**Introduction**

This document was generated using the RESFEN software, and with the help of a ChatGPT, and is intended as a directional document: the purpose of this document is to give good estimates for carbon impact for choices of window renovation for a theoretical 2500 sq foot single family house dating from 1884 in Brookline MA with a view to helping place the value of such an investment against other environmental investments.

Two carbon costs are considered – the differential energy costs for heating the house under multiple scenarios, and the production costs under two scenarios. The differential energy costs were generated using RESFEN. The production costs are a rough estimate from ChatGPT and should likely be independently confirmed.

These two costs were then combined over a 10-year period for a cumulative CO2 emissions cost, and then that cost was translated into something more meaningful – how would this investment compare to switching to an EV, or installing a solar roof?

[RESFEN](https://windows.lbl.gov/resfen-documentation) is an industry-standard mechanism for calculating heating and cooling impacts of different types of windows in different locations. It was developed by the Berkeley labs [using DOE methodologies](https://facades.lbl.gov/publications/resfen-30-pc-program-calculating), and is referenced in both [Energy Star](https://www.energystar.gov/products/building_products/residential_windows_doors_and_skylights/methodology_energy_star_savings_estimates_windows) literature as the software used in their calculations and in [MassSave](https://www.mass.gov/doc/selecting-energy-efficient-windows-in-massachusetts/download) literature as recommended software for doing custom wimdow calculations.

ChatGPT was used to calculate the production cost of windows and storm windows. ChatGPT was also used in a comparative analysis of installation costs.

**Scenarios**

The scenarios are targeted at the theoretical 1884 2500 sq foot house in Brookline. All U-values are in BTU/(hr·ft²·°F).

1. Installation of storm windows on top of single paned windows. A reasonable range for U-value in this scenario is between 0.35 to 0.53. For this analysis we will assume a value of 0.44. The SHGC was set to 0.65 and the air leakage was set to 0.15.
2. Replacement of single paned windows with replacement wooden double-paned windows. For this scenario we are targeting a good product, well-installed, but a replacement window. We have chosen Marvin Signature Ultimate Double-Glazed Double-Hung which have a U-value of between 0.28 to 0.45. For this analysis we will assume a U-value of 0.365. The SHGC was set to 0.65, an appropriate value for this type of window in colder climates, and the air leakage was set to 0.1.
3. Replacement of single-paned windows with new construction double paned windows. For this scenario we have chosen Pilkington Super Spacia with a U-Value of 0.12, which we are assuming can only be achieved with this high-quality window installed as a new construction double-glazed. Installation would require the replacement of the window casings, which are assumed to be inefficient. In thie case the SHGC was also 0.65, and the air leakage was 0.05.

**Results**

The results below show yearly consumption for each scenario, calculate a delta from the most efficient option, convert that delta to lbs of C02 based on a 90% efficient gas boiler, add in the production cost for the storms in scenario #1, and for the wooden double-glazed windows in scenarios #2 and #3, and then calculate a 10-year CO2 cost.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Scenario | Yearly Consumption | | | | 90% efficient gas boiler | Production Cost | 10-Year Cost |
| Heating | Cooling | Total | Delta | 130 |  |  |
| Mbtu | kWh | Mbtu | Mbtu | lbs CO2/Mbtu | lbs CO2 | lbs CO2 |
| 1 | 118.1 | 768 | 126 | 16.3 | 2119 | 15873 | 37063 |
| 2 | 114.3 | 775 | 122.2 | 12.5 | 1625 | 2645 | 18895 |
| 3 | 101.4 | 808 | 109.7 |  | 0 | 2645 | 2645 |

**Analysis**

Using high efficiency double-glazed windows generates significant emissions savings for CO2 over using storm windows over single-paned windows, and the better the double-glazed window the better the savings.

Lbs of CO2 is not a meaningful metric – the average person cannot assess what that means, or how to compare it to other environmental choices that can be made, for example: should I replace my ICE car, install a solar roof, or replace my windows?

These three examples provide good comparisons because each requires periodic replacement: the average lifetime of a car is 12 years, and it might be longer with an electric car; the average lifetime of a solar roof is assumed to be 25 to 30 years; the average lifetime of double-glazed windows is 20 to 30 years. And the costs are also broadly comparable: the average car of a Tesla Model 3 is $39,000 (minus possible rebates); the cost for installation of solar panels is $20,000 to $37,000 depending on the kWh produced (minus possible rebates); the cost for replacing windows might be $40,000 (minus the $15,000 cost of installing storm windows since this is a comparison, but no rebates). And for the installation of solar panels, or replacement of windows, there is also the possibility of an increase in the value of the home; and a car can be resold.

