# Modeling household energy retrofits through data-driven archetype formulation

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## Abstract

Existing buildings provide significant opportunities to reduce the share of the building sector on the overall energy consumption and greenhouse gas emissions. Energy efficiency retrofits have gained a huge momentum, however, the definition of optimal retrofit for a specific building is a complex process and stakeholders face significant challenges when making informed decisions. This research formulates a process workflow to model retrofits through the use of data-driven archetype modeling. The workflow derives the archetypes using data clustering and input features of the dataset. A preliminary analysis for the city of Victoria showed that the retrofit effectiveness varies significantly across the span of the formulated archetypes. Furthermore, the variation of retrofits for a single archetype signifies the behavioral aspects of implemented retrofits, giving an indication of the presence of (p)rebound effects.

## Introduction

Climate change is a major issue facing the world. As the major centres of population, and thus, energy consumption, it is vital that cities take steps to reduce their emissions. Energy-related $CO_2$ emissions from buildings have risen in recent years after flattening between 2013 and 2016. With the continued growth of energy demand from the building sector, renovation, retrofit, and refurbishment of existing buildings present an opportunity to enhance the existing energy performance and thereby, reduce the associated greenhouse gas emissions (Zhang et al. (2021)).

Direct and indirect emissions from electricity and commercial heat used in buildings rose to 10 $GtCO_2$ in 2019, the highest level ever recorded. Buildings sector energy intensity (final energy use per $m^2$) has been decreasing continuously by 0.5% to 1% per year since 2010. However, this rate is significantly below average annual floor area growth, which has remained around 2.5% since 2010 (Zhong et al. (2021)). A major way that cities could reduce their emissions is to retrofit existing residential buildings to be more energy efficient. In addition, home retrofits can be a great way for homeowners to save money over time. However, deciding which retrofits to perform on buildings is difficult, as it can be unclear which retrofits will be most effective for a given building.

Numerous studies in the literature focus on the identification of retrofit strategies in data-sparse environments and suggest a minimal list of features required to model the existing building stock (Ali et al. (2020)). However, the models produce case specific scenarios and the reproducibility is often limited to specific environments (Ye et al. (2021)). Hence, building stakeholders are not fully informed about the cost-effective nature of the retrofit strategy when implementing such models. Kontokosta (2016) examined the effects of ownership type, tenant demand, and real estate market location on building energy retrofit decisions in the commercial office sector through a detailed survey of asset managers of 763 buildings. Another study by Tingey et al. (2021) analyzed six local authority energy service models relevant to building retrofits in the UK. Each local initiative provided different retrofit mixes, with differing potential for energy savings. Regnier et al. (2018) et al. presented a case study in Hawaii to quantify the benefits of an integrated system retrofit approach that considers the interactions between systems when modeling the retrofits. This approach considered the correlation and interaction among the building's systems to target deep, holistic energy saving strategies and subsequently optimize envelope and internal load systems to enable a much lower energy HVAC system selection while maintaining thermal comfort.

A study by Rodrigues and Freire (2021) concluded that the influential attributes driving the environmental and cost impacts for building energy retrofits are indifferent to location, type of house and wall-system. The key drivers to eco-efficiency included discount rates and external wall insulation. Another study for the city of Phoenix analyzed the impacts of retrofits through pre-post treatment billing data including 201 residential buildings (Liang et al. (2018)). The popular retrofits for residential buildings included upgrades in air conditioner, insulation, duct sealing, air sealing, and shade screens. The study further concluded that building insulation retrofits provide a significant reduction in the overall building energy consumption. Uidhir et al. (2020) examined the suitability of popular retrofit combinations as these apply to nine distinct building archetypes in Ireland's housing stock portfolio. The authors concluded that the alternative retrofit combination differs by archetype and that additional energy efficiency gains of up to 86% can be achieved due to alternative retrofit choices.

