A MODEL FOR EVALUATING THE THERMAL EFFECTS OF WINDOWS ON THE CANADIAN HOUSING STOCK

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ABSTRACT

This paper presents the modeling methodology that is being employed to investigate the impact of windows upon the space heating and cooling energy consumption of the Canadian housing stock. Typical window construction is such that it has low thermal resistance, often resulting in significant heat loss, but also admits solar radiation into the dwelling which may offset the heat loss. The model presented here is designed to specifically identify the energy components related to passive solar gains and to examine the heating and cooling energy requirements due to windows in the Canadian housing stock. The model will also be used to evaluate the impact of retrofit upgrades.

An analysis of the housing stock database that is being used by the model was conducted. The database includes the window types, orientation, and area for each side of the dwelling. In general, there is no variation in window type distribution as a function of orientation or house type. The predominant national window type by area is double-glazed clear-glass with a 13 mm air-filled gap. Energy inefficient single-glazed windows appear in homes built prior to 1980 but are minor in newer homes. Distribution of triple-glazed windows is uniform across all vintages, indicating it is primarily used in retrofits. British Columbia has the highest percentage of single-glazed windows and the Prairies region has the highest percentage of triple-glazed windows, likely due to their mild and cold climates, respectively.

INTRODUCTION

The interest in the use of passive solar heating in dwellings is growing. Fenestration systems such as advanced windows provide an opportunity to reduce conventional energy consumption by reducing heat loss and increasing the capture and utilization of the renewable solar energy. In addition they may provide an aesthetically pleasing environment and natural lighting. Because of the important role windows play in the dwelling environment, an analysis of the present Canadian housing stock (CHS) was undertaken. The objective is to determine the impact that windows presently have on the heating and cooling energy consumption and to assess the impact of retrofit upgrades. Assessing the contribution of windows to the total energy consumed by the housing stock requires complicated simulation and results analysis to account for other building components and the variety of heat fluxes and paths. There are two aspects of windows which make this easier: (a) most of the short-wave (SW) radiation that passes through a window is absorbed within the dwelling's thermal zone, and (b) windows are opaque to long-wave (LW) radiation. However, there are aspects of windows that also impede assessment such as:

1) The location of the energy control volume around the thermal zone can make solar gains appear large or insignificant. For example, if the control volume is drawn around the exterior of the zone surfaces then entering solar radiation will appear be high, although a portion of it quickly rejects from the zone to ambient via convection or LW radiation from the window glass. Alternatively if the control volume is drawn around the interior air mass, then the solar gain is indistinguishable as it enters the air mass via convection from the interior surfaces.

2) There are conditions during which it is difficult to identify useful or adverse solar gains because of other heat gains such as appliances and lighting. For example, if a thermal zone at the cooling temperature set-point receives 1 kW solar heat gain and 1 kW of appliance and lighting heat gain, and it passively rejects 1

kW to the cooler ambient conditions via conduction, then the plant cooling system must remove 1 kW from the zone to maintain the temperature set-point. In this case, a hierarchal status must be assigned to the heat gains to determine if the solar gain is useful or adverse.

3) Windows are frequently shaded by exterior obstructions (e.g. other buildings or trees) and there is a lack of data which define these obstructions.

Windows are an area of active development and have undergone significant improvements in the past decades. These may be grouped into two areas: ‘center of glass’ and ‘glass edge’ (Mitchell et al. 2003). Regarding the center of glass, the migration from single-glazed (i.e. single glass pane) to double-glazed windows has been having a significant impact by almost doubling the thermal resistance. More recently, triple-glazed windows have become commonly available for residential applications. The gaps between the glazing layers come in a variety of widths, typically ranging from 6–13 mm with a slightly increasing thermal resistance as a function of thickness. The fill gas in the gaps has evolved from dry-air or nitrogen to argon and also krypton, increasing the gap thermal resistance by 10% or more. Low-emissivity (low-e) coatings may be applied to reduce the LW radiation losses between glazing layers. Coatings such as these can have a major impact on thermal resistance, in some cases more than doubling the effective gap resistance value. However, coatings also results in increased SW radiation absorption within the window. This restricts the amount of light that may be used or stored within a dwelling to offset conventional energy consumption.

