*Technical Appendix*

T.1 Simulation Run Documentation

We provide documentation on the three runs presented in this paper: Current Subsidies, where all subsidies described in section 2.2 are in effect; No Subsidies, where no subsidies are in effect; and Soft Cost Sensitivity Analysis.

No post-processing was used to present any of the figures, as they are all figures of variables in the model. The initial values for Initial Housing, Initial Average U Value, and Initial Area are taken from analysis of the EIA RECS data. They were inputted using a CIN file, which is in the supplemental files and for convenience is copied in T.2.

Most parameters are common to both runs and are hard coded in the model, and can be viewed in the model’s source code copied in T.3 and in the supplemental files. The model is not stochastic.

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Value in Current Subsidies** | **Value in No Subsidies** |
| HOMES High Subsidy Amount | $4,000/House | $0/House |
| HOMES Low Subsidy Amount | $2,000/House | $0/House |
| Mass Save Maximum Subsidy for Retrofits | $1e+38/House (no maximum) | $0/House |
| Mass Save Proportional Subsidy Rate for Retrofits | 0.75 | 0 |
| EEHIC Maximum Subsidy for Retrofits | $1,200/House | $0/House |
| EEHIC Proportional Subsidy for Retrofits | 0.3 | 0 |
| Mass Save Lump Sum Subsidy Amount of Heat Pumps | $10,000/House | $0/House |
| IRA Maximum Proportional Subsidy for Heat Pumps | $2,000/House | $0/House |
| IRA Proportional Subsidy Rate for Heat Pumps | 0.3 | 0 |
| Initial Housing | Same in both runs. Taken from processing of EIA (2023), inputted from CIN file in supplemental files and in T.2 | |
| Initial Average U Value |
| Initial Area |
| All other parameters | Same in both runs. Hard coded into model’s source code, located in T.3 and in supplemental files. | |
| TIME STEP | 0.03125 (Euler method, no sensitivity analysis done on this) | |
| Runtime | ~15 seconds | |
| Iterations per Run | 1 iteration | |
| Software | Vensim DSS 10.1.3 | |
| Hardware | 2021 MacBook Pro on macOS Sonoma 14.3.1 | |

The Soft Cost Sensitivity Analysis run has the same parameter values as Current Subsidies, except for “Homeowner Hours Spent Retrofitting.” In the sensitivity analysis (which is run using Vensim DSS’s standard sensitivity analysis dialogue), we vary this parameter from 0 to 1500 hours over a uniform distribution. While we saved a variety of variables, the only saved variable presented in this paper is Cumulative Emissions.

T.2 CIN File for Data from EIA RECS (EIA 2023)

We input data on the initial number of homes, their efficiency, and their area from the Energy Information Administration’s Residential Energy Consumption Survey from 2023. We use Massachusetts single family homes that used natural gas, distillate oil, or heat pumps. R scripts used to generate the analysis are available upon request.

We input the data using a CIN file, included in the supplemental files and copied here:

Initial Average U Value[New Cohorts] = 0

Initial Average U Value[ Before 1950 ] = 0.007557963

Initial Average U Value[ From 1950 to 1959 ] = 0.006878393

Initial Average U Value[ From 1960 to 1969 ] = 0.006567318

Initial Average U Value[ From 1970 to 1979 ] = 0.005545136

Initial Average U Value[ From 1980 to 1989 ] = 0.004669381

Initial Average U Value[ From 1990 to 1999 ] = 0.003679355

Initial Average U Value[ From 2000 to 2009 ] = 0.004424765

Initial Average U Value[ From 2010 to 2020 ] = 0.002647537

Initial Area[New Cohorts] = 0

Initial Area[ Before 1950 ] = 788745795

Initial Area[ From 1950 to 1959 ] = 393944901

Initial Area[ From 1960 to 1969 ] = 261145386

Initial Area[ From 1970 to 1979 ] = 245604066

Initial Area[ From 1980 to 1989 ] = 353346250

Initial Area[ From 1990 to 1999 ] = 397869770

Initial Area[ From 2000 to 2009 ] = 268396544

Initial Area[ From 2010 to 2020 ] = 109102070

Initial Housing[New Cohorts, Heating and Cooling System] = 0

Initial Housing[Preexisting Cohorts, Backup Heating] = 0

Initial Housing[ From 2010 to 2020 , Gas and Central AC ] = 34337.7

Initial Housing[ From 2010 to 2020 , Gas and No AC ] = 2457.609

Initial Housing[ From 2010 to 2020 , Gas and Window AC ] = 3826.12

Initial Housing[ From 2010 to 2020 , Heat Pump Only ] = 2530.661

Initial Housing[ From 2010 to 2020 , Oil and Central AC ] = 0

Initial Housing[ From 2010 to 2020 , Oil and No AC ] = 0

Initial Housing[ From 2010 to 2020 , Oil and Window AC ] = 0

Initial Housing[ Before 1950 , Gas and Central AC ] = 118220.4

Initial Housing[ Before 1950 , Gas and No AC ] = 20480.89

Initial Housing[ Before 1950 , Gas and Window AC ] = 164274.9

Initial Housing[ Before 1950 , Heat Pump Only ] = 0

Initial Housing[ Before 1950 , Oil and Central AC ] = 35686.55

Initial Housing[ Before 1950 , Oil and No AC ] = 22046.89

Initial Housing[ Before 1950 , Oil and Window AC ] = 92822.1

Initial Housing[ From 1950 to 1959 , Gas and Central AC ] = 52615.98

Initial Housing[ From 1950 to 1959 , Gas and No AC ] = 14023.11

Initial Housing[ From 1950 to 1959 , Gas and Window AC ] = 40477.7

Initial Housing[ From 1950 to 1959 , Heat Pump Only ] = 4650.852

Initial Housing[ From 1950 to 1959 , Oil and Central AC ] = 36112.95

Initial Housing[ From 1950 to 1959 , Oil and No AC ] = 9084.471

Initial Housing[ From 1950 to 1959 , Oil and Window AC ] = 74036.2

Initial Housing[ From 1960 to 1969 , Gas and Central AC ] = 30443.61

Initial Housing[ From 1960 to 1969 , Gas and No AC ] = 8190.481

Initial Housing[ From 1960 to 1969 , Gas and Window AC ] = 34092.6

Initial Housing[ From 1960 to 1969 , Heat Pump Only ] = 0

Initial Housing[ From 1960 to 1969 , Oil and Central AC ] = 20162.3

Initial Housing[ From 1960 to 1969 , Oil and No AC ] = 4378.575

Initial Housing[ From 1960 to 1969 , Oil and Window AC ] = 43090.11

Initial Housing[ From 1970 to 1979 , Gas and Central AC ] = 20851.07

Initial Housing[ From 1970 to 1979 , Gas and No AC ] = 4031.992

Initial Housing[ From 1970 to 1979 , Gas and Window AC ] = 29326.96

Initial Housing[ From 1970 to 1979 , Heat Pump Only ] = 3014.42

Initial Housing[ From 1970 to 1979 , Oil and Central AC ] = 20848.45

Initial Housing[ From 1970 to 1979 , Oil and No AC ] = 3055.018

Initial Housing[ From 1970 to 1979 , Oil and Window AC ] = 32114.37

Initial Housing[ From 1980 to 1989 , Gas and Central AC ] = 52836.86

Initial Housing[ From 1980 to 1989 , Gas and No AC ] = 2257.418

Initial Housing[ From 1980 to 1989 , Gas and Window AC ] = 30953.43

Initial Housing[ From 1980 to 1989 , Heat Pump Only ] = 14695.44

Initial Housing[ From 1980 to 1989 , Oil and Central AC ] = 32719.65

Initial Housing[ From 1980 to 1989 , Oil and No AC ] = 0

Initial Housing[ From 1980 to 1989 , Oil and Window AC ] = 21079.85

Initial Housing[ From 1990 to 1999 , Gas and Central AC ] = 51867.93

Initial Housing[ From 1990 to 1999 , Gas and No AC ] = 0

Initial Housing[ From 1990 to 1999 , Gas and Window AC ] = 17033.34

Initial Housing[ From 1990 to 1999 , Heat Pump Only ] = 3983.133

Initial Housing[ From 1990 to 1999 , Oil and Central AC ] = 29051.38

Initial Housing[ From 1990 to 1999 , Oil and No AC ] = 8817.457

Initial Housing[ From 1990 to 1999 , Oil and Window AC ] = 30059.32

Initial Housing[ From 2000 to 2009 , Gas and Central AC ] = 58935.58

Initial Housing[ From 2000 to 2009 , Gas and No AC ] = 0

Initial Housing[ From 2000 to 2009 , Gas and Window AC ] = 2274.553

Initial Housing[ From 2000 to 2009 , Heat Pump Only ] = 0

Initial Housing[ From 2000 to 2009 , Oil and Central AC ] = 29589.63

Initial Housing[ From 2000 to 2009 , Oil and No AC ] = 0

Initial Housing[ From 2000 to 2009 , Oil and Window AC ] = 7731.821

T.3. Model Source Code

We copy the model’s source code here. The actual .mdl file is included in the supplemental files. We also provide a summary of the model’s source code using Argonne’s SDM-Doc tool in the supplemental files.