Pasichnyi et al. (2019) identified the feasibility of the implementation of retrofit packages including heat recovery ventilation, energy-efficient windows and a combination of both for multi-family residential buildings. The authors assessed the changes in total energy demand from large-scale retrofitting scenarios and explored the impacts on the supply side. A recent study for the Canadian residential building stock highlighted the importance of a holistic perspective covering varying climatic conditions, macro-environments and the involvement of multiple stakeholders when identifying building energy retrofits (Prabatha et al. (2020)). The retrofits were evaluated in terms of the additional investment, energy use and cost reduction achieved over the life cycle, and life cycle emissions reduction. The provincial energy mix and the heating system of the house (i.e. electric or natural gas) play a major role in determining the effectiveness of a retrofit, and this "effectiveness" changes at different stakeholder levels. However, not all retrofits that reduce emissions make economic sense and vice versa when life cycle thinking comes into play. Furnace retrofits can be especially tricky, as there are a wide variety of fuel types and furnace types that a homeowner could choose.

When considering the process perspective on homeowner energy retrofits, Bobrova et al. (2022) identified that the prior homeowner knowledge about energy retrofit plays a significant role on the depth of a technological solution achieved during the retrofit. The study further concluded that the actual energy use post-retrofit depended on the extent of owners' involvement in the development of their retrofit design solutions. One of the crucial effects associated with homeowner perspectives on energy retrofits include prebound and rebound effects, where the prebound effect is defined as the shortfall in actual consumption compared to projected consumption and the rebound effect is defined as the direct increase on demand for an energy service as a result of improvements in technical efficiency in the use of energy (Galvin and Sunikka-Blank (2016)). Terés-Zubiaga et al. (2016) evaluated the feasibility of individual natural gas fired boiler-based heating systems in the retrofitting of buildings constructed in the 1960s in Bilbao (northern Spain). The retrofit scenarios were evaluated in terms of energy performance, economic aspects, and the influence of user behaviour. The occupants' behaviour had the highest impact on energy consumption reductions up to 89%. This was reinforced with the results related to the rebound effect that represented significant differences on energy consumption values.

The aforementioned studies provide useful insights into the implementation of residential building energy retrofits by homeowners. Individual retrofits are mostly formulated using hypothetical scenarios that may or may not represent the real world scenarios. The workflow devised in this study provides an overview of practical insights of implementing retrofits at the individual building and the building stock level. This paper presents a standardized data-driven workflow for modeling house archetypes and predicting the adoption and effectiveness of 14 different retrofits in single-family dwellings (SFDs) for the city of Victoria, British Columbia. The findings presented here are one of the early attempts in the formulation of a data-driven intelligent retrofit recommendation system that would facilitate virtual energy audits. These findings could assist the stakeholders in making informed decisions when recommending retrofits to homeowners.

The paper is structured as follows: Section 2 describes the overall process workflow and the implemented methods. Section 3 lists the results and findings. Section 4 provides a comprehensive discussion of the findings. Section 5 lists the conclusions and future work.

## Methods

Building stock datasets are gaining immense popularity in the built environment when modeling building energy retrofits at an urban scale. Due to the unstructured nature of the datasets, stakeholders often find it difficult to analyze the current energy performance and identify the current retrofit status of the building stock. The overall process workflow involves three individual workflows including input data, archetype development and analysis workflows (Figure 1). This study quantifies the retrofit actions taken by 6988 SFDs in Victoria between 2006 and 2017. This workflow further quantifies the uptake and effect of 14 retrofits.

The input data workflow extracts the required building stock data from two databases, BC Assessment