Regarding glass edge, different materials have been used to seal the gap and space the glazing layers, including aluminium, plastics, or silicon foams. These seek to reduce the conductive heat flow paths along the outer seal of the window. The frame of the window also plays a role as it conducts heat and also provides the seal and sliding mechanism which allows a window to open/close, presenting the opportunity for air infiltration. Many frame types (e.g. single-hung, casement) and frame materials (e.g. wood, vinyl) have been developed to fit the application and aesthetic requirement.

We have begun a study of the impacts of windows upon the energy consumption of the CHS. This paper discusses our techniques and identifies some of the difficulties in considering solar gains. An analysis of the present CHS window parameters is presented and energy results will soon be published.

CANADIAN HOUSING STOCK DATA

As this study evaluates the impact of windows on the CHS, a suitable database of window information is required. Such information is supplied by the Canadian Single-Detached and Double/Row Database (CSDDRD) which is a set of house descriptions representative of the CHS (Swan et al. 2009a). It is a subset of the EnerGuide for Houses (EGH) program database, which is the culmination of over 200,000 requested home energy audits collected from 1997 through 2006 by Natural Resources Canada (SBC 2006). The audits, conducted by professional auditors, measured and recorded the location, type, geometry, storeys, foundation, attic, construction materials including individual windows and doors, blower door test results (air-tightness), and DHW and space heating systems. Variables were entered in accordance with the definitions and available selections of the HOT2XP monthly bin type energy simulation software (SBC 2008).

Using an iterative selection process described in detail by Swan et al. (2009a), a total of 14,030 single-detached (SD) and 2922 double/row (DR) house records were selected from the EGH database, totalling 16,952 records which, based on the selection parameters, statistically represent the 8.9 million SD and DR houses of the CHS. The parameters used for selection were:

- House type (SD or DR)
- Region (Atlantic, Quebec, Ontario, Prairies, British Columbia)
- Vintage (1900-1945, 1946-1969, 1970-1979, 1980-1989, 1990-2003)
- Storeys (one through three, including half storeys)
- Living space floor area (25-56, 57-93, 94-139, 140-186, 187-232, 232-300 m^2; excluding basement or crawl space)
- Space heating system energy source (electricity, natural gas, oil, wood, propane)
- Domestic hot water system energy source (electricity, natural gas, oil).

The CSDDRD includes detailed information of the windows of each house. Windows are individually specified for each side of the house and contain the following descriptive information:

- Height, width, area, and facing direction
- Vertical and horizontal location with respect to eaves
- Number of glazing layers
- Glazing layer coatings
- Gap width and fill gas
- Gap seal and spacer type
- Frame type (e.g. slider with sash)
- Frame material (e.g. wood, vinyl)

A critical examination of the CSDDRD was completed and indicated that the detailed height, width, and vertical/horizontal location data are largely unreliable, as determined by their inappropriate values. However, the data on window areas and the facing direction as well as glazing characteristics are valid. The absence of detailed geometry data does not pose a significant detriment to modeling, as will be discussed in subsequent sections.

OVERVIEW OF THE MODELING TECHNIQUE

The characteristics of the housing stock vary significantly across Canada. This is due to both the materials used in the building thermal envelope and the regional climate. Therefore, to assess the impacts of windows on the energy consumption of the CHS, each house of the CSDDRD will be modeled. As the research is related to solar gains, an hourly or sub-hourly time-step will be used to suitably capture the dynamic effects of sunlight. In addition, the Canadian Weather for Energy Calculations (CWEC) climate data files (Environment Canada 2009) available for this project use a one hour time-step. CWEC weather data files include direct normal and diffuse solar insolation values.

The houses in the CSDDRD will be modeled using ESP-r, an integrated building simulation software described by Clarke (2001). The CSDDRD and ESP-r constitute the main components of the Canadian Hybrid Residential End-use Energy and Emissions Model described by Swan et al. (2009b, 2008). The ESP-r simulator uses numerical heat and mass balance methods applied at discrete time steps to a representation of the building using many finite volumes.

The model description of each house of the CSDDRD is being developed for ESP-r. Consideration is given to the windows and these are described as accurately as possible. The remainder of the house will be modeled using values provided by the CSDDRD with some simplifications to reduce model detail. To evaluate the impact of the windows, energy flows will be considered over an annual period and will be compared to the dwelling's overall heating/cooling requirement.

