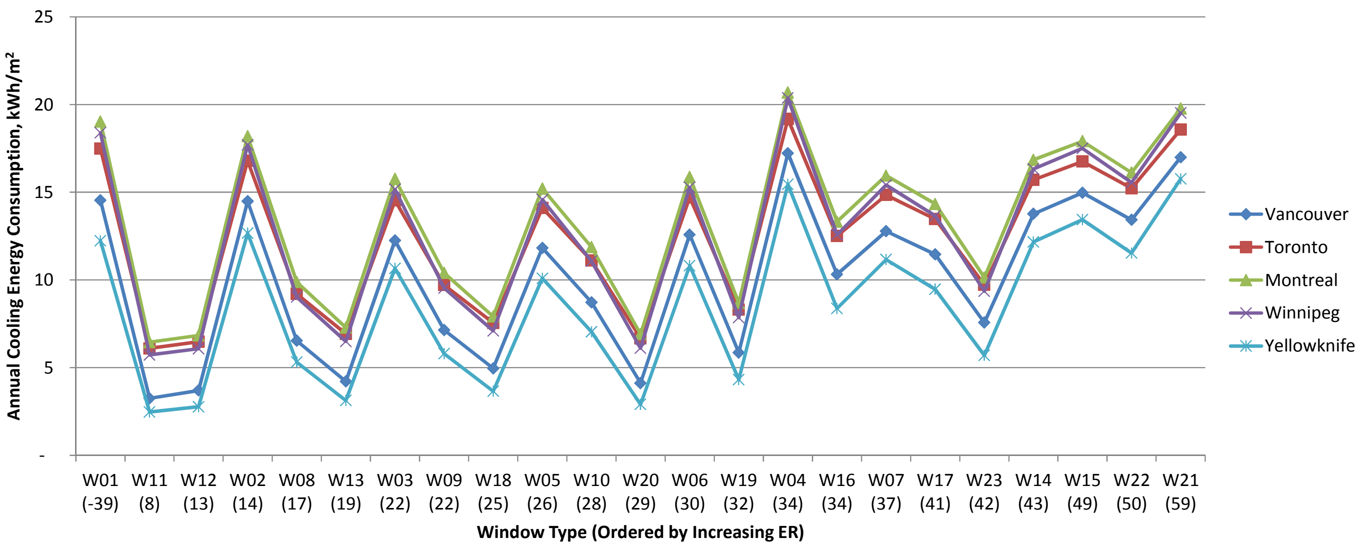


Fig.11.29 Annual cooling energy consumption for high-rise building with 60% WWR, kWh/m^2.

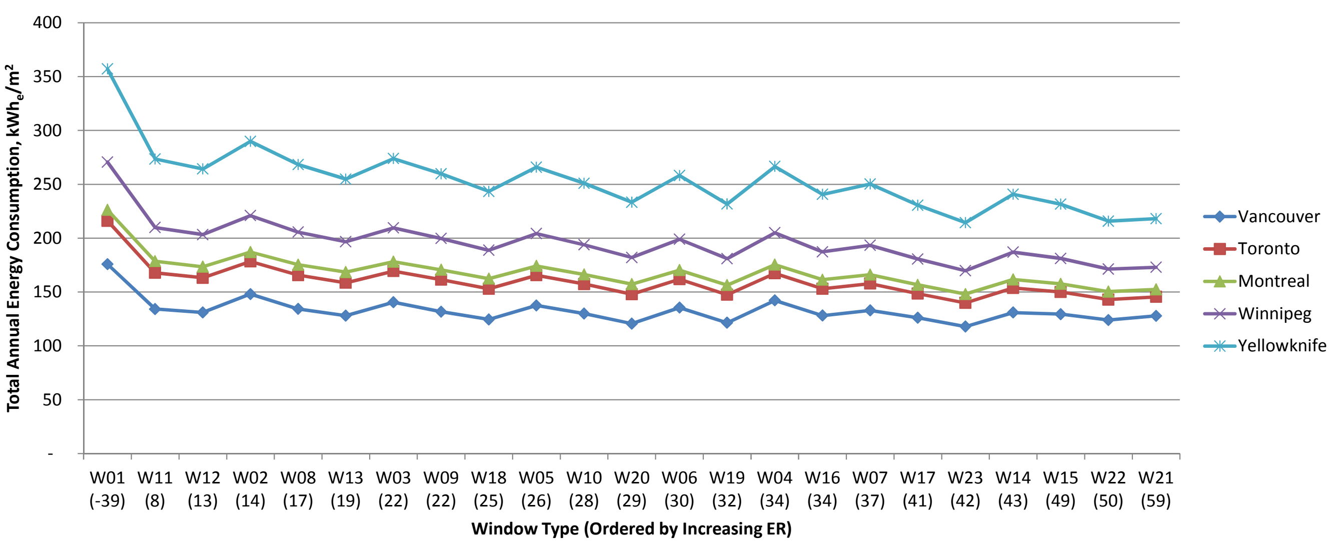


Fig.11.30 Total annual energy consumption for high-rise building with 60% WWR, kWh$_e$/m^2.