Cost of Bad Air Conditioning[Heating and Cooling System]

:EXCEPT: [Window AC Cooling], [No AC Cooling]=

0 ~~|

Cost of Bad Air Conditioning[Window AC Cooling]=

80000 ~~|

Cost of Bad Air Conditioning[No AC Cooling]=

100000

~ Dollar / House [0,100000,500]

~ Willingness of Window AC users and those without AC to pay for central AC or heat \

pumps due to those technologies' inability to heat homes and their \

noisiness.

Chosen to be sufficiently high that very few or no houses choose to keep \

window AC or no AC.

|

Peak Load from Heat Pumps on Coldest Days per Group[Cohort,Heat Pump Heating and Cooling\

,Retrofitting Status] :EXCEPT:

[Cohort, Fossil Fuel Heating, Retrofitting Status]=

Housing[Cohort,Heat Pump Heating and Cooling,Retrofitting Status] \* U Value by Grouping\

[Cohort,Heat Pump Heating and Cooling

,Retrofitting Status] \* Average Area[Cohort,Retrofitting Status] \* HDD on Coldest Day\

/ Heat Pump COP on Coldest Days /

(kBTU per kWH \* Days per Year) ~~|

Peak Load from Heat Pumps on Coldest Days per Group[Cohort,Fossil Fuel Heating,Retrofitting Status\

]=

0

~ kWH / Day

~ The load that houses with heat pumps will put on the grid due to providing \

heating on the coldest day of the year, when heat pumps are less efficient \

and per cohort and retrofit status.

|

Housing Starts Across Cohorts=

SUM(Housing Starts In Each Cohort[Cohort!])

~ House / Year

~ Housing starts across all cohorts.

|

Housing Starts In Each Cohort[Cohort]=

SUM(Housing Starts[Cohort,Heating and Cooling System!])

~ House / Year

~ Housing starts across heating and cooling systems.

|

Present Value Replacement Cost[Heating and Cooling System] :EXCEPT: [\

Heat Pump Heating and Cooling], [No AC Cooling

]=

Cost of Cooling System Replacement[Heating and Cooling System] / (Average Lifetime of Cooling Technology\

[Heating and Cooling System] \* Discount Rate) +

Cost of Heating System Replacement[Heating and Cooling System] / (Average Lifetime of Heating Technology\

[Heating and Cooling System] \* Discount Rate) ~~|

Present Value Replacement Cost[Heat Pump Heating and Cooling]=

Cost of Cooling System Replacement[Heat Pump Heating and Cooling] / (Average Lifetime of Cooling Technology\

[Heat Pump Heating and Cooling] \* Discount Rate) ~~|

Present Value Replacement Cost[No AC Cooling]=

0

~ Dollar / House

~ Present value of replacement costs of both Heating and Cooling System given \

continuous discounting and where systems have a constant hazard rate of \

failure. On average, 1/L of the systems will break every year, because we \

assume failure rate is constant and where L is the lifetime of the system. \

Therefore, the average home will incur an average cost of R/L (R is \

replacement or upfront cost) every year. We assume that the household \

ignores the fact that after a finite time they'll leave the house or sell \

the system, because we assume they'll be able to sell the system at a \

price equal to the NPV at that time. Thus, selling the system or moving \

house does not change the NPV of the system when making the decision to \

switch.

For houses that primarily use heat pumps, this formulation assures no \

double counting.

|

Cooling Energy Use Under Alternatives[Cohort, Heat Pump Heating and Cooling, Not Open to Retrofitting\

, Heating and Cooling System] :EXCEPT: [Cohort, Heat Pump Heating and Cooling, Not Open to Retrofitting\

, No AC Cooling]=

U Value by Grouping[Cohort,Heat Pump Heating and Cooling, Not Open to Retrofitting] \

\* Average Area[Cohort, Not Open to Retrofitting

] \* Cooling Degree Days / Cooling System Efficiency[Heating and Cooling System] ~~|

Cooling Energy Use Under Alternatives[Cohort, Traditional Cooling, Not Open to Retrofitting\

, Heating and Cooling System] :EXCEPT: [Cohort, Traditional Cooling, Not Open to Retrofitting\

, No AC Cooling]=

U Value by Grouping[Cohort,Traditional Cooling, Not Open to Retrofitting] \* Average Area\

[Cohort, Not Open to Retrofitting] \* Cooling Degree Days

/ Cooling System Efficiency[Heating and Cooling System] ~~|

Cooling Energy Use Under Alternatives[Cohort,Heating and Cooling System,Retrofitting Status\

,No AC Cooling]=

0 ~~|

Cooling Energy Use Under Alternatives[Cohort,Heat Pump Heating and Cooling,Open to Retrofitting\

,Heating and Cooling System] :EXCEPT: [Cohort,Heat Pump Heating and Cooling,Open to Retrofitting\

,No AC Cooling]=

MIN(U Value by Grouping[Cohort,Heat Pump Heating and Cooling,Open to Retrofitting], \

Optimal U Value for Existing Homes if no EEHIC Cap[Cohort,Heating and Cooling System\

]) \* Average Area[Cohort,Open to Retrofitting] \* Cooling Degree Days / Cooling System Efficiency\

[Heating and Cooling System] ~~|

Cooling Energy Use Under Alternatives[Cohort,Fossil Fuel Heating,Open to Retrofitting\

,Heating and Cooling System] :EXCEPT: [Cohort,Fossil Fuel Heating,Retrofitting Status\

,No AC Cooling]=

MIN(U Value by Grouping[Cohort,Fossil Fuel Heating,Open to Retrofitting], Optimal U Value for Existing Homes if no EEHIC Cap\

[Cohort,Heating and Cooling System]) \* Average Area[Cohort,Open to Retrofitting] \* \

Cooling Degree Days / Cooling System Efficiency[Heating and Cooling System]

~ kBTU / (House \* Year)

~ The cooling energy use of each group, if they were to switch into another heating \

and cooling source. That is, when they switch, their area and U stays the \

same, but the energy system's efficiency may change, meaning that each \

grouping (the first "Heating and Cooling System" subscript) must consider \

their cooling energy use under alternative systems (the second "Heating \

and Cooling Source" subscript).

Houses that are open to retrofitting consider the optimal U that they'll \

retrofit to, unless that U is actually greater than their current one.

|

Pounds per Ton=

2204.6

~ lb CO2 / tCO2

~ The number of pounds in a metric ton.

|

Average Emissions from Cooling by Grouping[Cohort, Heating and Cooling System,Retrofitting Status\

]=

Average Cooling Energy Use[Cohort,Heating and Cooling System,Retrofitting Status] \* \

Cooling Emissions Factor / Pounds per Ton

~ tCO2 / (House \* Year)

~ The GHG emissions from cooling the average home, by cohort, heating and \

cooling system, and retrofitting status.

|

Emissions by Grouping[Cohort, Heating and Cooling System, Retrofitting Status]=

Housing[Cohort,Heating and Cooling System,Retrofitting Status] \* Average Emissions by Grouping\

[Cohort,Heating and Cooling System

,Retrofitting Status]

~ tCO2 / Year

~ The total emissions for the most disaggregated grouping in the model.

|

Peak Load from Non Heating or Cooling Sources=

18344.8 \* 1000 \* 0.461799

~ kWH / Day [15000,250000,100]

~ The peak load coming from non-heating sources, like other household uses, commercial \

uses, industrial uses, etc. Approximated as the average peak load in \

September, October, April, and May of 2022 and 2023 from New England ISO \

data, since there is little heating or cooling demand in those swing \

months. We multiply by 0.46 as Massachusetts has 46% of New England's \

population and we assume demand is proportional to population.