WINDOW TYPES

Windows may be characterized primarily based on their thermal and optical properties. Although the gap seal type and window frame type/material have an impact, their contribution is limited as they typically represent less than 10% of the surface area of a window. Due to this small magnitude, and the wide variety of frame types and materials, and well as the complication in modeling these parallel thermal paths, the frame and seal of the window were neglected for the current study.

Three window parameters present in the CSDDRD were used to describe the thermal and optical properties of the windows. These are: glazing type, coatings, and gap-width/fill-gas. Each is described in the CSDDRD with a digit of a three-digit code. The parameter options present in the CSDDRD for these the characteristics are shown in Table 1, along with a code key in the first column. The key may be used to construct the three-digit code to describe the thermal and optical properties of the window. For example, code 203 would represent a DG window with clear glass and a 13 mm gap filled with argon gas.

Table 1. Window parameters shown with a corresponding key code digit value

Code digit value	Glazing type (digit 1)	Coatings* (digit 2)	Gap width and fill gas (digit 3)
0	-	Clear glass	13 mm – air
1	Single glazed (SG)	Low-e (0.04)	9 mm – air
2	Double glazed (DG)	Low-e (0.10)	6 mm – air
3	Triple glazed (TG)	Low-e (0.20)	13 mm – argon
4	-	Low-e (0.35)	9 mm – argon

* The low-e coating is applied to the gap facing side of the innermost glazing layer

The combination of these parameter options result in 51 different window types. However, analysis of the CSDDRD shows that only 25 unique types appear in the database. It is also recognized that the optical properties (e.g. transmittance and absorptance) of the window are defined solely by glazing type (digit 1) and coatings (digit 2). The combination of these with gap width and fill gas describes the thermal properties of the window. The analysis of the CSDDRD also showed that only 9 unique optical descriptions exist. The 9 unique optical codes and 25 unique thermal window codes are shown in Table 2. The table shows that the 13 mm gap width is a typical manufacturing size.

Table 2. Unique window codes present in the CSDDRD

First two	Three digit codes (shown as a function of gap width and fill gas)					
‘optical’ digits	No gap	13 mm – air	9 mm – air	6 mm – air	13 mm – argon	9 mm – argon
10	100*					
20		200	201	202	203	
21		210			213	
22		220			223	224
23		230	231		233	234
24		240			243	244
30		300	301			
32		320			323	
33		330	331		333	334

* The third digit of single-glazed windows defaults to zero although they do not have a gap

To conduct a thermal simulation of a house in ESP-r requires both the optical and thermal descriptions of the windows. The required values are:

- Construction material properties (thermal conductivity, density, specific heat, and thickness)
- LW emissivity of the internal and external surfaces
- Gap thickness and effective combined LW radiation and convection resistance (this accounts for low-emissivity coatings)
- Solar transmittance of the window as a function of angle
- Solar absorptance of each glazing layer as a function of angle

All window glass is 3 mm float glass. The solar transmittance and absorptance values of each optical type were obtained from Natural Resources Canada to be consistent with the intended glass during the EGH program. These optical values were calculated using Window 4.1, which is a freely available computer application (LBNL 1994). Gap resistances were calculated using Window 5.2 and representative glass with appropriate coatings using the NFRC 100-2001 Winter environmental conditions (LBNL 2001). Only the gap width, fill gas, and coatings are required to obtain gap resistance, so the use of slightly different glass than originally specified, but with identical coatings, will not impact the gap resistance results. An alternative method for calculating the gap resistance as a function of the conditions at each time-step is presently being developed by Lomanowski (2008). This advanced method may be incorporated into the model at a later point.

An example of thermal and optical window values are shown in Table 3. It is apparent that changing the gap width and fill gas has a 10–25% impact on effective gap resistance and no impact on the optical properties. Altering the coating substantially increases the effective gap resistance and reduces the solar transmittance. During the Canadian winter such a coating will reduce the sun-down heat loss, but will also reduce the sun-up solar heat gain, as compared to clear glass.