Fig.11.31, Fig.11.32 and Fig.11.33 show the annual heating, cooling and total energy consumption, respectively, for the high-rise building in Toronto with three different window to wall ratios. The results for the high-rise building are again similar to the low-rise building. The heating energy plot shows a similar trend to the results seen in Section 7 for the house, where higher WWRs use more heating energy for lower ER windows and less heating energy for higher ER windows. In this case, windows with an ER of around 41 to 43 have approximately the same heating energy consumption for all three WWRs. The three WWR cases still follow the same trend of increasing or decreasing heating energy and, therefore, the same comparison between windows can be made for a given WWR. For example, W09 uses less energy than W08 for all three WWRs.

The cooling energy plot shows that, as expected, the cooling energy does not increase or decrease with the ER, although the lines do follow the same trend for each WWR case. The difference in cooling energy is much greater for higher WWRs, as would be expected; that is, buildings with a higher WWR experience a greater increase in cooling energy for high SHGC windows.

As seen in the set of plots for all five cities, the total energy plot shows a greater number of anomalies than the heating energy plot, where a window with a higher ER has a greater total energy consumption. The variations are greatest for the building with the highest WWR. This is likely due to the larger impact of cooling in buildings with a higher WWR.

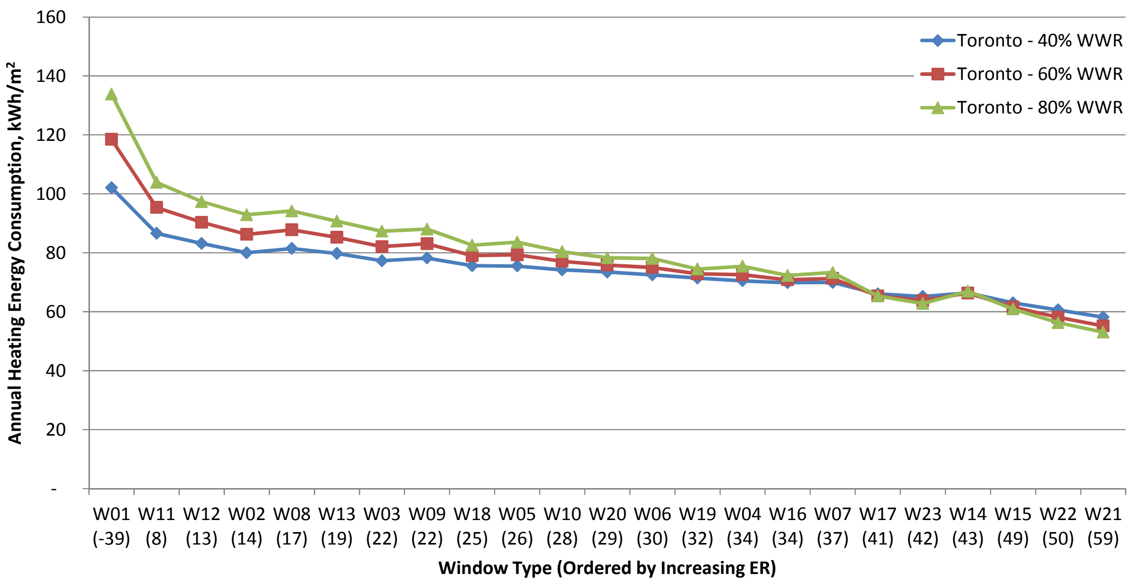


Fig.11.31 Annual heating energy consumption for high-rise building in Toronto, kWh_e/m^2.