Data source: \

https://www.iso-ne.com/isoexpress/web/reports/load-and-demand/-/tree/net-en\

er-peak-load

|

Average Emissions from Heating by Grouping[Cohort, Heating and Cooling System, Retrofitting Status\

]=

Average Heating Energy Use[Cohort,Heating and Cooling System,Retrofitting Status] \* \

Heating Emissions Factors[Heating and Cooling System

] / Pounds per Ton

~ tCO2 / (House \* Year)

~ Disaggregated carbon dioxide emissions from heating for each house, by \

cohort, retrofitting status, etc.

|

Energy Use by Gas Houses=

SUM(Energy Use by Grouping[Cohort!,Gas and Central AC,Retrofitting Status!]) + SUM(Energy Use by Grouping\

[Cohort!,Gas and Window AC,Retrofitting Status!]) + SUM(Energy Use by Grouping[Cohort\

!,Gas and No AC,Retrofitting Status!])

~ kBTU/ Year

~ The total amount of energy for heating and cooling used by homes which \

primarily use gas to heat their homes.

|

Energy Use by Heat Pump Houses=

SUM(Energy Use by Grouping[Cohort!,Heat Pump Only,Retrofitting Status!]) + SUM(Energy Use by Grouping\

[Cohort!,Heat Pump and Gas,Retrofitting Status!]) + SUM(Energy Use by Grouping[Cohort\

!,Heat Pump and Oil,Retrofitting Status!])

~ kBTU / Year

~ The amount of energy used for heating and cooling by homes which primarily \

use heat pumps to heat their home.

|

Energy Use by Oil Houses=

SUM(Energy Use by Grouping[Cohort!,Oil and Central AC,Retrofitting Status!]) + SUM(Energy Use by Grouping\

[Cohort!,Oil and Window AC,Retrofitting Status!]) + SUM(Energy Use by Grouping[Cohort\

!,Oil and No AC,Retrofitting Status!])

~ kBTU / Year

~ The total amount of energy for heating and cooling used by homes primarily \

using oil to heat their home.

|

Optimal U Value with No EEHIC Proportional Subsidy[Cohort,Heating and Cooling System]\

=

Reference U Value \* (Expected Reference Marginal Cost \* (1 - Expected MassSave Proportional Subsidy Rate for Retrofits\

) /Lifetime Marginal Cost Reductions from Retrofitting[Cohort,Heating and Cooling System\

])^(1/Sensitivity of Marginal Cost to U Value)

~ kBTU / (sf \* F \* Year)

~ Optimal U value if there is no proportional subsidy from the EEHIC at all.

|

Average Cooling Energy Use[Cohort, Heating and Cooling System, Retrofitting Status] :EXCEPT:\

[Cohort, No AC Cooling, Retrofitting Status

]=

U Value by Grouping[Cohort,Heating and Cooling System,Retrofitting Status] \* Average Area\

[Cohort,Retrofitting Status] \*

Cooling Degree Days / Cooling System Efficiency[Heating and Cooling System] ~~|

Average Cooling Energy Use[Cohort, No AC Cooling, Retrofitting Status]=

0

~ kBTU / (Year \* House)

~ The average energy use for cooling. Calculated by setting efficiency times \

a house's cooling energy use equal to total cooling temperature \

differential (CDD), multiplied by U (or divided by R), and solving for \

energy use.

|

Peak Load from Heat Pumps on Hottest Days per Group[Cohort, Heating and Cooling System\

,Retrofitting Status] :EXCEPT:

[Cohort, No AC Cooling, Retrofitting Status]=

Housing[Cohort, Heating and Cooling System,Retrofitting Status] \* U Value by Grouping\

[Cohort, Heating and Cooling System

,Retrofitting Status] \* Average Area[Cohort,Retrofitting Status] \* CDD on Coldest Day\

/ Cooling System Efficiency[Heating and Cooling System

] / (kBTU per kWH \* Days per Year) ~~|

Peak Load from Heat Pumps on Hottest Days per Group[Cohort,No AC Cooling,Retrofitting Status\

]=

0

~ kWH / Day

~ The load that houses with heat pumps will put on the grid due to providing \

heating on the coldest day of the year, per year and per cohort and \

retrofit status.

|

U Value at Which EEHIC Cap Binds[Cohort, Heating and Cooling System]=

IF THEN ELSE(U Value of Retrofitting Homes[Cohort,Heating and Cooling System] > 1e-06\

:AND: Expected EEHIC Proportional Subsidy Rate for Retrofits > 1e-06, Reference U Value\

\* ((Sensitivity of Marginal Cost to U Value - 1) \*(((Expected EEHIC Maximum Subsidy for Retrofits

- Expected EEHIC Proportional Subsidy Rate for Retrofits \* Expected Fixed Cost)/ (U Value of Retrofitting Homes

[Cohort,Heating and Cooling System] \* Expected EEHIC Proportional Subsidy Rate for Retrofits\

\* Expected Reference Marginal Cost

\* Average Area[Cohort,Open to Retrofitting])) - (1 / (-Sensitivity of Marginal Cost to U Value\

+ 1)) \* ((U Value of Retrofitting Homes

[Cohort,Heating and Cooling System] / Reference U Value)^(-Sensitivity of Marginal Cost to U Value\

+ 1)))^(1/(-Sensitivity of Marginal Cost to U Value

+1))), 0)

~ kBTU / (F \* sf \* Year)

~ This the U value at which the maximum subsidy from the Energy Efficiency Home \

Improvement Credit (from the IRA\_ will occur. Because the EEHIC pays for \

30% of a retrofit's costs up to $1200, once a home will retrofit beyond \

this point, IT will no longer receive an additional subsidy. Thus, this is \

the U value at which a discontinuity in the marginal cost curve will \

occur-- before it, a 30% subsidy on the marginal cost will cocur, and then \

afterwards were will be no proportional subsidy.

Formulation is derived by setting 30% of the retrofit cost from current U \

value to this U value equal to the maximum subsidy, and then solving for \

this U value. The retrofit cost from the current U to this U is equal to \

the definite integral from the current U to this U of the marginal cost, \

which is equal to Reference MC \* (Reference U / U) ^sensitivity

|

Optimal U Value for Existing Homes[Cohort,Heating and Cooling System]=

IF THEN ELSE(U Value at Which EEHIC Cap Binds[Cohort,Heating and Cooling System] < Optimal U Value for Existing Homes if no EEHIC Cap

[Cohort,Heating and Cooling System], Optimal U Value for Existing Homes if no EEHIC Cap\

[Cohort,Heating and Cooling System

],

IF THEN ELSE(Lifetime Marginal Cost Reductions from Retrofitting[Cohort,Heating and Cooling System\

] > Marginal Cost at Binding U Value without EEHIC[Cohort,Heating and Cooling System\

], Optimal U Value with No EEHIC Proportional Subsidy[Cohort,Heating and Cooling System\

], U Value at Which EEHIC Cap Binds[Cohort,Heating and Cooling System]))

~ kBTU / (sf \* F \* Year)

~ This is the optimal value at which homes will retrofit to. This is the value at \

which the marginal costs of retrofitting equal the marginal benefits.

This strange formulation comes from the fact that there is a discontinuity in the \

marginal cost curve. The intuition can be seen in this graph: \

https://www.desmos.com/calculator/4esbngkovt. In the graph, X is the U \

value to which to retrofit and y is the marginal benefit or cost, and the \

curved line is the marginal cost curve and the horizontal is the marginal \

benefit. Y, the marginal benefit, can be adjusted. I set reference \

marginal cost and reference U to 1 for clarity in this graph.