Table 3. Comparison of window thermal and optical characteristics for common types

Characteristic	Window code (variations italicized)				
	200†	202	203	220	300
	Base case	*6 mm*	*Argon*	*Low-e (0.10)*	*TG* ‡
Effective gap resistance (RSI)	0.19	0.14	0.21	0.38	0.20/0.18
Solar transmittance*	0.705	0.705	0.705	0.536	0.595
Solar absorptance* (outside layer)	0.094	0.094	0.094	0.104	0.098
Solar absorptance* (inside layer)	0.074	0.074	0.074	0.128	0.079/0.063

* For radiation normal to the surface

† Base case three digit code 200: glazing layers = DG, coating = clear, gap width = 13 mm, fill gas = air

‡ The additional values are for the second gap and third layer, respectively

These incidence-angle dependent solar absorptance and transmittance values were imported into nine optical descriptions in the ESP-r optical database. Additionally, the 25 unique window types, along with effective gap resistances, were imported into the ESP-r multilayer constructions database. This process was completed using an XML text database format and Perl scripting language (CPAN 2009).

COMPLETE HOUSE MODELS

The house models generated for each house of the CSDDRD are described by Swan et al. (2009b). In essence, houses are modeled as rectangular structures with floor area and width/depth ratio to match that specified in the CSDDRD. Up to three thermal zones are specified; these are main floor(s), basement, and attic. Windows are only placed on the main level. Because individual window data of the CSDDRD were found to be unreliable, only a single amalgamated window area was used for each side. The amalgamation of windows on each particular side also eases modeling description input with insignificant loss of accuracy as discussed by Purdy and Beausoleil-Morrison (2001).

The CSDDRD specifies the type and number of windows facing each direction. Because individual window areas were not available, the dominant (i.e. the most frequent) window type that appears on the side of the house was selected as the representative window type for that side. The appropriate thermal and optical construction was specified for the amalgamated window facing in each of the four directions.

The remaining opaque multilayer constructions of each house (e.g. walls, roof) were developed using standard construction materials representative of the CHS. Although individual information is available for each construction type (e.g. foundation, floor, walls, ceiling), the complexity to model all of the variations is high. Therefore, at this stage of the model development each house was assigned the same opaque constructions with the insulation layer modified to account for the overall thermal resistance value of the actual construction. The typical wall construction employed is wood siding, plywood sheathing, fibreglass insulation, and 13 mm thick drywall. This simplification is appropriate for modeling focused on solar gains as the overall thermal opaque envelope characteristics are taken into consideration. The only deviation is that of thermal mass which may be used to store solar energy. This will not significantly affect the absorbed solar radiation, but may affect the ratio of that absorbed solar energy being applied to the air-point or into thermal storage. For this reason, in the final version of the model, the actual construction will be used.

In addition to the description of the house thermal envelope, other energy related considerations required for appropriate solar energy modeling include:

- Natural air infiltration, which was modeled using the air infiltration model (AIM-2) algorithm of ESP-r using air-tightness measurements of each house listed in the CSDDRD.
- Active air exchange, which was modeled using the central ventilation system (CVS) algorithm of ESP-r using equipment specification of each house listed in the CSDDRD.
- Appliance and lighting loads, which were modeled using a generated hourly profile with a total annual gain of 30 GJ, as described by Knight et al. (2007) and Armstrong et al. (2009).

- A simplified active energy heating/cooling system (e.g. oil-fired furnace), which was specified with capacity limitations as listed in the CSDDRD. Only the delivered heating/cooling is considered as this is not an investigation of the effect of the heating/cooling system's characteristics. The heating/cooling system maintains the zone set-point temperature at 20 ˚C (heating) and 25 ˚C (cooling), which are the average values of CHS thermostat settings (OEE 2006).

There is no available information regarding exterior obstructions that shade components of the house, and as such, the houses are considered non-shaded for this study.

SIMULATION AND RESULTS ANALYSIS

An annual energy simulation will be conducted for each dwelling using the ESP-r simulation engine. The simulation process for the entire housing set will soon be conducted on two dedicated quad-core dual-processor computers and is expected to take two days.

A simplified analysis of solar heat gains could be done by comparing the results of two simulations: one standard simulation and another treating the windows as opaque constructions. This will identify the macro consideration for the active energy injection/extraction system, but does not provide knowledge of the exchanges of energy and solar contributions. To assess the impacts of windows with regard to both their loss and transmission of solar energy to the dwelling, a detailed analysis of the energy flows is required.

