

# Estimating Benefits of Deep Retrofit Scenarios Based on Passivhaus Standards in the Residential Sector of Waterloo Region

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**Abstract.** This paper investigates the potential benefits of deep retrofit scenarios on the energy consumption of houses in Waterloo Region. The building envelop is the primary focus, especially upgrading wall, attic, and foundation insulation. The sample houses are divided into six categories based on their construction date. A deep retrofit upgrade scenario is applied to a typical house of each category and the potential energy savings and CO<sub>2</sub> emissions reduction of each typical house are estimated after completing the corresponding retrofit scenario. One of the six retrofitted houses achieves the Passive House energy intensity standard. Finally, the total potential savings for Waterloo Region are obtained based on the Regional housing census. According to the above analysis, it can be concluded that applying deep retrofit scenarios to in the residential sector of Waterloo Region can make significant contributions to reducing 14.16×10<sup>9</sup> MJ/yr energy consumption and 7.83×10<sup>8</sup> kg/yr CO<sub>2</sub> emissions.

## 1 Introduction

In Canada, the residential sector is the third largest energy consumer, accounting for 17% of the total national energy consumption and 15% of greenhouse gas emissions [1]. In Waterloo Region, the residential and business activities emitted approximately 3.6 million tonnes of greenhouse gases in 2010, and the residential sector accounted for 22% of the total [2]. This situation prompts us to examine the potential impacts of increasing energy efficiency and reducing energy consumption in homes. Residential retrofit scenarios to reduce energy consumption are developed for Waterloo Region [3].

The objective of this research is to evaluate scenarios to improve residential energy performance and reduce CO<sub>2</sub> emissions by applying retrofit scenarios based on Passivhaus Standards to houses [4] in Waterloo Region.

The data employed in this study are derived from a standard residential energy computer model (Hot2XP), prepared as part of the residential energy efficiency project (REEP) [5] and data tables from Statistics Canada [6]. The sample houses were divided into six categories according to their construction date, and then a typical house from each category was selected based on the similarities between its energy consumption characteristics and the corresponding category. Retrofit scenarios are applied to the six typical houses and then the energy savings and CO<sub>2</sub> emissions reduction of these six typical houses are estimated. The total potential energy savings and CO<sub>2</sub> emissions reduction of Waterloo Region can be obtained based on the Waterloo Region housing census and the number of houses in each age category.

## 2 Methodology

In this study, the sample houses are divided into six categories based on the age classification of occupied private dwellings (Table 1).

**Table 1.** Classification of occupied private dwellings

Classification	C1	C2	C3	C4	C5	C6
Construction Period	Before 1946	1946-1960	1961-1970	1971-1980	1981-1990	1991-2000

Typical houses were selected based on the similarities between their energy consumption characteristics and the average values of the corresponding category. Key energy characteristics include the total energy consumption, the amount of heat loss through air leakage, foundation floor / walls, attic, main walls, and windows / doors. The six selected houses, were constructed in 1945, 1959, 1966, 1975, 1986, and 1995, respectively.

The comparison of current R values of segments of the six typical houses to the deep retrofit R values is presented in Table 2.

**Table 2.** Comparison of current and deep retrofit R values

Design Component	Current R Value						deep retrofit R Value
	T1	T2	T3	T4	T5	T6	
Attic	8.91	28.16	28.79	22.43	26.18	30.15	60
Foundation Walls	2.73	2.95	8.57	2.95	11.53	10.56	20
Walls	9.71	10.62	10.16	9.60	14.71	14.88	40
Windows	2	2	2	2	3	3	7
Air Changes Per Hour (50p)	10.88	5.72	7.22	5.1	5.52	3.31	0.6

Typical R values of windows have changed over time. Single-glazed windows with an R value of 1 (plus an outer storm window with R value of 1) were installed before the 1970s, double-glazed windows with an R value of 2 were installed from the 1970s to the 1980s, and double-glazed windows with a low-E coating and argon filled cavity (R value of 3) were installed after 1980s. In this study, it assumes that the R value of the windows of houses built before 1980 is 2 and the R value of the windows of houses built after 1980 is 3. For window retrofits, all windows are replaced with 2 low-e coatings, argon filled triple-glazed windows with an R value of 7 (Table 3). In addition, the window category also includes doors, and the doors can be retrofitted from solid wood to

steel with foam insulation so that they can achieve a similar upgrade to the windows. Therefore, this study includes window and door surface areas in a single category.