Because the Energy Efficiency Home Improvement Credit takes of 30% of the \

retrofit cost up to $1200, there is a U value (x\_cap in the graph) at \

which, below it, marginal costs benefit from the EEHIC's 30% subsidy (the \

red line in the graph). After that, there is no such 30% subsidy, and the \

marginal cost curve is shifted up (blue line in the graph). What then is \

the optimal U? The first if then else statement captures the fact that if \

the marginal cost curve with the 30% subsidy intersects the marginal \

benefit line, then homes just retrofit to that point. The EEHIC cap is not \

binding. If the cap is binding, then the second if then else statement \

captures the fact that if the marginal benefit is still greater than the \

marginal costs after the cap in EEHIC -- that is, it's still worth to \

retrofit even without a 30% subsidy-- then homes retrofit to the point \

where the higher MC curve intersects the marginal benefit. If this is not \

true -- if the marginal cost at the discontinuity jumps above the marginal \

benefit-- then retrofitting beyond the discontinuity means marginal costs \

are greater than marginal benefits, and so they'll retrofit to the \

discontinuity.

|

Optimal Cooling Energy Use[Cohort,Heating and Cooling System,Retrofitting Status] :EXCEPT:\

[Cohort, No AC Cooling, Retrofitting Status]=

Optimal U Value for Existing Homes if no EEHIC Cap[Cohort,Heating and Cooling System\

] \* Average Area[Cohort,Retrofitting Status] \* Cooling Degree Days / Cooling System Efficiency\

[Heating and Cooling System] ~~|

Optimal Cooling Energy Use[Cohort,No AC Cooling,Retrofitting Status]=

0

~ kBTU / (Year \* House)

~ The energy used for cooling, for the average household, if U is optimal. \

Calculated by setting efficiency times energy use equal to total cooling \

temperature differential(CDD), multiplied by optimal U, and solving for \

energy use.

|

Marginal Cost at Binding U Value without EEHIC[Cohort, Heating and Cooling System]=

Expected Reference Marginal Cost \* (ZIDZ(Reference U Value,U Value at Which EEHIC Cap Binds\

[Cohort,Heating and Cooling System]))^Sensitivity of Marginal Cost to U Value

~ (Dollar / sf) / (kBTU / (sf \* F \* Year))

~ This is the marginal cost of retrofitting when the cap from the EEHIC is \

binding. That is, this is the value the marginal cost curve jumps to at \

the discontinuity.

|

Average Subsidized Retrofit Cost=

SUM(Housing[Cohort!,Heating and Cooling System!,Open to Retrofitting] \* Subsidized Retrofit Cost\

[Cohort!,Heating and Cooling System!]) / SUM(Housing[Cohort!,Heating and Cooling System\

!,Open to Retrofitting])

~ Dollar / House

~ The average subsidized retrofit cost across all houses.

|

Lifetime Marginal Cost Reductions from Retrofitting[Cohort,Heating and Cooling System\

]=

Marginal Cost Reductions from Retrofitting[Cohort,Heating and Cooling System] / Discount Rate

~ Dollar \* Year \* F / kBTU

~ The amount of marginal emissions reductions over the model's lifetime. \

Assumes constant continuous discounting at the discount rate and infinite \

time horizon -- homeowners are so concerned about emissions that they \

consider emissions that occur after they move out.

|

Initial Fraction of Homes Retrofitting=

0.1

~ dmnl [0,1,0.05]

~ Initial fraction of homes open to retrofitting. Heuristically chosen to be \

0.1 to match low level of retrofitting that current occurs.

|

Average Area of Housing Starts=

Increase in Area per Year \* (Time - INITIAL TIME) + Initial Average Area of Housing Starts

~ sf / House

~ The average area of housing starts.

|

Actual EEHIC Subsidy for Retrofits[Cohort,Heating and Cooling System]=

MIN(Unsubsidized Retrofit Cost[Cohort,Heating and Cooling System] \* Implemented EEHIC Subsidy Proportional Rate for Retrofits\

, Implemented EEHIC Maximum Subsidy for Retrofits)

~ Dollar / House

~ The actual subsidy for retrofits by the Energy Efficiency Home Improvement \

Credit, not the expected value.

|

Actual HOMES Subsidy for Retrofits[Cohort,Heating and Cooling System]=

IF THEN ELSE(Energy Savings[Cohort,Heating and Cooling System] < HOMES Cut Off for Savings\

, HOMES Implemented Lower Subsidy, HOMES Implemented High Subsidy)

~ Dollar/ Home

~ The lump sum subsidy offered by the Home Owner Managing Energy Savings \

rebate (from the IRA), as opposed to the expected value.

|

Actual MassSave Subsidy for Retrofits[Cohort,Heating and Cooling System]=

MIN(Unsubsidized Retrofit Cost[Cohort,Heating and Cooling System] \* Implemented MassSave Subsidy Proportional Rate for Retrofits\

, Implemented MassSave Maximum Subsidy for Retrofits)

~ Dollar / House

~ The actual subsidy offered for retrofits by MassSave, not the expected \

value.

|

EEHIC Expected Subsidy for Retrofits[Cohort,Heating and Cooling System,Retrofitting Status\

]=

MIN(Proportional Subsidy Switch for Retrofits \* Expected EEHIC Proportional Subsidy Rate for Retrofits\

\* Unsubsidized Retrofit Cost Intensity

[Cohort,

Heating and Cooling System] \* Average Area[Cohort,Retrofitting Status], Expected EEHIC Maximum Subsidy for Retrofits

)

~ Dollar / House

~ The proportional subsidy offered against the retrofit cost intensity, \

taking into account whether it has gone into effect, from the Energy \

Efficient Home Improvement Credit.

|

EEHIC Maximum Subsidy for Retrofits=

1200

~ Dollar / House [0,?]

~ The maximum proportional subsidy that will be offered from Energy \

Efficient Home Improvement Credit, regardless of that subsidy's discount. \

Source: https://www.nrdc.org/stories/consumer-guide-inflation-reduction-act

|

Annual Federal Subsidies=

Federal Annual Heat Pump Subsidy + Federal Annual Retrofit Subsidy

~ Dollar / Year

~ The amount of money the federal government spends on subsidies for heat \

pumps and retrofits, each year.

|

Annual Heat Pump Subsidy=

Federal Annual Heat Pump Subsidy + Massachusetts Annual Heat Pumps Subsidy

~ Dollar / Year

~ The amount of money the government spends to subsidize heat pumps, \

including state and federal government.

|

Proportional EEHIC Subsidy Implementation Year for Retrofits=

2023

~ Year [2010,2050]

~ Time at which the proportional subsidy will take effect from the Energy Efficiency \

Home Improvement Credit.

Source: https://www.nrdc.org/stories/consumer-guide-inflation-reduction-act

|

Annual MA Subsidies=

Massachusetts Annual Retrofit Subsidy + Massachusetts Annual Heat Pumps Subsidy

~ Dollar / Year

~ The subsidies that the Massachusetts state government gives out per year \

for both retrofits and heat pumps.

|

Annual Retrofit Subsidy=

Federal Annual Retrofit Subsidy + Massachusetts Annual Retrofit Subsidy

~ Dollar / Year

~ The subsidies for retrofits paid out every year.

|

Annual Subsidies=

Annual Heat Pump Subsidy + Annual Retrofit Subsidy

~ Dollar / Year

~ The amount of subsidies spent on heat pumps and retrofits every year.

|

kBTU per kWH=

3.41214

~ kBTU / kWH [3.41214,3.41214]

~ The number of kilo-British Thermal Units per kilowatt hour.

|

Cumulative Subsidies for Heat Pumps= INTEG (

Annual Heat Pump Subsidy,

0)

~ Dollar

~ The total amount of dollars spent on subsidizing heat pumps throughout the \

model's run.

|

Energy Savings[Cohort,Heating and Cooling System]=

MAX(0, ABS(ZIDZ((Optimal U Value for Existing Homes if no EEHIC Cap[Cohort,Heating and Cooling System\

] - U Value by Grouping[Cohort,Heating and Cooling System, Open to Retrofitting]),

U Value by Grouping[Cohort,Heating and Cooling System, Open to Retrofitting])))

~ dmnl

~ The amount of energy savings that not refitting houses would achieve if \

they were to retrofit. Because we assume area, HDD, and efficiency stay \

the same before and after retrofitting, this saving is solely from \

changing the U value.