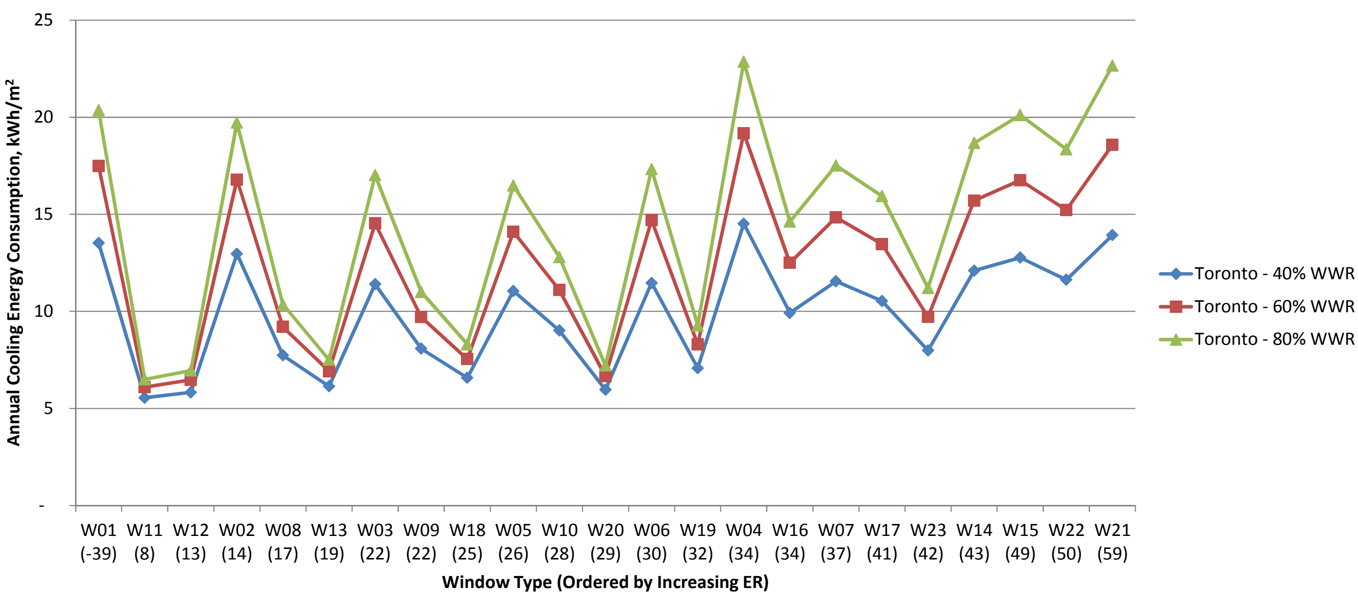


Fig.11.32 Annual cooling energy consumption for high-rise building in Toronto, kWh/m^2.

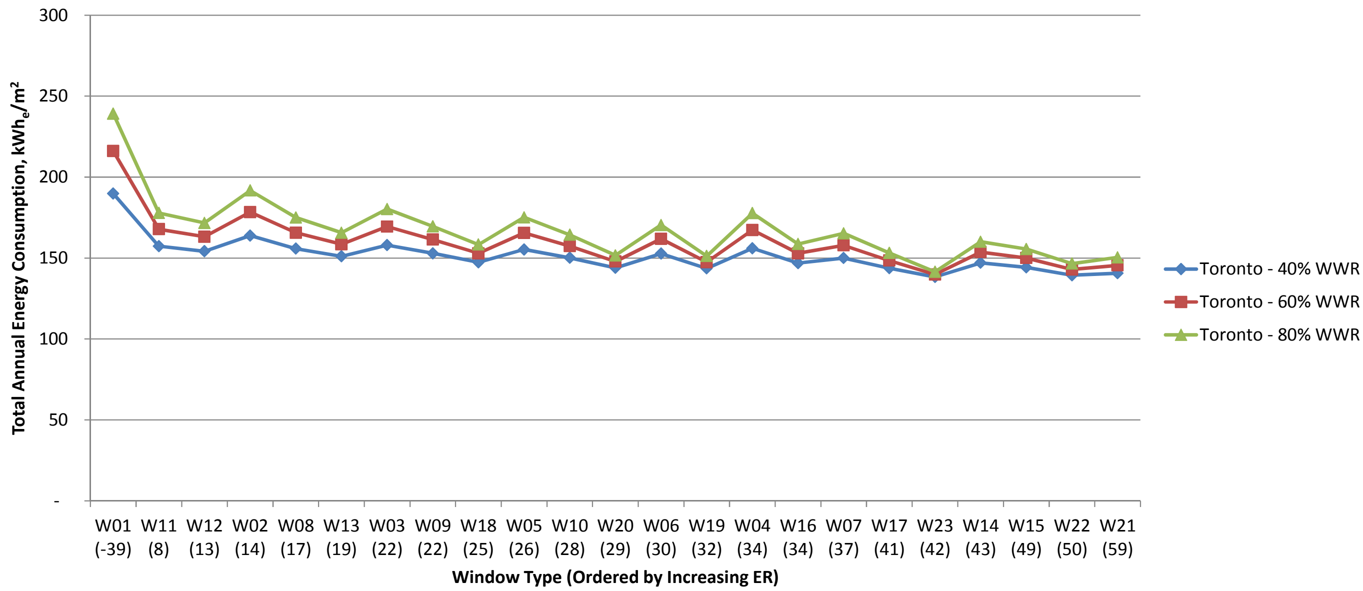


Fig.11.33 Total annual energy consumption for high-rise building in Toronto, kWh_e/m^2.