**Table 3.** The heat loss reduction from window improvement

	T1	T2	T3	T4	T5	T6
R Value before retrofits	2	2	2	2	3	3
R Value after retrofits (PH Standard)	7	7	7	7	7	7
Heat Loss Before Retrofits (MJ)	26,990	27,892	30,134	20,445	29,007	26,754
Heat Loss After Retrofits (MJ)	7,711	7,969	8,610	5,841	12,432	11,466
Heat Loss Reduction (MJ)	19,279	19,923	21,524	14,604	16,575	15,288

For attic, foundation walls, and main walls retrofits, spray foam is often selected to be used as the insulation material. Spray foam is an excellent option inside wall cavities where it seals air leaks as well as adds high insulation values. The completed closed-cell spray polyurethane foam application provides an air and vapour barrier. Spray foam has a long lifetime and needs no replacement or replenishment. In this study, extruded polystyrene is selected to insulate the foundation floor because it is typically cheaper than spray foam. The foundation floor is rarely insulated when houses were built, so it assumes that there is no insulation in foundation floor of the six selected houses in this study. Given the R values per inch of closed-cell spray polyurethane foam and the extruded polystyrene: 6 and 5 respectively, the thickness of insulation materials required to insulate attic, foundation floor, foundation walls, and main walls can be calculated. In practice, the heat loss performance after the R value of foundation floor is raised to 10 and the R value of foundation walls raised to 20, is approximately equal because of the colder temperatures experienced outside the upper portion of the foundation wall. Finally, the heat loss reduction of each segment can be estimated according to the formula

$$R = \Delta T / Q \quad (1)$$

$\Delta T$  represents temperature difference across the insulated segment (wall, floor, etc.) and  $Q$  represents the heat transfer per unit area per unit time (Table 4).

**Table 4.** The heat loss reduction after retrofitting main segments of typical houses

	Insulation added	Foundation Floor	Foundation Walls	Attic	Main Walls
T1	Thickness (inch)	2	2.88	8.50	5.05
	Total amount (m <sup>3</sup> )	3.25	5.78	13.82	20.25
	Heat Loss Before Retrofits (MJ)	38,675		16,203	36,692
	Heat Loss After Retrofits (MJ)	5,279		2,406	8,907
	Heat Loss Reduction (MJ)	33,396		13,797	27,785
	Thickness (inch)	2	2.84	5.31	4.90

T2	Total amount (m <sup>3</sup> )	4.57	6.76	12.14	11.67
	Heat Loss Before Retrofits (MJ)	39,426		6,831	20,986
	Heat Loss After Retrofits (MJ)	5,815		3,206	5,572
	Heat Loss Reduction (MJ)	33,611		3,625	15,414
T3	Thickness (inch)	2	1.88	5.20	4.97
	Total amount (m <sup>3</sup> )	4.88	4.71	12.68	12.46
	Heat Loss Before Retrofits (MJ)	26,137		6,285	17,608
	Heat Loss After Retrofits (MJ)	11,120		3,016	4,472
T4	Heat Loss Reduction (MJ)	14,937		3,269	13,136
	Thickness (inch)	2	2.84	6.26	5.07
	Total amount (m <sup>3</sup> )	4.88	7.12	15.26	12.71
	Heat Loss Before Retrofits (MJ)	35,516		7,408	18,425
T5	Heat Loss After Retrofits (MJ)	5,239		2,769	4,422
	Heat Loss Reduction (MJ)	30,277		4,638	14,003
	Thickness (inch)	2	1.42	5.64	4.22
	Total amount (m <sup>3</sup> )	3.56	3.03	10.03	17.98
T6	Heat Loss Before Retrofits (MJ)	21,958		5,769	24,863
	Heat Loss After Retrofits (MJ)	12,659		2,517	9,143
	Heat Loss Reduction (MJ)	9,299		3,252	15,720
	Thickness (inch)	2	1.57	4.98	4.19
T6	Total amount (m <sup>3</sup> )	3.56	3.35	8.85	17.86
	Heat Loss Before Retrofits (MJ)	17,152		6,331	27,683
	Heat Loss After Retrofits (MJ)	9,056		3,181	10,298
	Heat Loss Reduction (MJ)	8,096		3,150	17,385

Air leakage is defined as the flow of air through gaps and cracks in the building envelop. In order to reduce the heat loss from air flow, air sealing is necessary. For air-sealing materials, weather stripping is a cost-effective way to reduce air leakage. In addition, caulking is used on the interior to seal small cracks and penetrations on the inside surface of walls and floors, and urethane foam is also good for filling larger joints and cavities. According to the PH air change standard, heat loss is proportional to air changes. However, the PH air change standard is very difficult to achieve in retrofit work, so this study assumes that a 50% heat loss reduction in air leakage from that portion of the building envelop where retrofits are applied (Table 5).