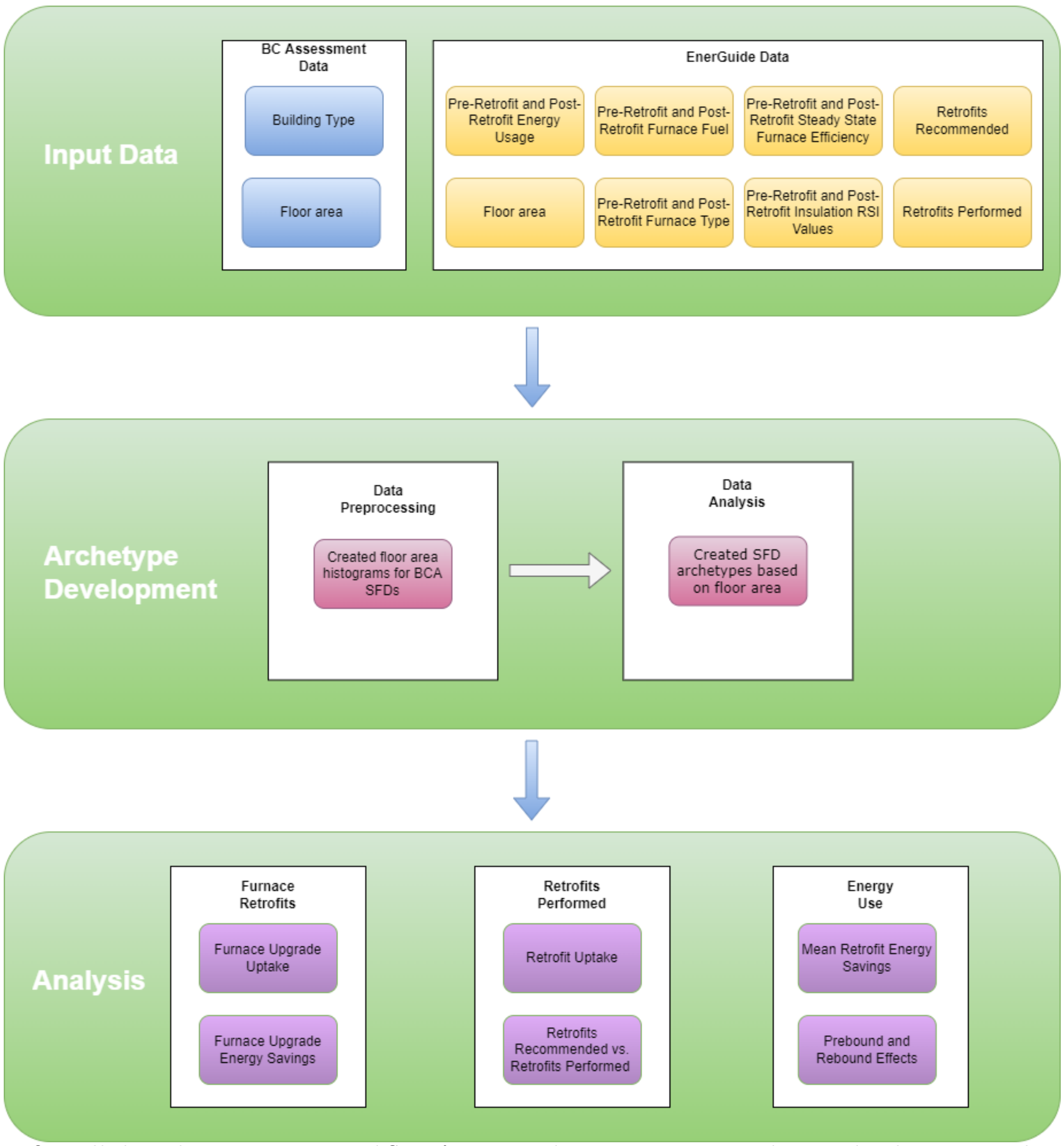


*Figure 1: Overall data-driven process workflow for input data acquisition, archetype development and analysis to model the retrofit.*

(BCA) database and the EnerGuide for Houses (EGH) database. The authors would like to mention that the datasets are used and represented on an aggregate stock level due to the associated privacy issues. The BC Assessment dataset comprises information on the building type and the floor area. The BC Assessment develops and maintains real property assessments throughout British Columbia in addition to providing real property information and produces independent, uniform and efficient property assessments on an annual basis for all property owners in the province. The EnerGuide for Houses (EGH) database is a management information tool and central depository for tracking residential energy evaluations and measuring benefits from the energy evaluations delivered across Canada. The EGH database is a comprehensive computer-based system developed by Natural Resources Canada (NRCan) for the management of its energy efficiency oriented programs (Blais et al. (2005)). Energy advisors perform detailed house energy efficiency evaluations and use the energy analysis software to recommend energy efficiency measures to homeowners. The EnerGuide dataset is used for the bulk of the analysis, as the dataset contains information on the floor area, retrofits performed, and pre-and-post-retrofit energy usage.