To view the correlation between ER and heating energy, and the difference in ranking by U-value and ER, heating energy and total energy were plotted versus U-value and ER. Plots are shown here for the 20-storey building with 60% window to wall ratio, while the 40% and 80% WWR cases are included in Appendix G.

Fig.11.34 and Fig.11.35 show the heating energy and total energy, respectively, plotted versus the ER. These plots show a better correlation for heating energy than for total energy. Fig.11.36 and Fig.11.37 show the heating energy and total energy, respectively, plotted versus the U-value. Like the four-storey building, these plots show a better correlation for total energy than for heating energy, opposite to the plots versus ER. Interestingly, the plot of total energy vs. U-value has lower R^2 values than the plot of total energy vs. ER. This highlights the greater impact of cooling energy in this building with a higher WWR.

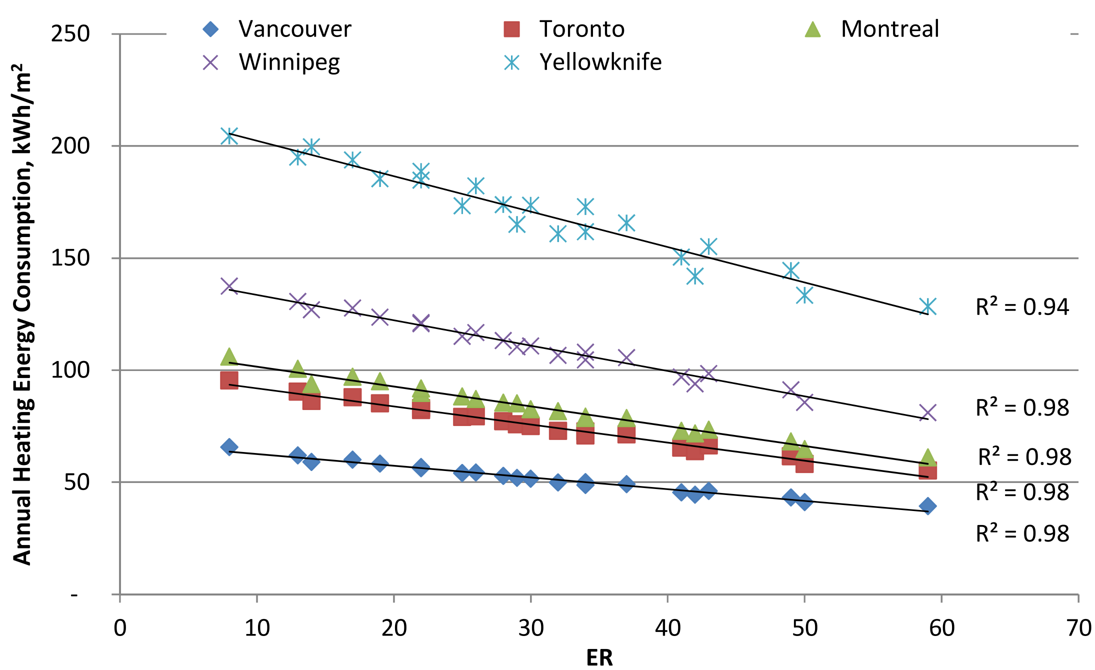


Fig.11.34 Annual heating energy versus ER, 60% WWR, kWh/m^2.