|

Initial Code U Value=

0.003

~ kBTU / (sf \* F \* Year)

~ The initial value of code U. For initial paper, assume that this is \

between initial optimal U (nearly 0) and average U (0.006).

|

Federal Annual Heat Pump Subsidy=

Total Heat Pump Sales \* IRA Actual Subsidy for Heat Pumps

~ Dollar / Year

~ The amount of subsidies the federal government spends on heat pumps \

through the Inflation Reduction Act every year.

|

Expected EEHIC Maximum Subsidy for Retrofits=

SMOOTH3(Implemented EEHIC Maximum Subsidy for Retrofits, Delay in Changing Subsidy Expectations\

)

~ Dollar / House

~ Expected maximum proportional subsidy that lowers subsidized retrofit \

costs from the Energy Efficiency Home Improvement Credit, taking into \

account information delays.

|

Expected EEHIC Proportional Subsidy Rate for Retrofits=

SMOOTH3(Implemented EEHIC Subsidy Proportional Rate for Retrofits, Delay in Changing Subsidy Expectations\

) \* Proportional Subsidy Switch for Retrofits

~ dmnl

~ Expected proportional subsidy rate that lowers subsidized retrofit costs, \

taking into account information delays.

|

IRA Actual Subsidy for Heat Pumps=

MIN(IRA Implemented Subsidy Proportional Rate for Heat Pumps \* Unsubsidized Cost of Heat Pumps\

, Implemented IRA Maximum Proportional Subsidy for Heat Pumps)

~ Dollar / House

~ The actual implemented subsidy for heat pumps from the Inflation Reduction \

Act, as opposed to the expected subsidy value.

|

HOMES Subsidy Final Year=

2032

~ Year

~ Final year of Home Owner Managing Energy Savings rebate, assumed to be the \

same as that of the EEHIC.

|

Massachusetts Annual Retrofit Subsidy=

SUM(Houses Retrofitting per Year[Cohort!,Heating and Cooling System!] \* Actual MassSave Subsidy for Retrofits\

[Cohort!,Heating and Cooling System!])

~ Dollar / Year

~ Amount of money Massachusetts spends on MassSave subsidies for retrofits, \

yearly.

|

Federal Annual Retrofit Subsidy=

SUM((Actual EEHIC Subsidy for Retrofits[Cohort!,Heating and Cooling System!] + Actual HOMES Subsidy for Retrofits\

[Cohort!,Heating and Cooling System!]) \* Houses Retrofitting per Year[Cohort!,Heating and Cooling System

!])

~ Dollar / Year

~ The amount of federal subsidies spent by the federal government, through \

the IRA.

|

Cumulative Federal Subsidy= INTEG (

Annual Federal Subsidies,

0)

~ Dollar

~ The amount of money the federal government spends on subsidies for heat \

pumps and retrofits since the beginning of the model's run.

|

Cumulative MA Subsidy= INTEG (

Annual MA Subsidies,

0)

~ Dollar

~ The amount of subsidies that the Massachusetts state government has given \

out for heat pumps and retrofits since the beginning of the model's run.

|

Cumulative Subsidies=

Cumulative Subsidy for Retrofits + Cumulative Subsidies for Heat Pumps

~ Dollar

~ The amount spent on subsidies for both heat pumps and retrofits by both \

since state and federal governments the beginning of the model run.

|

Average Indicated Fraction of Homes Retrofitting=

SUM(Indicated Homes Retrofitting[Cohort!,Heating and Cooling System!] )/ Total Housing Stock

~ dmnl

~ The average fraction of homes that will retrofit retrofitting after \

decision delayacross all housing.

|

Massachusetts Annual Heat Pumps Subsidy=

Total Heat Pump Sales \* MassSave Implemented Lump Sum Subsidy for Heat Pumps

~ Dollar / Year

~ The actual subsidy provided for purchase of heat pumps by Massachusetts, \

as opposed to what the subsidy expected by homeowners is.

|

Monthly Total Heat Pump Sales=

Total Heat Pump Sales / Months per Year

~ Houses/ Month

~ The number of homes buying heat pumps, every year.

|

Months per Year=

12

~ Month / Year [12,12]

~ The number of months per year.

|

MassSave Implemented Lump Sum Subsidy for Heat Pumps=

MIN(Unsubsidized Cost of Heat Pumps, IF THEN ELSE(Time >= MassSave Lump Sum Subsidy Implementation Year for Heat Pumps\

:AND: Time <= MassSave Lump Sum Subsidy for Heat Pumps Final Year

, MassSave Lump Sum Subsidy Amount for Heat Pumps

, 0))

~ Dollar / House

~ Lump sum subsidy from MassSave that is actually implemented. Equal to zero \

before implementation year and to lump sum subsidy after implementation \

year.

|

HOMES Cut Off for Savings=

0.35

~ dmnl [0,1,0.01]

~ The percent energy savings needed to get the higher subsidy amount from \

the Home Owner Managing Energy Savings rebate. Taken from: \

https://www.nrdc.org/bio/lauren-urbanek/theres-no-better-time-consider-home\

-energy-upgrades#: \

:text=The%20HOMES%20Rebate%20Program%20provides,or%20from%20measured%20ener\

gy%20savings.

|

Average Income=

55

~ Dollar / Hour / House [30,100,1]

~ The average income of single family homeowners in Massachusetts. \

Calculated from 2020 EIA RECS data for MA SFH, where each individual was \

assigned the average income of their reported income bracket, other than \

those making more than $150K/year, who were assigned $175,000. Hourly wage \

calculated by assuming working 8 hours a day, 5 days a week, for 50 weeks \

in a year.

|

EEHIC Proportional Subsidy Rate for Retrofits=

0.3

~ dmnl [0,1,0.05]

~ Proportion of total retrofit cost that will be credited with the Energy Efficiency \

Home Improvement Credit.

Source: https://www.nrdc.org/stories/consumer-guide-inflation-reduction-act

|

Cumulative Subsidy for Retrofits= INTEG (

Annual Retrofit Subsidy,

0)

~ Dollar

~ The total amount spent on retrofits since the beginning of the model's run.

|

EEHIC Subsidy for Retrofits Final Year=

2033

~ Year

~ The year in which the EEHIC is phased out. If final time, then has no ending data.

Source: \

https://www.irs.gov/credits-deductions/energy-efficient-home-improvement-cr\

edit

|

Houses Retrofitting per Year[Cohort,Heating and Cooling System]=

IF THEN ELSE(Optimal U Value for Existing Homes if no EEHIC Cap[Cohort,Heating and Cooling System\

] < U Value by Grouping[Cohort,Heating and Cooling System,Open to Retrofitting], Housing\

[Cohort,Heating and Cooling System,Open to Retrofitting] / Retrofit Delay, 0)

~ House / Year

~ The number of homes retrofitting per year. This is an approximation \

because the number of homes actively retrofitting is equal to the number \

of homes open to retrofitting only if their average U value is less than \

optimal U. Assumes that if, say, the retrofitting delay is 5 years, then \

on average 20% of homes are retrofitting every year.

|

Implemented EEHIC Maximum Subsidy for Retrofits=

IF THEN ELSE(Time >= Proportional EEHIC Subsidy Implementation Year for Retrofits :AND:\

Time <= EEHIC Subsidy for Retrofits Final Year, EEHIC Maximum Subsidy for Retrofits

, 0)

~ Dollar / House

~ Maximum proportional subsidy from EEHIC that is actually implemented. \

Equal to zero before implementation year and to maximum proportional \

subsidy after implementation year.

|

HOMES High Subsidy Amount=

4000

~ Dollar / House [0,8000,1]

~ The subsidy from the home owner managing energy savings rebate for retrofits saving \

more than 35% of energy.