After data acquisition, the data is first pre-processed to formulate the dwelling archetypes in the archetype development workflow. The data preprocessing involves binning the buildings categorized as one-storey and two-storey single-family dwellings (SFDs) in the BC Assessment dataset by floor area and creating new archetypes based on the most common floor area bins. These are then mapped to individual buildings in the EnerGuide dataset. Three SFD archetypes are identified using the floor area data as listed below. The archetypes are formulated using the floor area information because floor area is the only metric common to both datasets.

- One-storey SFD or $1-sty$ (93-139 $m^2$/1000-1500 sq. ft);
- Small two-storey SFD or Small $2-sty$ (139-186 $m^2$/1500-2000 sq. ft) and,
- Large two-storey SFD or Large $2-sty$ (186+ $m^2$/2000+ sq. ft).

In the analysis workflow, the adoption and effects of retrofits are analyzed through examining the uptake of retrofits and the corresponding change in energy use resulting from each retrofit. The furnace retrofits are examined separately from the 13 other retrofits due to the large variation in furnace retrofits.

This workflow identifies the percentage of houses of each archetype that underwent different furnace up-

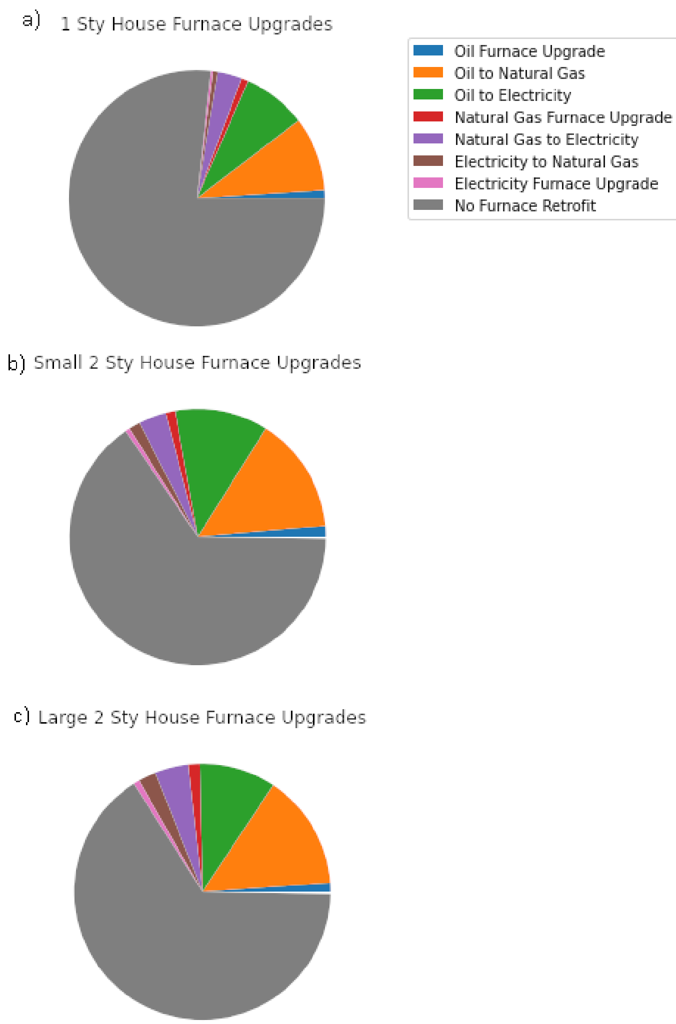


*Figure 2: Furnace upgrades performed by each house archetype identified using the BCA and EGH databases.*

grades (Figure 2). Each archetype comprises a pre-and-post-retrofit fuel and furnace type. An analysis of the effectiveness of different furnace retrofits is performed by finding the change in energy use of houses that only underwent furnace retrofits. The change in home energy use is then divided by the change in furnace efficiency. The mean energy change per step change in efficiency for each furnace retrofit is calculated, as is the standard deviation. This rate is expressed in MJ per percent efficiency change and as a fraction of the pre-retrofit energy use.