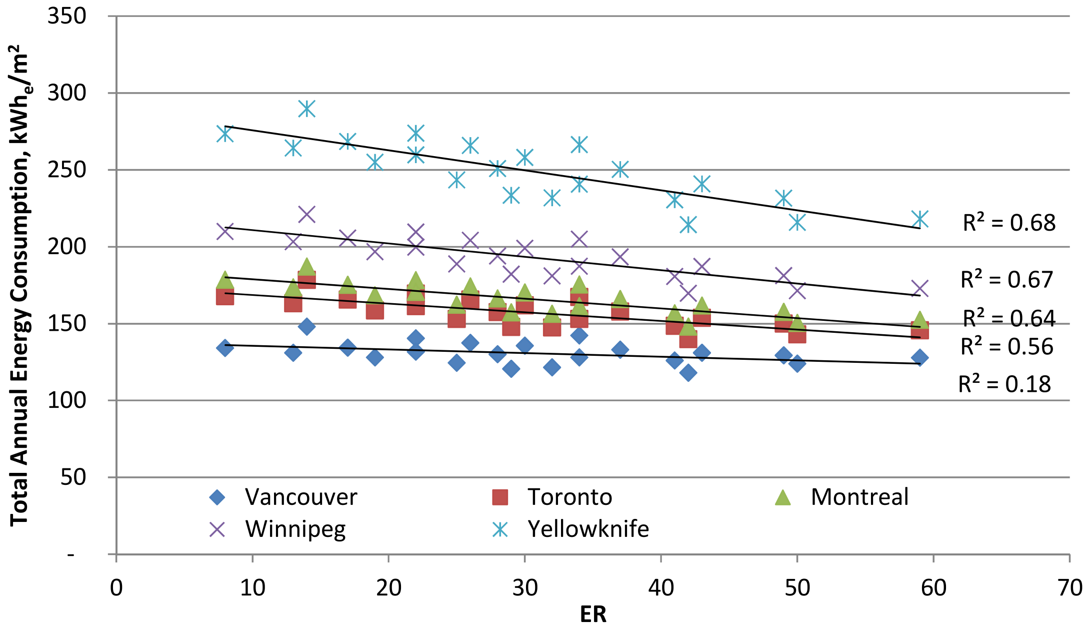


Fig.11.35 Total annual energy versus ER, 60% WWR, kWh_e/m^2.

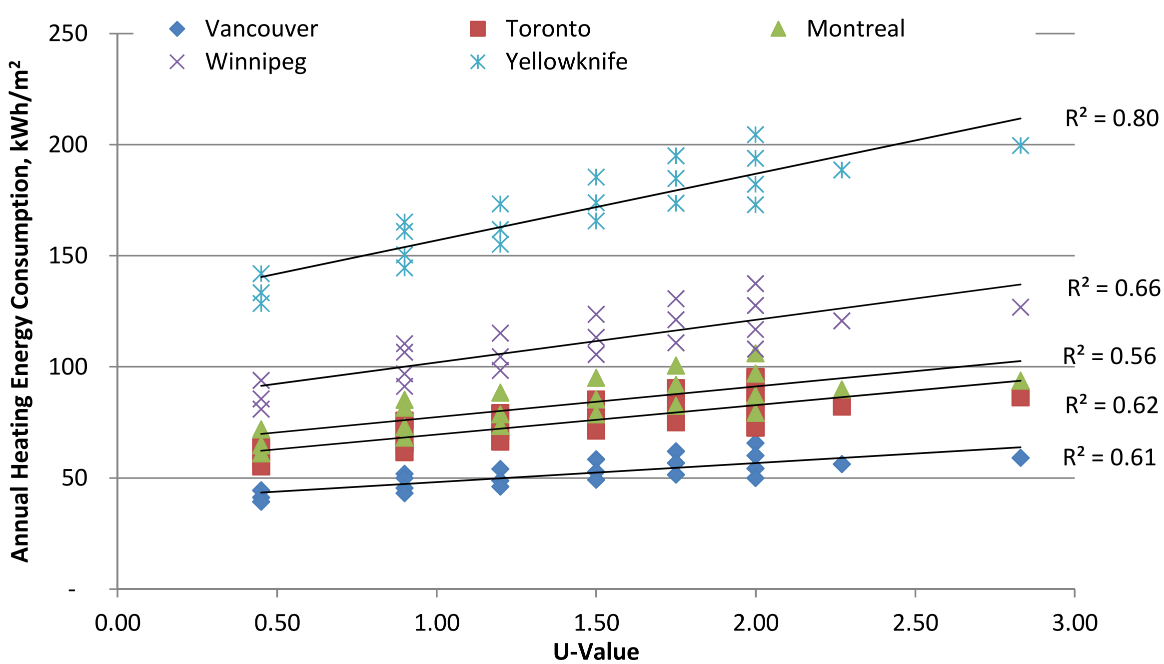


Fig.11.36 Annual heating energy versus U-Value, 60% WWR, kWh/m^2.