Based on the assumptions below the replacement of single-paned windows with storm windows is both a good financial investment, and a good environmental investment when compared to purchasing an EV:

* Over the lifetime of the windows, you would have to purchase 2-3 EVs, as a best-case scenario: while the average lifetime of a car might be 12 years, many people replace them more often. Perhaps the utility of cars is higher, or perhaps we need to factor in that cars need to be replaced whether it is an EV or an ICE car. There will be modest financial savings from installing double-glazed windows, assuming the same energy source; there may be cost savings for an EV vs an ICE car although since energy costs cannot be predicted that is hard to assess. A reasonable person might conclude that while the car will certainly cost you more over the lifetime of the windows, maybe there are too many factors to conclude that the overall costs are better on either side.
* In considering the environmental impact, if you drove about 7,500 miles a year, then the positive environmental impact of the EV would be about the same as installing very high efficiency new construction windows over a 10-year period but note that the windows will last 20-30 years, and will consequently have a better environmental impact. While the average person in MA drives 11,000 miles per year, it is reasonable to assume that the average person in Brookline, an urban center, will drive less far. This suggests a better environmental impact vs the purchase of an EV.

When considering solar roofs, it appears that they are a better financial investment and a better environmental investment than window replacement. They will be comparably priced to install and need to be replaced over the same period, but they will generate more savings, either in a reduction in electricity used, or in excess electricity sold back to the grid. And they will certainly generate a bigger reduction in CO2.

NOTE: while some online articles suggest that the embodied carbon in existing single-paned wooden windows should be a consideration, that is not the finding in this analysis, for two reasons: the first is that the CO2 savings from installing double-glazed windows will quickly exceed the carbon production cost of those windows; the second is that the alternative is to install aluminum storm windows which CO2 construction cost greatly exceeds the embodied carbon savings in wooden windows.

NOTE: while an argument could be made that people might install wooden storm windows, which would have a lower CO2 production cost than aluminum storm windows, that argument was not considered because most storm windows are aluminum. Wooden storm windows are more expensive, heavy, do not offer the utility of triple-track aluminum windows, and require more maintenance. An analysis must be based on reality, not aspirations.

**Conclusion**

Installation of high efficiency double-glazed wooden windows in an older single-family home is a good environmental and financial choice with positive environmental impacts comparable to switching from an ICE car to an EV in a MA town such as Brookline.

While it may be less positive from an environmental and economic perspective than the installation of rooftop solar panels it should still be considered a very positive direction and should be encouraged and should likely be part of Brookline’s zero emissions strategy.

While it is not discussed in detail in this document, the installation of efficient double-glazed windows also has other material downstream effects beyond the reduction of CO2 : to move to an all-electric future will require a massive increase in electrical infrastructure – to the extent that we can reduce the amount of electricity we require, we can also reduce that investment/cost/timeline ; double-glazed windows offer a more comfortable home; less efficient homes will require the installation of heating and cooling appliances with a higher load, the production of which have a higher CO2 cost, and so on.

**Assumptions for BTU Calculations using RESFEN**

RESFEN is a [program provided by the Berkeley Lab](https://windows.lbl.gov/resfen-downloads). We assumed:

1. A 2-story existing frame building, 2500 square feet
2. 240 square feet of windows, with NESW of 60, 40, 100, 40 sq. feet respectively
3. A location of Boston MA
4. Both an 80% and an 90% efficient gas boiler

**Production estimates using ChatGPT:**

The calculation was produced using the values below, but then corrected to a window area of 240 sq feet and converted to lbs from kg.

* **Window Area**: Previously calculated as 375 sq. ft.
* **Emissions Factor for Aluminum Storm Windows**: Aluminum production is highly energy-intensive, with emissions factors ranging widely. A rough estimate could be around 10-20 kg CO2e per kg of aluminum, considering the global average, including bauxite mining, alumina refining, and aluminum smelting.
* **Emissions Factor for Vinyl Storm Windows**: Vinyl (PVC) production involves emissions of around 2-3 kg CO2e per kg of PVC, considering the production and processing of PVC.
* **Emissions Factor for Wooden Windows**: The carbon sequestration effect of wood can offset some emissions, but let's assume an emissions factor that accounts for harvesting, processing, and manufacturing, possibly around -1 to 5 kg CO2e per kg, considering the potential carbon storage minus the emissions from processing and manufacturing.

**Simplified Estimation Approach:**

* **Average weight per square foot for storm windows**: Approximately 1.5-2.5 kg/sq. ft. for aluminum or vinyl, including glass and frame.
* **Average weight per square foot for wooden double-glazed windows**: Approximately 2-3 kg/sq. ft., considering the heavier frame and double glazing.

Given these broad assumptions, let's estimate the carbon emissions for manufacturing both types of windows for the entire window area needed. We'll use the median values for emissions factors and weights for a rough estimate. This calculation will be very general and should be taken as an indicative approximation rather than a precise figure.

Based on the rough estimation:

* The carbon emissions for manufacturing aluminum storm windows for the entire window area needed are approximately 11,250 kg CO2e.
* The carbon emissions for manufacturing wooden double-glazed windows for the same area are approximately 1,875 kg CO2e.