To conduct such an analysis requires an energy control volume (CV) to be drawn around the thermal zone. This presents a variety of options:

1. If the CV is drawn around the exterior of the dwelling, the SW radiation across the control volume at the windows will artificially inflate the value of solar gain. This is because a portion of this radiation is absorbed within the glazing layers, resulting in increased LW radiation and convection from the window back to the ambient environment. This portion does not contribute to solar gains, but is indistinguishable with such a CV.
2. If the CV is drawn around the interior of the dwelling (i.e. only surrounding the air-mass), it will be impossible to determine the impact of solar gains as only convection from the interior surfaces to the air-mass will be distinguished.
3. If the CV is drawn to encompass the interior surface layer of the opaque constructions (e.g. gypsum board), the thermal storage aspects may be considered. When a transparent layer is encountered, the CV jogs around the interior glazing layer. This eliminates the consideration of absorbed SW radiation on the transparent surfaces, as this primarily manifests into conduction and LW radiation and rejects back out through the window to ambient. Such a control volume is shown in Figure 1.

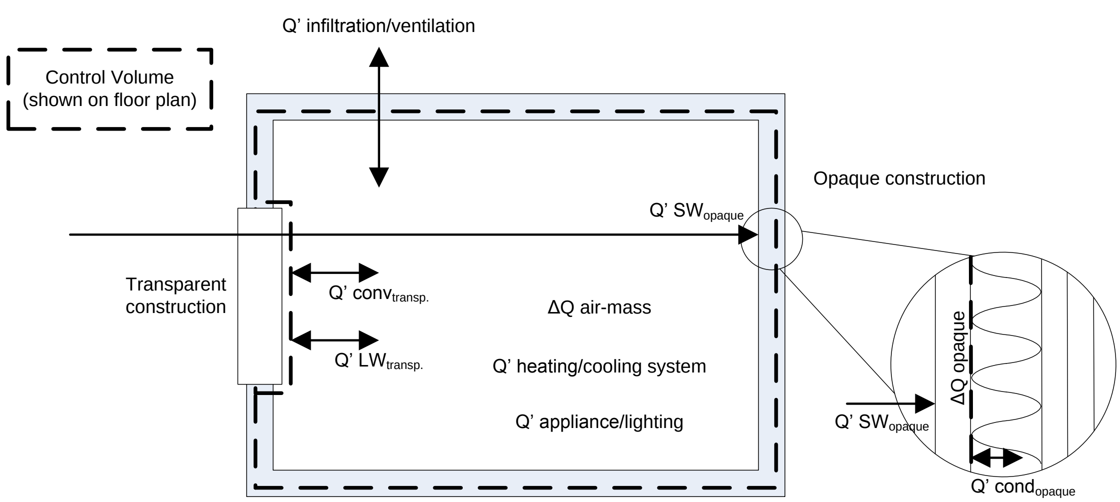

Figure 1. Control volume encompassing interior opaque layer and not encompassing the transparent layer (shown in floor plan view)

Control volume #3 has advantages for determining the component heat fluxes within the dwelling. It does not include the absorbed solar radiation in the transparent construction, a large part of which is quickly lost to the exterior. It does include the thermal storage characteristics of the opaque layer which are significant. It focuses on solar radiation that enters and is absorbed within the confines of the insulated zone. The identified change in heat storage (ΔQ) and heat fluxes (Q') shown in Figure 1 may be used to construct an energy balance equation for the control volume. This method will be used to post-process the simulation results to examine the component heat fluxes and distinguish the effects of solar gains. Fluxes will be considered hierarchically and the injected/extracted energy will be compared to the absorbed solar radiation at the opaque interior surface (solar gain).

ANALYSIS OF THE WINDOW CHARACTERISTICS OF THE CSDDRD

As the model is not yet complete, energy results were unavailable for this paper. However, an analysis of the window parameters as a function of the following house characteristics was undertaken: window facing direction, type of house, house vintage, and region. The analysis of window types is indicative of retrofit potential and how it varies by house characteristics such as vintage (construction year) or region. The analysis results will be used as a guide when evaluating the impact of retrofit upgrades using the model.

A frequency distribution analysis of the window code for each side of each house of the CSDDRD was conducted. It was found that only 8 of the 25 window codes were present in more than 0.5 % of the houses. For all subsequent analysis (e.g. by vintage or region) these 8 important window codes reoccurred.