**Table 5.** The heat loss reduction from air tightness improvement

	T1	T2	T3	T4	T5	T6
Air Changes Per Hour (50p) before retrofits	10.88	5.72	7.22	5.10	5.52	3.31
Air Changes Per Hour (50p) (PH Standard)	0.6	0.6	0.6	0.6	0.6	0.6
Heat Loss Before Retrofits(MJ)	45,487	28,139	31,128	29,896	35,178	38,930
Heat Loss After Retrofits(MJ)	22,744	14,070	15,564	14,948	17,589	19,465
Heat Loss Reduction (MJ)	22,744	14,070	15,564	14,948	17,589	19,465

Furthermore, in order to reduce natural gas consumption and CO<sub>2</sub> emissions, a combination of solar water heater (effectively the pre-heater) and electric water heater will be used to replace natural gas for heating water. Therefore, approximately 50% of water heating needs can be met from solar, and the other 50% would be met from electricity [7, 8].

### 3 Results and discussion

As mentioned before, the natural gas consumed for heating water is replaced with solar energy and electricity which has low carbon intensity. Given an energy density of one cubic meter of natural gas approximately equals 38MJ, the changes of heat loss of different segments are listed from table 6 to table 11. The CO<sub>2</sub> emission reduction is estimated according to formula (2).  

$$\text{kgCO}_2 = \text{Electricity} * 0.097 \text{ kg/kWh} + \text{Natural Gas} * 1.88 \text{ kg/m}^3 + \text{Oil} * 2.83 \text{ kg/L} + \text{Propane} * 1.51 \text{ kg/L}$$
 (2)

**Table 6.** Comparison between before and after retrofit of a house built in 1945 (169 m<sup>2</sup>)

Fuel Type	Before Retrofit Annual Consumption	After Retrofit Annual Consumption
Electricity	9,389 KWh/yr	13,500 KWh/yr
Natural Gas	Space Heating 4,533 m <sup>3</sup> /yr (78%)	1,454 m <sup>3</sup> /yr (96%)
	Water Heating 779 m <sup>3</sup> /yr (55%)	0
Solar Energy	0	14,801 MJ/yr
Attic Heat Loss	16,203 MJ	2,406 MJ
Attic Heat Loss Savings	85%	
Foundation Heat Loss	38,675 MJ	5,279 MJ
Foundation Heat Loss Savings	86%	
Walls Heat Loss	36,692 MJ	8,907 MJ
Walls Heat Loss Savings	76%	
Windows/Doors Heat Loss	26,990 MJ	7,711 MJ
Windows/Doors Heat Loss Savings	71%	
Air Leaks Heat Loss	45,487 MJ	22,744 MJ
Air Leaks Heat Loss Savings	50%	
Space Heating Energy (Natural Gas)	172,264 MJ/yr	55,263 MJ/yr (> 50kWh/m <sup>2</sup> a)
Total Energy (Electricity+Natural Gas)	231,708 MJ/yr	103,863 MJ/yr (> 120kWh/m <sup>2</sup> a)
Total Energy Savings	55%	
CO <sub>2</sub> Emissions Reduction	6,854 kg/yr	