Source: \

https://www.nrdc.org/bio/lauren-urbanek/theres-no-better-time-consider-home\

-energy-upgrades#: \

:text=The%20HOMES%20Rebate%20Program%20provides,or%20from%20measured%20ener\

gy%20savings.

|

HOMES Implemented High Subsidy=

IF THEN ELSE(Time >= HOMES Subsidy Implementation Year :AND: Time <= HOMES Subsidy Final Year\

, HOMES High Subsidy Amount, 0)

~ Dollar / House

~ Implemented higher subsidy from the HOMES rebate program.

|

Total Heat Pump Sales=

SUM(Houses Switching Sources[Cohort!,Heating and Cooling System!,Retrofitting Status\

!,Heat Pump Only] + Houses Switching Sources[Cohort!,Heating and Cooling System!,Retrofitting Status\

!,Heat Pump and Gas] + Houses Switching Sources[Cohort!,Heating and Cooling System\

!,Retrofitting Status!,Heat Pump and Oil])

~ House / Year

~ Number of houses buying heat pumps every year.

|

Homeowner Hours Spent Retrofitting=

750

~ Hour [20,1000,10]

~ The amount of hours a homeowners spends retrofitting their home \

themselves, i.e., the hours spent deciding to retrofit, supervising \

audits, moving out of the home as necessary, etc. No hard data on this, \

calibrated so that the initial fraction of homes willing to retrofit is \

10%.

|

Soft Costs of Retrofitting=

Average Income \* Homeowner Hours Spent Retrofitting

~ Dollar / Home

~ The "hassle cost" of retrofitting a home, that is not due to economic \

costs but rather from the time and hassle spent on a homeowner \

retrofitting (such as having to move out). This is calculated as the \

opportunity cost of all the time spent retrofitting, using the average \

hourly income for MA SFH homeowners.

|

Implemented EEHIC Subsidy Proportional Rate for Retrofits=

IF THEN ELSE(Time >= Proportional EEHIC Subsidy Implementation Year for Retrofits :AND:\

EEHIC Subsidy for Retrofits Final Year >= Time, EEHIC Proportional Subsidy Rate for Retrofits

, 0)

~ dmnl

~ The implemented proportional subsidy rate for retrofits from the IRA, \

taking into account whether a proportional subsidy has been implemented. \

Equal to zero before implementation year and proportional subsidy discount \

afterwards.

|

HOMES Expected Higher Subsidy=

SMOOTH3(HOMES Implemented High Subsidy, Delay in Changing Subsidy Expectations)

~ Dollar / House

~ Expected lump sum subsidy that lowers subsidized retrofit costs, taking \

into account information delays. This is for homes that save more than 35% \

of energy

|

IRA Expected Proportional Subsidy for Heat Pumps=

MIN(Proportional IRA Subsidy Switch for Heat Pumps \* Expected IRA Proportional Subsidy Rate for Heat Pumps\

\* Unsubsidized Cost of Heat Pumps, Expected Maximum IRA Proportional Subsidy for Heat Pumps

)

~ Dollar / House

~ The IRA's subsidies for a heat pump's upfront costsintensity, taking into \

account whether it has gone into effect.

|

Heat Pump COP on Coldest Days=

2.16438

~ dmnl [1.5,4,0.1]

~ The heat pump COP on coolest day of the year.

Taken from NYSERDA/MassCEC study on heat pump performance on 41 heat \

pumps: \

https://e4thefuture.org/wp-content/uploads/2022/06/Residential-ccASHP-Build\

ing-Electrification\_060322.pdf (pg. 24). Regressed COP on temperature and \

its square. Using daily data on HDD (set point 65°F) for 2021-2023 from \

degreedays.net, calculated temperature of coldest day on average. Plugged \

that into regression model to find COP on coldest day.

|

Peak Cooling Load on Grid=

SUM(Peak Load from Heat Pumps on Hottest Days per Group[Cohort!,Heating and Cooling System\

!,Retrofitting Status!])

~ kWH / Day

~ Annual load from heat pumps providing heating on the coldest day, across \

all groups.

|

CDD on Coldest Day=

17.1

~ F [15,30,0.1]

~ The total CDD from hottest day.

Data from https://www.degreedays.net/ for KOWD, weather station nearest to \

centre of population for MA, Natick. Calculated by finding CDDs from the \

past three years (February 2021 - January 2024), finding the highest CDD \

in each year, and averaging them. Following industry standard, used 65°F \

as set point.

|

Proportional IRA Subsidy Switch for Heat Pumps=

1

~ dmnl [0,1,1]

~ Turns proportional subsidy's effect on retrofit cost on/off.

|

Implemented IRA Maximum Proportional Subsidy for Heat Pumps=

IF THEN ELSE(Time >= IRA Proportional Subsidy Implementation Year for Heat Pumps :AND:\

Time <= IRA Lump Sum Subsidy for Heat Pumps Final Year, IRA Maximum Proportional Subsidy for Heat Pumps

, 0)

~ Dollar / House

~ Maximum proportional subsidy for heat pumps that is actually implemented. \

Equal to zero before implementation year and to maximum proportional \

subsidy after implementation year.

|

Increase in Area per Year=

10.76

~ sf / Year / House [3,1,0.01]

~ The exogenous increase in area per year, found by regressing area on year \

house was built in RECS 2020 data for MA SFG.

|

Effect of Air Leakage from Window AC on Efficiency=

0.9\* 10 / 11

~ dmnl

~ A window air conditioner typically does not perfectly cover its intended cavity, \

leading to more air leakage and therefore reducing efficiency.

Taken from: \

https://www.energy.gov/sites/prod/files/2014/08/f18/ba\_innovations\_1-2-5\_wi\

ndow\_ac.pdf

|

Cooling System Efficiency[Heat Pump Heating and Cooling]=

Heat Pump Cooling COP TABLE(Time) ~~|

Cooling System Efficiency[Central AC Cooling]=

2.93 ~~|

Cooling System Efficiency[Window AC Cooling]=

2.49 \* Effect of Air Leakage from Window AC on Efficiency ~~|

Cooling System Efficiency[No AC Cooling]=

:NA:

~ dmnl

~ The COP of different air conditioning technologies on an average day. This is not \

in terms of energy efficiency rating or seasonal efficiency rating, \

although some are calculated from those figures.

For central ac: assume value of ten

For window AC (under portable AC): https://learnmetrics.com/eer-rating/

All are very rough, and non-heat pump cooling systems are assumed to have \

constant efficiency.

|

MassSave Expected Lump Sum Subsidy for Heat Pumps=

SMOOTH3(MassSave Implemented Lump Sum Subsidy for Heat Pumps, Delay in Changing Subsidy Expectations\

)

~ Dollar / House

~ Expected lump sum subsidy that lowers subsidized retrofit costs from the \

state, taking into account information delays.

|

MassSave Lump Sum Subsidy Amount for Heat Pumps=

10000

~ Dollar / House [0,20000,10]

~ The total amount of money offered by the lump sum subsidy.

Taken from: \

https://www.masssave.com/residential/rebates-and-incentives/heating-and-coo\

ling/heat-pumps/air-source-heat-pumps.

|

MassSave Lump Sum Subsidy for Heat Pumps Final Year=

2200

~ Year

~ The year in which the state's subsidy for heat pumps is phased out.

|

MassSave Lump Sum Subsidy Implementation Year for Heat Pumps=

2020

~ Year [2010,2050,1]

~ The year in which the state's lump sum subsidy for heat pumps will \

activate.

|

IRA Implemented Subsidy Proportional Rate for Heat Pumps=

IF THEN ELSE(Time >= IRA Proportional Subsidy Implementation Year for Heat Pumps :AND:\

IRA Lump Sum Subsidy for Heat Pumps Final Year >= Time, IRA Proportional Subsidy Rate for Heat Pumps

, 0)

~ dmnl

~ The implemented proportional subsidy rate, taking into account whether a \

proportional subsidy has been implemented. Equal to zero before \

implementation year and proportional subsidy rate afterwards.

|

IRA Lump Sum Subsidy for Heat Pumps Final Year=

2032

~ Year [2032,2032]

~ The year in which the subsidy is phased out. If final time, then has no \

ending date.

|

IRA Maximum Proportional Subsidy for Heat Pumps=

2000

~ Dollar / House [0,?,1]

~ The maximum proportional subsidy for heat pumps that will be offered, regardless of \

the subsidy rate. For instance, if the proportional subsidy is 50% but the \

maximum is $1000, then for a retrofit project that costs $3000 only a \

$1000 subsidy will be given.