**Assumptions for CO2 conversions to miles driven**

The amount of CO2 emissions from an average internal combustion engine (ICE) family car depends on the vehicle's fuel efficiency. A common estimate for gasoline-powered vehicles is that burning one gallon of gasoline produces about 19.6 pounds of CO2.

If we assume an average fuel economy of about 25 miles per gallon for a typical ICE family car, we can calculate the emissions for driving 1,000 miles as follows:

CO2 emissions=(1,000 miles25 mpg)×19.6 lbs CO2 per gallonCO2 emissions=(25 mpg1,000 miles​)×19.6 lbs CO2 per gallon

An average internal combustion engine (ICE) family car produces about 784 pounds of CO2 when driving 1,000 miles, assuming an average fuel economy of 25 miles per gallon and that burning one gallon of gasoline produces approximately 19.6 pounds of CO2. **​**

**Assumptions for production cost in CO2 for a Tesla Model 3**

The CO2 production costs of a Tesla Model 3 would be approximately 24,250 to 26,455 lbs of CO2 for the entire manufacturing process, including the battery. We will assume 25,000 lbs of CO2 for this analysis.

**Calculation for savings by buying an electric car**

Based on the above, we can calculate how much CO2 you might save by switching to an electric car, where that calculation depends on how far you drive. As you can see from the figure below, the savings over a 10-year period will depend on the average number of miles driven.

|  |  |  |  |
| --- | --- | --- | --- |
| Miles driven per year | per year | Production cost | 10-Year Savings |
|  | lbs CO2 | lbs CO2 | lbs CO2 |
| 5000 | 3920 | 25000 | 14200 |
| 7500 | 5880 | 25000 | 33800 |
| 10000 | 7840 | 25000 | 53400 |

**Assumptions for Solar Panel production**

To estimate how much electricity could be generated from a solar roof on a 2500 square foot two-story house in Brookline, MA, we need to consider several factors:

1. Solar Panel Efficiency: Modern solar panels typically have an efficiency ranging from 15% to 22%, which affects how much electricity is generated per square foot of solar panel.
2. Roof Usable Area for Solar Panels: Not all the square footage of the house will be usable for solar panels. The actual area available will depend on the roof's shape, orientation, pitch, and any obstructions like chimneys or trees.
3. Solar Irradiance: This is the amount of sunlight received in Brookline, MA, and it varies by location and season. Solar irradiance is measured in kilowatt-hours per square meter per day (kWh/m²/day).

Assuming an average solar irradiance for Massachusetts and a typical installation efficiency, we can make a rough estimate. Let's use the following assumptions for our calculation:

* About 40% of the house's roof area is usable for solar panels due to the factors mentioned above. This is a rough estimate and can vary significantly.
* An average solar panel efficiency of 18%.
* The average solar irradiance in Massachusetts is about 4.5 kWh/m²/day.

Based on the assumptions made:

* The usable roof area for solar panels on a 2500 square foot two-story house in Brookline, MA, is approximately 46.45 square meters.
* This setup could generate approximately 37.63 kWh of electricity per day.
* Monthly, this translates to about 1128.77 kWh.
* Annually, the solar roof could generate approximately 13733.39 kWh of electricity.

These figures are rough estimates. The actual amount of electricity generated can vary based on several factors, including the exact orientation of the roof, the specific type of solar panels used, and any shading from trees or other buildings.

By producing 13,733.39 kWh of electricity from rooftop solar panels, you would save approximately 12,634.72 lbs of CO2.

**Assumptions for Solar Panel installation**

For 50 square meters (approximately 538 square feet) of solar panels, the installation cost can vary widely depending on the location, the type of panels, and the overall system configuration. To provide a rough estimate, we can calculate based on an average cost per watt for solar installations. Using the range of $2.50 to $3.50 per watt as a general guide:

1. Calculate the potential capacity in kilowatts (kW): Solar panels typically produce about 15 to 20 watts per square foot. Using square meters, this translates to approximately 161 to 215 watts per square meter. For 50 square meters, the total potential capacity would be:

50 m2×161 watts/m2=8,050 watts

50 m2×215 watts/m2=10,750 watts

This gives us a range of approximately 8.05 to 10.75 kW for the potential system size.

1. Estimate the cost: Applying the average cost per watt:
   * For an 8.05 kW system at $2.50 per watt: $20,125
   * For an 8.05 kW system at $3.50 per watt: $28,175
   * For a 10.75 kW system at $2.50 per watt: $26,875
   * For a 10.75 kW system at $3.50 per watt: $37,625

These are broad estimates and the actual costs can vary based on specific system components, installation complexity, and available incentives. Also, prices for solar installations have been decreasing over time, so it's possible that costs could be lower depending on the current market. It's advisable to get multiple quotes from reputable providers to get a more accurate estimate for your specific situation.