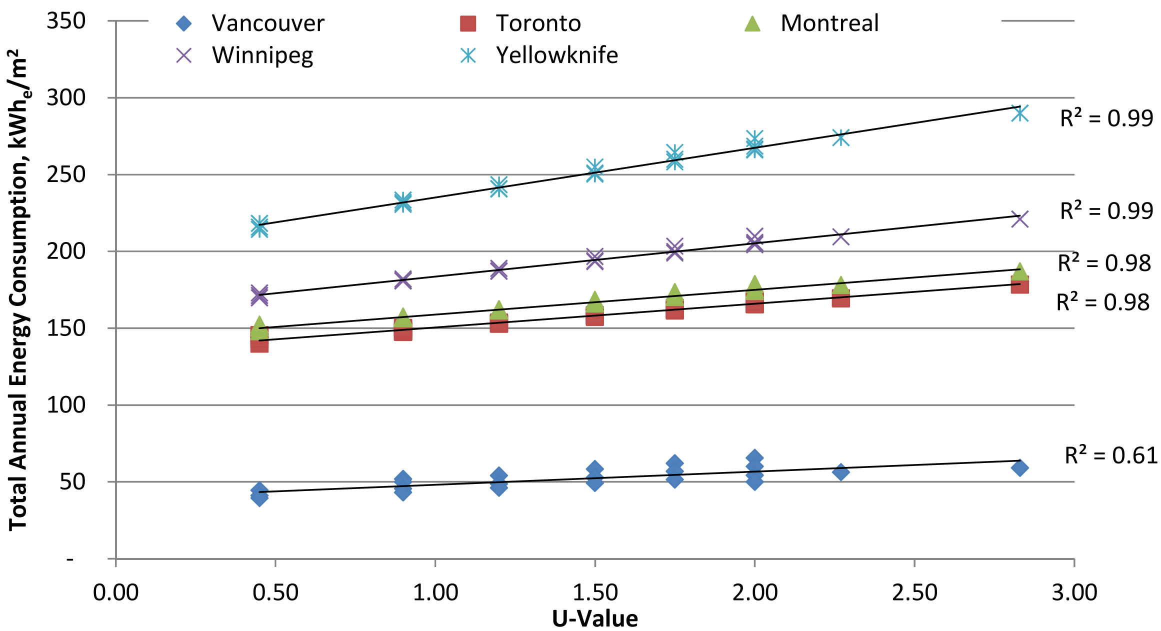


Fig.11.37 Total annual energy versus U-Value, 60% WWR, kWh_e/m^2.

11.4. Summary

The purpose of this section was to investigate the use of the ER to rate windows in multi-unit residential buildings. Three types of buildings were investigated: a row house, a four-storey building and a 20-storey building. Whole building energy simulations were completed in the same manner as the previous sections using the same 23 window types to allow for comparison.

The results of the row house simulations were consistent with the results for the single detached house, where the ER generally provides a good ranking of heating and total energy consumption, with a few small anomalies. The low-rise and high-rise multi-unit residential buildings showed the same trend for heating energy, however the plots for total energy resulted in a greater number of cases where a higher ER resulted in higher total energy. These buildings have higher window to wall ratios and therefore more cooling energy, which had a greater impact on the total energy consumption of the building.

12. Conclusions

12.1. Summary

This project involved a thorough review and analysis of the Canadian *Energy Rating* (ER) metric for windows. The literature review identified several studies related to window energy consumption, however very few of these specifically related the ER to energy consumption.

The ER calculation methodology was analyzed, and a sensitivity analysis of each variable was performed. The sensitivity analysis indicated that for both window and location dependent variables, the air leakage term has a relatively small effect on the ER. The calculation of the location dependent variables in the original ER development report (Enermodal, 1989) utilizes several parameters that are now uncommon in the fenestration industry. For example, the location dependent variables are calculated using a window with a U_{SI}-value of 2.77 W/m²-K, a SHGC of 0.58, and an air leakage rate of 6.6 m³/h-m at 75 Pa. The Canadian ENERGY STAR® program and many building codes now require windows with better performance (for example, the ENERGY STAR® U-value path requires U_{SI} 1.80 for zone A). Also, with the development of low-e coating technology, many window products have lower SHGCs than in the late 1980s.

Windows and Energy

In order to assess how the ER rates the thermal performance of windows several parameters were defined for use throughout the analysis in this study. Archetypical houses, a range of geographic locations and a selection of window types (defined by U-value and SHGC) were selected through a review of codes and standards, climate data and the ENERGY STAR® database of windows. The goal of the analysis was to simulate a wide range of archetype house variables to assess the effectiveness of the ER in ranking energy consumption for different types of windows in different Canadian climates.