Taken from: https://www.energystar.gov/about/federal-tax-credits

|

MassSave Subsidy for Retrofits Final Year=

FINAL TIME

~ Year

~ The year in which the subsidy is phased out. If final time, then has no \

ending data.

|

IRA Proportional Subsidy Implementation Year for Heat Pumps=

2023

~ Year [2010,2050,0.5]

~ Time at which the proportional subsidy will take effect from the Inflation \

Reduction Act, from \

https://www.nrdc.org/stories/consumer-guide-inflation-reduction-act

|

IRA Proportional Subsidy Rate for Heat Pumps=

0.3

~ dmnl [0,1,0.05]

~ Proportion of total heat pump cost that will be credited as part of a proportional \

subsidy.

Taken from: https://www.energystar.gov/about/federal-tax-credits

|

Subsidized Cost of Heat Pumps=

MAX(0,Unsubsidized Cost of Heat Pumps - Expected Subsidy for Heat Pumps)

~ Dollar / House

~ The upfront cost of heat pump once subsidies are taken into account.

|

Cost of Cooling System Replacement[Heat Pump Heating and Cooling]=

Subsidized Cost of Heat Pumps ~~|

Cost of Cooling System Replacement[Central AC Cooling]=

5800 ~~|

Cost of Cooling System Replacement[Window AC Cooling]=

1600 ~~|

Cost of Cooling System Replacement[No AC Cooling]=

0

~ Dollar / House

~ The cost of installing a cooling system in each house. Assumed to be constant, \

except for heat pumps.

Central AC cost from: \

https://www.angi.com/articles/how-much-does-installing-new-ac-cost.htm

Window AC cost from: https://homeguide.com/costs/window-ac-unit-cost

|

Cost of Heating System Replacement[Heat Pump Heating and Cooling]=

Subsidized Cost of Heat Pumps ~~|

Cost of Heating System Replacement[Gas Heating]=

10000 ~~|

Cost of Heating System Replacement[Oil Heating]=

7450

~ Dollar / House [0,20000,100]

~ The cost of buying and installing a heating system in each house.

Took upper limits of estimates for each, since MA tends to be a more expensive \

state.

Oil and gas cost assumed to be constant.

Initial heat pump cost is from: \

https://www.masssave.com/en/residential/rebates-and-incentives/heating-and-\

cooling/heat-pumps/air-source-heat-pumps, and then I assume that the cost \

improves in proportion to the trajectory in Mass. gov's deep \

decarbonization report:

Gas furnace cost from: https://www.angi.com/articles/common-gas-furnace-prices.htm

Oil furnace cost from: \

https://modernize.com/hvac/heating-repair-installation/furnace/oil

|

Unsubsidized Cost of Heat Pumps=

Unsubsidized Cost of Heat Pump Over Time TABLE(Time)

~ Dollar / House

~ The unsubsidized cost of heat pumps, instantiated at each time.

|

Expected Subsidy for Heat Pumps=

MassSave Expected Lump Sum Subsidy for Heat Pumps + IRA Expected Proportional Subsidy for Heat Pumps

~ Dollar / House

~ Total subsidy offered against retrofit cost across both lump sum and \

proportional subsidies.

|

Expected IRA Proportional Subsidy Rate for Heat Pumps=

SMOOTH3(IRA Implemented Subsidy Proportional Rate for Heat Pumps, Delay in Changing Subsidy Expectations\

) \* Proportional IRA Subsidy Switch for Heat Pumps

~ dmnl

~ Expected proportional subsidy rate that lowers subsidized retrofit costs, \

taking into account information delays.

|

Expected Maximum IRA Proportional Subsidy for Heat Pumps=

SMOOTH3(Implemented IRA Maximum Proportional Subsidy for Heat Pumps, Delay in Changing Subsidy Expectations\

)

~ Dollar / House

~ Expected maximum proportional subsidy that lowers subsidized retrofit \

costs, taking into account information delays.

|

Fraction of Housing by Heating and Cooling System[Heating and Cooling System]=

Housing by Heating and Cooling System[Heating and Cooling System] / Total Housing Stock

~ dmnl

~ The fraction of the total housing stock using each heating and cooling \

system.

|

Initial Average Area of Housing Starts=

2347

~ sf / House [1900,3000,1]

~ Initial average area of housing starts. Taken from average area of MA SFH \

homes built from 2015 to 2020, from EIA RECS data.

|

Average Cooling Energy Use Across All Homes=

ZIDZ(Total Cooling Energy Use, Total Housing Stock)

~ kBTU / Year / House

~ The amount of energy an average home spends on cooling, regardless of \

cohort, retrofit status, etc.

|

Average Heating Cost Across All Homes=

ZIDZ(Total Heating Cost, SUM(Housing[Cohort!,Heating and Cooling System!,Retrofitting Status\

!]))

~ Dollar / Year / House

~ The average amount a home spends on heating, regardless of cohort or \

heating and cooling system.

|

Total Heating Cost=

SUM(Average Heating Cost[Cohort!,Heating and Cooling System!,Retrofitting Status!] \*\

Housing[Cohort!,Heating and Cooling System!,Retrofitting Status!])

~ Dollar / Year

~ The total amount of money spent on heating homes.

|

Housing Fractional Growth Rate=

0.02

~ 1 / Year [0,1]

~ The annual growth rate in housing. Heuristically chosen so that total \

housing stock grows at net 1%/year.

|

Housing Starts[Cohort, Heating and Cooling System]=

Housing Fractional Growth Rate \* SUM(Housing[Cohort!,Heating and Cooling System,Retrofitting Status\

!]) \* Active Cohort Indicator[Cohort] \* (1 - No Turnover Switch)

~ Houses / Year

~ Homes being built. Assumed to be equal to the total number of homes times \

a constant fractional growth rate and only homes that are not open to \

retrofits will be built.

|

Total Area=

SUM(Area[Cohort!,Retrofitting Status!])

~ sf

~ The total area across all housing.

|

Total Cooling Energy Use=

SUM(Average Cooling Energy Use[Cohort!,Heating and Cooling System!,Retrofitting Status\

!] \* Housing[Cohort!,Heating and Cooling System!,Retrofitting Status!])

~ kBTU/ Year

~ The total amount of energy spent on cooling homes.

|

Average Cooling Cost Across All Homes=

Total Cooling Cost /SUM(Housing[Cohort!,Heating and Cooling System!,Retrofitting Status\

!])

~ Dollar / House/ Year

~ The average cost to cool a home, for all cohorts and systems.

|

Average Heating Energy Use Across All Homes=

ZIDZ(Total Heating Energy Use,Total Housing Stock)

~ kBTU / (Year \* House)

~ The average heating energy use per home, regardless of cohort, system,etc.

|

Total Cooling Cost=

SUM(Average Cooling Cost[Cohort!,Heating and Cooling System!,Retrofitting Status!] \*\

Housing[Cohort!,Heating and Cooling System!,Retrofitting Status!])

~ Dollar / Year

~ The total amount of money spent on cooling homes, per year.

|

Total Housing Starts=

SUM(Housing Starts[Cohort!,Heating and Cooling System!])

~ House/ Year

~ The total housing starts across all cohorts and sources.

|

Total Heating Energy Use=

SUM(Average Heating Energy Use[Cohort!,Heating and Cooling System!,Retrofitting Status\

!]\* Housing[Cohort!,Heating and Cooling System!

,Retrofitting Status!])

~ kBTU/ Year

~ The total amount of energy spent on heating per year.

|

Initial Housing[Cohort, Heating and Cooling System]=

2.2e+06

~ House

~ The total number of houses that begin in each cohort and heating and \

cooling source. Taken from CIN file.

|

New Cohorts:

From 2021 to 2030, From 2031 to 2040, From 2041 to 2050

~

~ |

Backup Heating:

Heat Pump and Gas, Heat Pump and Oil

~

~ |

Peak Heating Load on Grid=

SUM(Peak Load from Heat Pumps on Coldest Days per Group[Cohort!,Heating and Cooling System\

!,Retrofitting Status!])

~ kWH / Day

~ Annual load from heat pumps providing heating on the coldest days, across \

all groups.

|

Average Daily Load from Heat Pumps=

Annual Load from Heat Pumps / Days per Year

~ kBTU / Day

~ The average load on the electric grid from heat pumps, per day.

|

HDD on Coldest Day=

55.2333

~ F [30,100,1]

~ The total HDD from coldest day.