A similar process is used to find the effectiveness of the other retrofits. However, the process is modified depending on the retrofit. Some retrofits comprise related variables that could affect the energy change, such as the RSI value of the insulation or the number of

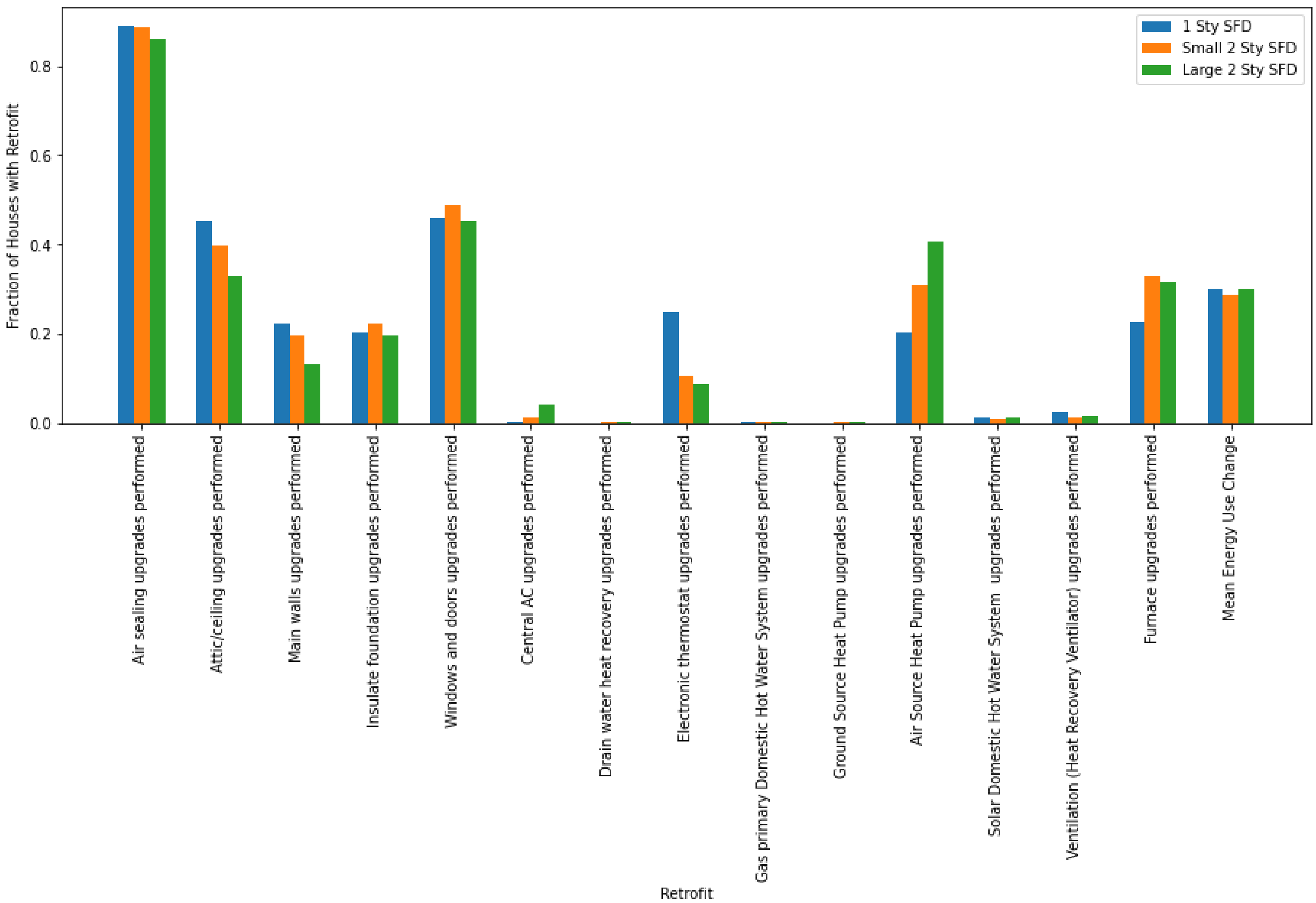


*Figure 3: Fraction of each house archetype performing each retrofit*

doors and windows installed. Other retrofits only consist of information on whether these are performed or not. The energy change from retrofits that has a related variable is divided by that variable, while the energy change from the other variables is expressed as an absolute change in MJ or as a fraction of the pre-retrofit energy use.