The window energy analysis shows that, in general, windows with a higher ER use less heating energy. However, a number of windows were simulated where a slightly higher ER results in higher heating energy consumption. Though the ER does not rank cooling energy appropriately (as expected), cooling energy consumption in houses is very low compared to heating energy in all Canadian locations under worst-case cooling conditions. Therefore, when looking at energy consumption alone, heating energy considerations far outweigh cooling. The same trends where a higher ER window generally uses less heating energy were seen for the majority of the geographic locations simulated. The exception to this finding is Yellowknife (i.e. the far north), where significant differences in heating energy trends are seen compared to the other locations. It is thought that this is due to the low amount of solar radiation that Yellowknife receives in the winter, resulting in less benefit from high SHGC windows.

The same trends, where higher ER correlates directly with lower heating energy consumption, are also seen for all of the archetype house parameters that were simulated (variables not directly related to the windows). These parameters include natural ventilation (instead of mechanical cooling), electric baseboard heating with zoned thermostat control, high internal gains, no basement, new enclosure thermal performance, high thermal mass, walkout basement with fenestration, and house size. This suggests that a representative archetype house is appropriate for use in the development of an ER to rank windows.

The simulations of different window orientations and shading strategies indicate varying trends. This analysis suggests that rating windows with a single ER number may not necessarily indicate comparative energy consumption for houses with non-typical window orientations and shading strategies.

Greenhouse gas emissions trends are generally the same as energy consumption trends. Where electrical GHG conversion factors are higher, this places a greater weight on cooling energy (in a gas-heated house), making the impact of cooling emissions more significant.

Windows and Thermal Comfort

Windows have a significant impact on the thermal comfort of a space, however, a quantitative analysis of thermal comfort is challenging since it is impacted by many occupant-dependant variables. ASHRAE Standard 55 "Thermal Environmental Conditions for Human Occupancy" was used as a guideline for this analysis. A range of comfortable temperatures was established for operative temperature and surface temperature, and the number of hours outside of this range were counted based on simulations for selected window types and locations.

The assessment of operative temperature indicates that the number of "warm hours," or overheating hours recorded, is much greater than the number of "cold hours." Windows with a high SHGC had a greater number of overheating hours than windows with a low SHGC. The number of cold hours is relatively low for most locations except the far north. U-value has a greater impact on the number of cold hours, with low U-value windows performing best. The assessment of surface temperature, on the other hand, shows the number of cold hours was much higher than the number of warm hours. Windows with low U-value had a significantly lower number of cold hours than windows with higher U-values. SHGC has less of an impact on surface temperature than on operative temperature.

Many of the trends visible in the baseline simulations for Vancouver are similar for other locations, generally varying based on their heating and cooling degree days. Cities with more HDDs experience more cool discomfort hours and cities with more CDDs experience more warm discomfort hours, as expected. However, the relationship between window performance and thermal comfort in the various locations remains fairly constant with the prominent exception of Prince Rupert and St John's, which both experience relatively low annual solar radiation.

Several different variables were investigated relative to thermal comfort, including natural ventilation, electric baseboard heating, house size, thermal mass, and orientation. The results for each variable typically follow the same trends for U-value and SHGC when compared in a single location across five representative window types. For natural ventilation (and no mechanical cooling), the five locations examined indicate a direct relationship between the SHGC and the level of thermal discomfort, where a higher SHGC indicates more thermal discomfort hours. Rotating the building to investigate different orientations has the most significant impact on thermal comfort when evaluating either warm or cool hours of a specific room, since the orientation of that room changes. As expected, when a room is located on a south and/or west exposure, it experiences the most solar gain and therefore the highest number of warm discomfort hours, and the fewest number of cool discomfort hours. Higher WWRs were not modeled for thermal comfort; however, by extension of the cooling energy consumption findings, higher WWRs would likely increase the impacts on thermal comfort for both overheating and cold surface temperatures.

Broadly speaking, the correlation between ER and comfort was not as clear as the correlation between Solar Heat Gain Coefficient (SHGC) and operative temperature discomfort, or the correlation between U-value and surface temperature discomfort. However, if the ER is used to select windows for a typical single family dwelling, additional measures may need to be taken to prevent overheating, particularly for windows oriented south and west, and for very high window to wall ratios.

Doors and Skylights

An analysis was completed to investigate the potential application of the ER calculation to doors and skylights. The ER applies to fenestration systems installed in a vertical orientation; therefore, the ER applies to doors but not skylights. Several door and skylight products were selected for energy analysis using the NRCan ENERGY STAR® database of doors and skylights. For doors, the results indicate that the ER does not appropriately compare opaque doors with glazed doors. However when comparing door products that are the same type (e.g. opaque doors to opaque doors, or fully glazed doors to fully glazed doors), products with a higher ER generally have a lower heating and total energy consumption. This is consistent with the findings for windows. It is anticipated that if a larger number of doors were simulated, with ER values that are close together, some small anomalies would be seen as with the window findings. Therefore, the ER is an appropriate metric to rank fully glazed doors.