**Table 7.** Comparison between before and after retrofit of a house built in 1959 (191 m<sup>2</sup>)

Fuel Type	Before Retrofit Annual Consumption	After Retrofit Annual Consumption
Electricity	10,760 KWh/yr	14,106 KWh/yr
Natural Gas	Space Heating 3,256 m <sup>3</sup> /yr (78%)	975 m <sup>3</sup> /yr (96%)
	Water Heating 634 m <sup>3</sup> /yr (55%)	0
Solar Energy	0	12,046 MJ/yr
Attic Heat Loss	6,831 MJ	3,206 MJ
Attic Heat Loss Savings	53%	
Foundation Heat Loss	39,426 MJ	5,815 MJ
Foundation Heat Loss Savings	85%	
Walls Heat Loss	20,986 MJ	5,572 MJ
Walls Heat Loss Savings	73%	
Windows/Doors Heat Loss	27,892 MJ	7,969 MJ
Windows/Doors Heat Loss Savings	71%	
Air Leaks Heat Loss	28,139 MJ	14,070 MJ
Air Leaks Heat Loss Savings	50%	
Space Heating Energy (Natural Gas)	123,710 MJ/yr	37,067 MJ/yr (> 50kWh/m <sup>2</sup> a)
Total Energy (Electricity+Natural Gas)	183,665 MJ/yr	87,849 MJ/yr (> 120kWh/m <sup>2</sup> a)
Total Energy Savings	52%	
CO <sub>2</sub> Emissions Reduction	5,805 kg/yr	

**Table 8.** Comparison between before and after retrofit of a house built in 1966 (204 m<sup>2</sup>)

Fuel Type	Before Retrofit Annual Consumption	After Retrofit Annual Consumption
Electricity	10,818 KWh/yr	14,148 KWh/yr
Natural Gas	Space Heating 3,082 m <sup>3</sup> /yr (78%)	1,281 m <sup>3</sup> /yr (96%)
	Water Heating 631 m <sup>3</sup> /yr (55%)	0
Solar Energy	0	11,989 MJ/yr
Attic Heat Loss	6,285 MJ	3,016 MJ
Attic Heat Loss Savings	52%	
Foundation Heat Loss	26,137 MJ	11,120 MJ
Foundation Heat Loss Savings	57%	
Walls Heat Loss	17,608 MJ	4,472 MJ
Walls Heat Loss Savings	75%	
Windows/Doors Heat Loss	30,143 MJ	8,610 MJ
Windows/Doors Heat Loss Savings	71%	
Air Leaks Heat Loss	31,128 MJ	15,564 MJ
Air Leaks Heat Loss Savings	50%	
Space Heating Energy (Natural Gas)	117,114 MJ/yr	48,684 MJ/yr (> 50kWh/m <sup>2</sup> a)
Total Energy (Electricity+Natural Gas)	177,304 MJ/yr	99,617 MJ/yr (> 120kWh/m <sup>2</sup> a)
Total Energy Savings	44%	
CO <sub>2</sub> Emissions Reduction	4,249 kg/yr	

**Table 9.** Comparison between before and after retrofit of a house built in 1975 (166 m<sup>2</sup>)

Fuel Type		Before Retrofit Annual Consumption	After Retrofit Annual Consumption
Electricity		9,600 KWh/yr	13,643 KWh/yr
Natural Gas	Space Heating	2,871 m <sup>3</sup> /yr (78%)	806 m <sup>3</sup> /yr (96%)
	Water Heating	766 m <sup>3</sup> /yr (55%)	0
Solar Energy		0	14,554 MJ/yr
Attic Heat Loss		7,408 MJ	2,769 MJ
Attic Heat Loss Savings		63%	
Foundation Heat Loss		35,516 MJ	5,239 MJ
Foundation Heat Loss Savings		85%	
Walls Heat Loss		18,425 MJ	4,422 MJ
Walls Heat Loss Savings		76%	
Windows/Doors Heat Loss		20,445 MJ	5,841 MJ
Windows/Doors Heat Loss Savings		71%	
Air Leaks Heat Loss		29,896 MJ	14,948 MJ
Air Leaks Heat Loss Savings		50%	
Space Heating Energy (Natural Gas)		109,094 MJ/yr	30,624 MJ/yr (> 50kWh/m <sup>2</sup> a)
Total Energy (Electricity+Natural Gas)		170,087 MJ/yr	79739 MJ/yr (> 120kWh/m <sup>2</sup> a)
Total Energy Savings		53%	
CO <sub>2</sub> Emissions Reduction		4,930 kg/yr	