The adoption of retrofits is examined by comparing the fraction of houses of each archetype that performed each retrofit (Figure 3) and by determining the rate at which recommended retrofits are performed.

A rudimentary analysis of the rebound effect is performed. The percentage of houses that experience an increase in their energy use post-retrofit is found and the corresponding fraction increase in energy use post-retrofit. The distribution of houses by energy increase is then plotted (Figure 4).

## Results

$1 - sty$ houses are less likely to get a furnace upgrade than either type of $2 - sty$ house. 76.8% of $1 - sty$ houses did not get a furnace retrofit, vs. 65.3% of small $2 - sty$ houses and 65.7% of large $2 - sty$ houses. The most common furnace upgrade comprises the upgrade from an oil furnace to a natural gas furnace (9.4% for $1 - sty$, 14.7% for small $2 - sty$, or 14.6% for large $2 - sty$) (Figure 2).

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Of the 121 furnace retrofits (changes in fuel type, furnace type, or furnace efficiency), only 11 are shown to have a significant effect on energy use change analyzed using the methods used (Table 1). Of the 11 furnace retrofits analyzed, upgrading from an oil boiler with flame retention head to a natural gas condensing boiler results in the greatest energy savings of 1.36% per 1% increase in furnace efficiency, with a standard deviation of 0.547%.

*Table 1: Pre- and post-retrofit fuel and heating system types with corresponding mean energy savings(%) per 1% increase in efficiency.*

| Fuel Type | | Heating System Type | | Mean Percentage Energy Savings Per 1% Efficiency Increase | Standard Deviation |
|---|---|---|---|---|---|
| Pre-retrofit | Post-retrofit | Pre-retrofit | Post-retrofit | | |
| Oil | Natural Gas | Boiler | Condensing boiler | 1.02 | 0.0379 |
| Oil | Natural Gas | Boiler with flame retention head | Condensing boiler | 1.36 | 0.547 |
| Oil | Natural Gas | Furnace with flue vent damper | Condensing furnace | 0.713 | 0.226 |
| Oil | Natural Gas | Furnace | Condensing furnace | 0.755 | 0.126 |
| Oil | Oil | Boiler with flue vent damper | Direct vent, non-condensing boiler | 1.13 | 0.0 |
| Oil | Oil | Furnace with flame retention head | Direct vent, non-condensing boiler | 0.636 | 0.0 |
| Natural Gas | Natural Gas | Furnace with continuous pilot | Condensing furnace | 1.16 | 0.102 |
| Natural Gas | Natural Gas | Induced draft fan furnace | Condensing furnace | 0.578 | 0.249 |
| Natural Gas | Natural Gas | Furnace with spark ignition | Condensing furnace | 1.08 | 0.279 |
| Natural Gas | Natural Gas | Furnace with spark ignit.,vent dmpr | Condensing furnace | 0.817 | 0.0 |
| Natural Gas | Natural Gas | Condensing furnace | Condensing furnace | 0.824 | 0.703 |

*Table 2: Retrofit Uptake and Energy Savings represented as a fraction of the total.*