The window codes in the CSDDRD are listed with regards to front, right, back, and left sides of the house, along with front orientation. Front orientation is defined by cardinal directions (S, E, N, and W) and intermediate directions (SE, NE, NW, and SW). To reduce the current analysis to the four cardinal direction, the intermediate directions SE and SW are considered S, and NE and NW are considered N.

An analysis of window types as a function of cardinal direction was conducted. This was completed by two methods: count and surface area. The count method simply bins each occurrence of a window type for a given direction. The surface area method is similar, but instead of binning the occurrence, it bins the window surface area. The surface area method is more applicable for energy investigation as it attributes more significance to larger windows. Interestingly, both methods produced similar distribution of results, indicating that window size is not correlated to window type for a given cardinal direction.

Table 4 shows the distribution of window types for each cardinal direction using the surface area method. DG windows with clear glass and a 13 mm air filled gap (code 200) are the dominant type for all cardinal directions, and thus the CHS in general. Single pane windows (code 100) are also significant. Table 4 also shows that the distribution of window types for the two considered housing types (single-detached and double/row) are very similar. The similarity of window type distributions for cardinal directions and house types is expected as homebuilders tend to install similar window types on all four sides of the house, and do not differentiate window type as a function of dwelling detachment.

Table 4. Distribution of window types corresponding to each cardinal direction and each house type (by surface area)

Window type (code)	Cardinal direction (%)				House type (%)	
	S	E	N	W	SD	DR
100	7.4	8.1	7.0	8.2	7.7	6.8
200	74.4	75.0	74.9	74.4	74.0	79.2
202	5.3	5.1	5.9	5.4	5.7	3.9
231	3.5	3.2	3.4	3.2	3.4	3.2
234	6.6	5.9	6.2	6.1	6.4	5.3
331	0.2	0.2	0.2	0.3	0.2	0.1
301	1.6	1.6	1.6	1.7	1.7	0.9
334	0.6	0.5	0.6	0.6	0.6	0.3

Window type distributions as a function of vintage or region are shown in Table 5. An obvious decreasing trend for SG windows (code 100) is seen for newer homes. Recently built homes have a negligible amount of SG windows. Interestingly, this has not been offset by an increase in DG (code 200) window types. Instead, homeowners have been opting for low-e coatings and argon fill gas. The code 23X series shows a significant increase in homes built from 1990–2003. It may also be seen that TG windows (code 3XX) have been applied somewhat uniformly to all vintages, and as such do not appear to be gathering market share from DG windows.

Table 5 also shows window type distributions as a function of region. The regions are Atlantic (AT), Quebec (QC), Ontario (OT), Prairies (PR), and British Columbia (BC). BC has a high level of SG and ‘thin’ (6 mm) DG windows, owing at least partially to its mild climate relative to other Canadian regions. PR shows increased use of TG windows, owing to its very cold climate.

Table 5. Distribution of window types corresponding to each house vintage and each region (by surface area)

Window Code	Vintage (%)					Region (%)				
	Prior to 1946	1946–1969	1970–1979	1980–1989	1990–2003	AL	QC	OT	PR	BC
100	15.7	11.8	9.3	2.1	0.4	7.7	3.1	5.3	3.0	26.3
200	73.8	73.7	71.1	78.5	76.1	82.7	77.8	77.9	71.3	59.2
202	2.6	3.4	8.6	8.6	4.3	2.7	4.5	5.4	3.1	11.4
231	1.9	2.6	2.3	2.4	6.9	1.6	4.6	2.8	5.6	1.6
234	3.8	5.6	5.9	5.4	9.7	4.7	7.6	7.7	5.6	1.3
301	1.5	1.9	1.5	2.0	1.0	0.1	1.2	0.3	7.5	0.2
331	0.2	0.2	0.2	0.2	0.3	0.0	0.2	0.0	1.0	0.0
334	0.4	0.6	0.7	0.5	0.7	0.0	0.5	0.1	2.7	0.0

CONCLUSION

This paper describes a modeling methodology that is presently being implemented to evaluate the impact of windows on the energy consumption of the Canadian housing stock. A modeling methodology has been developed to perform hourly simulation on a database that statistically represents the CHS, with the intention of determining the losses and gains of windows, and the transmission of useful and adverse solar energy into the dwelling.

A detailed examination of the present windows found in a database of the CHS was conducted. It was found that windows vary in the CHS due to vintage and region, and that there are a number of significant window types that must be considered when using the model.

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