**Table 10.** Comparison between before and after retrofit of a house built in 1986 (207 m<sup>2</sup>)

Fuel Type		Before Retrofit Annual Consumption	After Retrofit Annual Consumption
Electricity		9,433 KWh/yr	13,471 KWh/yr
Natural Gas	Space Heating	2,810 m <sup>3</sup> /yr (78%)	1,167 m <sup>3</sup> /yr (96%)
	Water Heating	765 m <sup>3</sup> /yr (55%)	0
Solar Energy		0	14,535 MJ/yr
Attic Heat Loss		5,769 MJ	2,517 MJ
Attic Heat Loss Savings		56%	
Foundation Heat Loss		21,958 MJ	12,659 MJ
Foundation Heat Loss Savings		42%	
Walls Heat Loss		24,863 MJ	9,143 MJ
Walls Heat Loss Savings		63%	
Windows/Doors Heat Loss		29,007 MJ	12,432 MJ
Windows/Doors Heat Loss Savings		57%	
Air Leaks Heat Loss		35,178 MJ	17,589 MJ
Air Leaks Heat Loss Savings		50%	
Space Heating Energy (Natural Gas)		106,778 MJ/yr	44,343 MJ/yr (> 50kWh/m <sup>2</sup> a)
Total Energy (Electricity+Natural Gas)		167,153 MJ/yr	92,838 MJ/yr (> 120kWh/m <sup>2</sup> a)
Total Energy Savings		44%	
CO <sub>2</sub> Emissions Reduction		4,135 kg/yr	

**Table 11.** Comparison between before and after retrofit of a house built in 1995 (278 m<sup>2</sup>)

Fuel Type		Before Retrofit Annual Consumption	After Retrofit Annual Consumption
Electricity		10,824 KWh/yr	13,922 KWh/yr
Natural Gas	Space Heating	2,247 m <sup>3</sup> /yr (78%)	579 m <sup>3</sup> /yr (96%)
	Water Heating	587 m <sup>3</sup> /yr (55%)	0
Solar Energy		0	11,153 MJ/yr

Attic Heat Loss	6,331 MJ	3,181 MJ
Attic Heat Loss Savings	50%	
Foundation Heat Loss	17,152 MJ	9,056 MJ
Foundation Heat Loss Savings	47%	
Walls Heat Loss	27,683 MJ	10,298 MJ
Walls Heat Loss Savings	63%	
Windows/Doors Heat Loss	26,754 MJ	11,466 MJ
Windows/Doors Heat Loss Savings	57%	
Air Leaks Heat Loss	38,930 MJ	19,465 MJ
Air Leaks Heat Loss Savings	50%	
Space Heating Energy (Natural Gas)	85,368 MJ/yr	21,984 MJ/yr (< 50kWh/m <sup>2</sup> a)
Total Energy (Electricity+Natural Gas)	144,548 MJ/yr	72,103 MJ/yr (< 120kWh/m <sup>2</sup> a)
Total Energy Savings	50%	
CO <sub>2</sub> Emissions Reduction	3,939 kg/yr	

Tables 6-11 summarise the heat loss reduction in attic, foundation, walls, windows/doors and air leaks after deep retrofits are undertaken. The primary PH standard is that the maximum annual space heating energy consumption is no more than 15 kWh/m<sup>2</sup>a. However, the northern European target of 50 kWh/m<sup>2</sup>a would be more feasible for Canadian retrofits because of more similar weather conditions. Therefore, the retrofit goals in this study are that the maximum annual space heating energy consumption is 50 kWh/m<sup>2</sup>a instead of 15 kWh/m<sup>2</sup>a and the total maximum annual energy consumption is 120 kWh/m<sup>2</sup>a.