| Upgrade | 1 STY Uptake | Small 2 STY Uptake | Large 2 STY Uptake | Recommendation Compliance Rate (%) | 1 STY Mean Energy Savings | Standard Deviation | Small 2 STY Mean Energy Savings | Standard Deviation | Large 2 STY Mean Energy Savings | Standard Deviation | Units |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Air sealing | 0.888 | 0.887 | 0.861 | 87.9 | 0.0558 | 0.0585 | 0.0728 | 0.0969 | 0.0669 | 0.0726 | Absolute |
| Attic/ceiling | 0.451 | 0.398 | 0.328 | 49.9 | -0.0074 | 0.0411 | 0.0180 | 0.0064 | 0.0273 | 0.1016 | per m2C/W |
| Main walls | 0.221 | 0.197 | 0.131 | 41.5 | 0.1668 | 0.0422 | 0.2138 | 0.0623 | 0.1795 | 0.0587 | per m2C/W |
| Insulate foundation | 0.203 | 0.222 | 0.196 | 36.2 | 0.0 | 0.0 | 0.0826 | 0.0469 | 0.0100 | 0.0 | per m2C/W |
| Windows and doors | 0.460 | 0.488 | 0.451 | 56.4 | 0.0111 | 0.00854 | 0.00990 | 0.00727 | 0.00457 | 0.00819 | per window/door |
| Central AC | 0.00284 | 0.0116 | 0.0404 | 80.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Absolute |
| Drain water heat recovery | 0.0 | 0.00174 | 0.000685 | 0.352 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Absolute |
| Electronic thermostat | 0.247 | 0.105 | 0.0863 | 98.9 | 0.103 | 0.0922 | 0.0 | 0.0 | 0.0288 | 0.0668 | Absolute |
| Gas primary Domestic Hot Water System | 0.00142 | 0.000578 | 0.00114 | 0.136 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Absolute |
| Ground Source Heat Pump | 0.0 | 0.00116 | 0.00366 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | Absolute |
| Air Source Heat Pump | 0.203 | 0.308 | 0.406 | 83.5 | 0.0718 | 0.0242 | 0.0909 | 0.0240 | 0.0969 | 0.0250 | divided by change in COP |
| Solar Domestic Hot Water System | 0.0128 | 0.00752 | 0.0126 | 4.2 | 0.0734 | 0.0 | 0.0 | 0.0 | 0.0194 | 0.00633 | Absolute |
| Ventilation (Heat Recovery Ventilator) | 0.0241 | 0.0110 | 0.0162 | 6.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00370 | 0.0657 | Absolute |

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Of the 121 furnace retrofits (changes in fuel type, furnace type, or furnace efficiency), only 11 are shown to have a significant effect on energy use change analyzed using the methods used (Table 1). Of the 11 furnace retrofits analyzed, upgrading from an oil boiler with flame retention head to a natural gas condensing boiler results in the greatest energy savings of 1.36% per 1% increase in furnace efficiency, with a standard deviation of 0.547%.

The most popular retrofits across all house archetypes include air sealing, performed on 89% of $1-sty$ houses, 89% of small $2-sty$ houses, and 86% of large $2-sty$ houses (Figure 3). The most popular retrofit package is a combination of air sealing and windows/doors retrofits, performed on 9.6% of $1-sty$ homes, 14.1% of small $2-sty$ homes, and 13.9% of large $2-sty$ homes.

Most retrofits have similar rates of uptake across all archetypes, but there exist a few outliers. Electronic thermostat upgrades are much more popular in $1-sty$ houses than in $2-sty$ houses. Air source heat pumps are more popular in $2-sty$ houses.

The most frequently performed retrofit recommendation is electronic thermostat upgrades, at a compliance rate of 98.8% (Table 2). The compliance rate varied greatly between different retrofits.

From the data on energy changes due to retrofits, the best insulation retrofit across all three archetypes is main wall insulation, in terms of fraction energy savings per $m^{2o}C/W$ (0.167 for $1 - sty$, 0.214 for small $2 - sty$, 0.180 for big $2 - sty$). Even with the wide standard deviation of the insulation savings (0.042 for 1 sty, 0.062 for small 2 sty, 0.059 for big 2 sty), this retrofit still outperforms other types of insulation.

The most effective "absolute" (not adjusted for a measurement unit) retrofit varies between archetypes. For $1 - sty$ houses, the most effective absolute retrofit is electronic thermostat upgrades, with fraction energy savings of 0.103 with a standard deviation of 0.0922. For both $2 - sty$ archetypes, the most effective absolute retrofit in terms of fraction energy savings is air sealing (0.0728 with standard deviation 0.0969 for small $2 - sty$ houses and 0.0669 with standard deviation 0.0726 for large $2 - sty$ houses).