For skylights (flat glazed and TDD products), a number of anomalies are evident where a product with a much higher ER value results in greater heating energy consumption than a product with a lower ER value. This means that the ER does not appropriately rank skylights.

Multi-Unit Residential Buildings

This analysis was completed to assess the potential use of the ER to rate windows in multi-unit residential buildings. Three types of buildings were investigated: a row house, a four-storey building and a 20-storey building. The ER is said to apply to low-rise residential buildings (three-storeys or less, with an area less than 600 m^2), which would include the row house archetype. Whole building energy simulations were completed in the same manner as houses using the same 23 window types to allow for comparison.

The results of the row house simulations are consistent with the results for the single detached house, where the ER generally provides a good ranking of heating and total energy consumption, with a few small anomalies. The low-rise and high-rise multi-unit residential buildings show the same trend for heating energy, however the plots for total energy result in a greater number of cases where a higher ER results in higher total energy. These buildings have higher window to wall ratios and therefore more cooling energy, which has a greater impact on the total energy consumption of the building. Based on these findings, the ER is appropriate for row houses, but not for larger low-rise and high-rise buildings. Factors related to shading, orientation and window to wall ratio have a greater impact in these building types. By extension, thermal comfort concerns would also be greater in such buildings.

12.2. Conclusions

Energy

The ER is an appropriate tool for comparing windows on the basis of energy consumption for typical Canadian houses. The ER provides a better ranking of window energy consumption than U-value alone. Where anomalies occur (i.e. a window with a higher ER uses more energy), the differences in both the ER value and energy consumption are small. The ER however is not the only metric one may want to consider when choosing windows for a specific home, in a specific location, with a specific orientation. In particular, the ER on its own is not an appropriate measure to compare windows under the following non-typical conditions for houses and low-rise residential buildings:

- Far north locations, including the Canadian Territories
- Windows with significant winter exterior shading
- A house with windows oriented primarily in one direction

Despite these exceptions, the current ER formula works in most common house situations, in most locations, and therefore it is an appropriate metric for rating the relative energy performance of windows. However, for houses that are non-typical, have more site-specific design or energy efficient design, it would be best to select windows based on its U-value and SHGC rather than only the ER. If the ER is incorporated into standards then it should be accompanied by explanatory text regarding when it is appropriate and when it is not appropriate. Likewise, if the U-value alone is used to select energy efficient windows, explanatory text regarding the potential energy savings of a high or a moderate SHGC should also be provided. While the ER should be maintained, provisions to keep the alternate U-value compliance path are necessary because of these non-typical conditions.

Thermal Comfort

Although the ER is appropriate for selection based on lower energy consumption, a high SHGC window can result in overheating, which may be a concern even in typical houses with standard window to wall ratios. Overheating should be evaluated on a case-by-case basis, depending on project-specific factors such as location, orientation, shading, and window to wall ratio. Additional guidance is needed to assist consumers in selecting appropriate windows (and SHGC factors) for energy consumption and thermal comfort.

Doors and Skylights

It is recommended that the current approach of only using an ER for sliding glass doors is maintained, and the ER not be used for opaque or partially glazed doors. Also, it is recommended that the current ER formula not be used for skylights.

Multi-Unit Residential Buildings

The same ER findings apply to low-rise multi-family buildings with low window to wall ratios. However, it is recommended that the ER not be used for low- and high-rise multi-unit residential buildings with higher window to wall ratios.

Possible Future Work

A number of research opportunities have been identified as a result of the present work, including the following:

- Investigate the impact of re-calculating the ER location dependent variables, following the same methodology used in the 1989 study, but using parameters more representative of current construction and technology.
- Perform calculations following the ISO procedure, and investigate whether this rating would perform better than the existing rating calculation.
- The far north was consistently identified as an anomaly where the ER may not appropriately rate windows. However, the ER still resulted in a better ranking of heating energy consumption than U-value alone. A revised ER calculation would likely provide better results for the far north with solar heat gain weighted differently. One option would be to have a separate calculation (i.e. different location-dependant parameters) for different climate zones.
- Explore the possibility of adding either a standardized cooling energy rating (ERC), or some other rating to indicate thermal comfort. This would be an additional rating to the current ER.