According to above analysis, it can be concluded that only the sixth typical house built in 1995 achieves the PH standard. Its annual space heating energy consumption changes from 86 kWh/m<sup>2</sup>a to 22 kWh/m<sup>2</sup>a which is less than the PH standard of 50 kWh/m<sup>2</sup>a, and its total annual energy consumption changes from 144 kWh/m<sup>2</sup>a to 87 kWh/m<sup>2</sup>a which is less than the PH standard of 120 kWh/m<sup>2</sup>a after retrofits. The annual space heating energy consumption of the first typical house built in 1945 changes from 283 kWh/m<sup>2</sup>a to 91 kWh/m<sup>2</sup>a, and its total annual energy consumption changes from 381 kWh/m<sup>2</sup>a to 171 kWh/m<sup>2</sup>a after retrofits. The annual space heating energy consumption of the second typical house built in 1959 changes from 178 kWh/m<sup>2</sup>a to 54 kWh/m<sup>2</sup>a, and its total annual energy consumption changes from 267 kWh/m<sup>2</sup>a to 128 kWh/m<sup>2</sup>a after retrofits. The annual space heating energy consumption of the third typical house built in 1966 changes from 159 kWh/m<sup>2</sup>a to 66 kWh/m<sup>2</sup>a, and its total annual energy consumption changes from 241 kWh/m<sup>2</sup>a to 136 kWh/m<sup>2</sup>a after retrofits. The annual space heating energy consumption of the fourth typical house built in 1975 changes from 183 kWh/m<sup>2</sup>a to 52 kWh/m<sup>2</sup>a, and its total annual energy consumption changes from 285 kWh/m<sup>2</sup>a to 133 kWh/m<sup>2</sup>a after retrofits. The annual space heating energy consumption of the fifth typical house built in 1986 changes from 143 kWh/m<sup>2</sup>a to 59 kWh/m<sup>2</sup>a, and its total annual energy consumption changes from 224 kWh/m<sup>2</sup>a to 125 kWh/m<sup>2</sup>a after retrofits. Therefore, the first five typical houses do not achieve the PH standard after the proposed deep retrofits.

Since the energy consumption of the typical house represents the average level of energy consumption of

corresponding house category, the total amount of energy savings and CO<sub>2</sub> emissions reduction of each house category can be calculated by multiplying the number of houses in this category with the amount of energy savings and CO<sub>2</sub> emissions reduction of corresponding typical house (Table 12).

**Table 12.** Energy savings and CO<sub>2</sub> emissions reduction after retrofits

House Category	Number of Houses	Energy savings (*10 <sup>9</sup> MJ/yr)	CO <sub>2</sub> Emissions Reduction (*10 <sup>8</sup> kg/yr)
C1	21,665	2.77	1.48
C2	21,080	2.02	1.22
C3	27,090	2.10	1.15
C4	32,845	2.97	1.62
C5	31,450	2.34	1.30
C6	26,995	1.96	1.06
Total	161,125	14.16	7.83

As shown in Table 12, the total amounts of potential annual energy savings and CO<sub>2</sub> emissions reduction are  $14.16 \times 10^9$  MJ/yr and  $7.83 \times 10^8$  kg/yr if deep retrofits are made to all houses in Waterloo Region.

## 4 Conclusion

This study shows the potential retrofit benefits to the public by estimating the energy savings and CO<sub>2</sub> emissions reduction from retrofitted houses of Waterloo Region. This paper estimates that the total potential annual energy savings and CO<sub>2</sub> emissions reductions are  $14.16 \times 10^9$  MJ/yr and  $7.83 \times 10^8$  kg/yr if Waterloo Region adopts deep retrofit standards to move the residential sector toward PH levels of energy performance.

According to the calculations, it can be concluded that after implementing the deep retrofit scenario, only the house built in 1995 achieves the PH standard with annual space heating energy consumption of 37 kWh/m<sup>2</sup>a and annual energy consumption of 87 kWh/m<sup>2</sup>a. In addition, the energy consumption and CO<sub>2</sub> emissions of the house built in 1945 after retrofits are reduced by 55% and 63%. The energy consumption and CO<sub>2</sub> emissions of the house built in 1959 after retrofits are reduced by 52% and 69%. The energy consumption and CO<sub>2</sub> emissions of the house built in 1966 after retrofits are reduced by 44% and 53%. The energy consumption and CO<sub>2</sub> emissions of the house built in 1975 after retrofits are reduced by 53% and 63%. The energy consumption and CO<sub>2</sub> emissions of the house built in 1986 after retrofits are reduced by 44% and 54%. Therefore, these five typical houses do not achieve the PH standard after retrofits, and the results indicate that in order to achieve the PH energy intensity standard, even deeper retrofits would be required. In practice, the PH energy intensity standard is difficult to achieve in retrofit projects. Firstly, the European PH standard is not appropriate for retrofitting houses in Canada because the climates are not comparable. Canada has colder design heating loads than German locations which means that the insulation required to meet the German energy budget are thicker in Canada. Secondly, the PH standard is based on modeled performance instead of measured

performance. It is difficult to be widely applied in actual work.

This paper demonstrates the potential benefits of deep residential retrofits to homeowners, researchers, and governments. It will also be helpful for future residential energy research and making environmentally friendly policies and regulations.

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