A slight rebound effect is observed (Figure 4), with 0.9% of houses displaying an increase in energy usage post-retrofit. Of the houses that displayed rebound behaviour, the majority increased their energy usage by 5% or less over their pre-retrofit energy usage.

While the methodology is used to consider behaviour with respect to retrofit choice, it does not consider the rebound effect as it applies to shortfall in energy savings due to behaviour. The rebound effect has no impact on these results, as it is assumed that the dwellings take back some of the energy savings regardless of the retrofit choice and it is the relative difference between the two scenarios which quantifies the potential savings possible due to alternate retrofits. There was insufficient data to make any reasonable connection between the scale of rebound effect associated with any specific retrofit measure combination

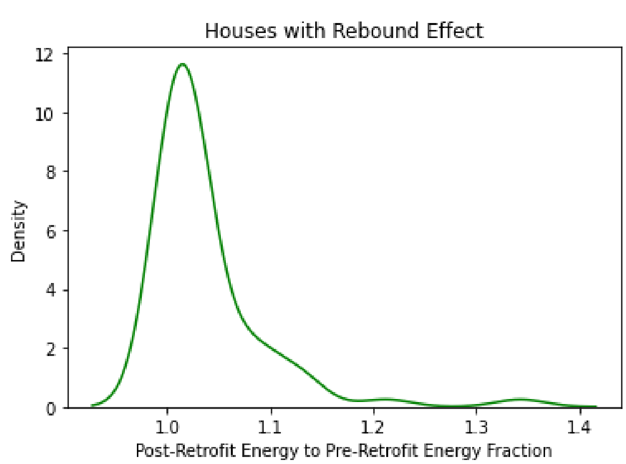


*Figure 4: Ratio of post-retrofit to pre-retrofit energy use for houses showcasing a rebound effect.*

## Discussions

Finding both the popularity and effectiveness of retrofits is crucial because it is important to know if homeowners are performing effective retrofits or not. If they are not, this information could be used to determine how to encourage homeowners to perform more effective retrofits.

It is reasonable that air sealing and window/door retrofits are the components of the most popular retrofit packages, as replacing windows and doors with more efficient ones can reduce air leakage.

While some retrofits had high compliance rates, many others did not. For a majority of retrofits, fewer than half of households followed the recommendations to perform the retrofit. Given the low rate of compliance for many retrofits, recommendations are not a consistent way to predict which retrofits will be performed.

There was a large standard deviation in the energy change from retrofits across the same house archetype. Therefore, determining which retrofits are performed combined with the floor area of the house is not a perfect predictor of energy savings. This information might be required to combine with other information not included in the dataset, such as age, building materials, or building shape. The large standard deviation in air sealing is also enabled by the lack of differentiation in the quantity of air sealing performed. Unlike many retrofits, such as insulation retrofits, there was no additional information given that could indicate the extent of air sealing retrofits. As a result of this, air sealing retrofits of varying effectiveness are grouped together.

The analysis on energy change due to retrofits was limited by the small quantity of houses that performed only one retrofit. Many retrofits only had a few houses that performed only a given retrofit and some retrofits did not have any houses that exclusively performed them. This issue was especially apparent with furnace retrofits, where only 11 out of 121 furnace retrofits are performed by houses that did not perform any other retrofits.

## Conclusions and Future Work

From the analysis of the change in energy use as a result of different retrofits, it can be concluded that the most effective retrofits are air sealing retrofits, main wall insulation, and switching from an oil boiler with flame retention head to a natural gas condensing boiler. However, the effectiveness of all retrofits varied significantly between houses of the same archetype.

The rate of adoption for most retrofits is similar across all three archetypes, but there is little correlation between retrofits recommended and retrofits performed. Future analysis on determining why homeowners are not responding to recommendations could be useful for municipalities looking to encourage homeowners to perform energy-saving retrofits.

The scope of the analysis of the effectiveness of retrofits, especially furnace retrofits, is limited by the exclusive use of houses that only performed one retrofit, as it limited the sample size for the analysis of each retrofit.

Future analysis could focus on the effectiveness of different retrofit packages instead of looking at retrofits individually. A cost analysis could also be useful, especially with determining how to best increase the number of recommended retrofits performed.

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