Data from https://www.degreedays.net/ for KOWD, weather station nearest to \

centre of population for MA, Natick. Calculated by finding HDDs from the \

past three years (February 2021 - January 2024), finding the highest HDD \

in each year, and averaging them. Following industry standard, used set \

point of 65°F.

|

Days per Year=

365

~ Day / Year [365,365.25,0.25]

~ The number of days each year. Used to convert yearly measures to daily \

ones.

|

Annual Load from Heat Pumps=

SUM(Energy Use by Grouping[Cohort!,Heat Pump Heating and Cooling!,Retrofitting Status\

!])

~ kBTU / Year

~ The load on the electric grid from servicing heating and cooling demand \

from heat pumps, across the whole year.

|

Average Heating Energy Use[Cohort, Heating and Cooling System, Retrofitting Status]=

U Value by Grouping[Cohort,Heating and Cooling System,Retrofitting Status] \* Average Area\

[Cohort,Retrofitting Status] \*

Heating Degree Days / Heating System Efficiency[Heating and Cooling System]

~ kBTU / (Year \* House)

~ The average energy use for heating annually. Calculated by setting \

efficiency times energy use equal to total HDD, multiplied by U (or \

divided by R) and divided by year (to get annual use), and solving for \

energy use.

|

Initial Average U Value[Cohort]=

0.006

~ kBTU/(Year\*sf\*F)

~ The initial average U, equal to the average U value of MA SFH in 2022, \

from EIA RECS.

|

Gas COP TABLE(

[(2020,0)-(2050,1)],(2020,0.9),(2030,0.925),(2040,0.95),(2050,0.95))

~ dmnl

~ Efficiency of gas systems over time. Taken as the average of projected \

efficiency for reference gas boilers and gas furnaces, from MassDEP's \

Energy Pathways for Deep Decarbonization Report (pg. 97): \

https://www.mass.gov/doc/energy-pathways-for-deep-decarbonization-report/do\

wnload

|

Heat Pump Cooling COP TABLE(

[(2020,0)-(2050,10)],(2020,4.3),(2030,4.8),(2040,5.17),(2050,5.28))

~ dmnl

~ The COP of heat pumps when used for cooling. Calculated by assuming the ratio of \

heating and cooling COP is constant over time -- as heating COP improves \

the ability to cool improves proportionally-- finding cooling COP in \

2020, finding the COP for cooling of heating in 2018, and then using the \

ratio between the two in 2020 to project future values. Data on this was \

difficult to find.

Projected heating COP from pg. 97 of MassDEP's Energy Pathways for Deep \

Decarbonization: \

https://www.mass.gov/doc/energy-pathways-for-deep-decarbonization-report/do\

wnload

Cooling COP in 2020 here: \

https://www.raleighheatingandair.com/blog/is-a-heat-pump-more-effective-at-\

cooling-or-heating/

|

Oil COP TABLE(

[(2020,0)-(2050,1)],(2020,0.835),(2030,0.84),(2050,0.84))

~ dmnl

~ Efficiency of oil systems over time. Taken as the average of projected \

efficiency for reference distillate boilers and furnaces, from MassDEP's \

Energy Pathways for Deep Decarbonization Report (pg. 97): \

https://www.mass.gov/doc/energy-pathways-for-deep-decarbonization-report/do\

wnload

|

Heat Pump Heating COP TABLE(

[(2020,0)-(2050,10)],(2020,2.485),(2030,2.785),(2040,2.99),(2050,3.05))

~ dmnl

~ The efficiency of heat pumps for heating, over time. Taken as the average \

of projected COP for reference ASHP and ductless mini-splits from \

MassDEP's Energy Pathways Report (pg. 97): \

https://www.mass.gov/doc/energy-pathways-for-deep-decarbonization-report/do\

wnload

|

Unsubsidized Cost of Heat Pump Over Time TABLE(

[(2020,5000)-(2050,10000)],(2020,22000),(2030,20483.7),(2040,18967.3),(2050,17448.6)\

)

~ Dollar/ House

~ The cost of installing and buying a heat pump over time. Initial value taken from: \

https://www.masssave.com/en/residential/rebates-and-incentives/heating-and-\

cooling/heat-pumps/air-source-heat-pumps, and then assume that ratio of \

future prices to initial is the same as average of reference and ductless \

heat pumps in MassDEP's Energy Pathways Report (pg. 97): \

https://www.mass.gov/doc/energy-pathways-for-deep-decarbonization-report/do\

wnload. (That is, I took the ratio of the initial price to the initial \

price in that report, then I multiplied that ratio times all projections \

of future heat pump prices). I was unable to use the MassDEP report's \

prices directly, because they are based on national estimates from NREL, \

and MA is typically a more expensive state. In particular, the MassDEP \

projections say that heat pumps cost only $9K, but MassSave subsidy is \

$10K!

Assumes rates of change are linear between projected points.

|

Heating System Efficiency[Heat Pump Heating and Cooling]=

Heat Pump Heating COP TABLE(Time) ~~|

Heating System Efficiency[Gas Heating]=

Gas COP TABLE(Time) ~~|

Heating System Efficiency[Oil Heating]=

Oil COP TABLE(Time)

~ dmnl

~ The COP (for heat pumps) or annual fuel utilization efficiency of heating \

systems. Varies over time.

|

Cumulative Emissions= INTEG (

Emissions,

0)

~ tCO2

~ The total amount of CO2 emitted into the atmosphere during the course of \

the model's run.

|

Average Emissions by Heating and Cooling System[Heating and Cooling System]=

ZIDZ(Emissions by Heating and Cooling System[Heating and Cooling System], Housing by Heating and Cooling System\

[Heating and Cooling System])

~ tCO2 / Year / House

~ The average CO2 emissions for each house, by heating and cooling system.

|

Emissions by Heating and Cooling System[Heating and Cooling System]=

SUM(Emissions by Grouping[Cohort!,Heating and Cooling System,Retrofitting Status!])

~ tCO2 / Year

~ The total amount of emissions for houses by Heating and Cooling System.

|

Fraction of Houses in Each Heating and Cooling System[Heating and Cooling System]=

XIDZ(Housing by Heating and Cooling System[Heating and Cooling System], Total Housing Stock\

, :NA:)

~ dmnl

~ The fraction of houses using each heating and cooling system

|

Emissions=

SUM(Emissions by Grouping[Cohort!,Heating and Cooling System!,Retrofitting Status!])

~ tCO2 / Year

~ The total amount of emissions across all housing groups.

|

Average Emissions=

ZIDZ(Emissions, Total Housing Stock)

~ tCO2 / House / Year

~ The average CO2 emissions for a household, not disaggregated into any \

grouping.

|

Average Emissions by Grouping[Cohort, Heating and Cooling System, Retrofitting Status\

]=

Average Emissions from Cooling by Grouping[Cohort,Heating and Cooling System,Retrofitting Status\

] + Average Emissions from Heating by Grouping[Cohort,Heating and Cooling System,Retrofitting Status\

]

~ tCO2 / (Year \* House)

~ The total average emissions from heating and cooling, by cohort, \

retrofitting status, and Heating and Cooling System.

|

Cooling Emissions Factor=

614 / 3414.43

~ lb CO2 / kBTU

~ Amount of CO2 emitted from using one kBTU to cool a home. Emissions factor is \

common, and is for electricity.

Taken from: \

https://www.mass.gov/doc/2020-summary-massachusetts-ghg-emissions-reports-f\

or-retail-sellers-of-electricity/download

|

Heating Emissions Factors[Heat Pump Heating and Cooling]=

684 / 3414.43 ~~|

Heating Emissions Factors[Gas Heating]=

116.65/1000 ~~|

Heating Emissions Factors[Oil Heating]=

163.45/1000

~ lb CO2 / kBTU

~ The pounds of CO2 emitted per kBTU of heating energy provided, for each heating \

fuel.

Data for heat pumps (electricity) is: \

https://www.mass.gov/doc/2020-summary-massachusetts-ghg-emissions-reports-f\

or-retail-sellers-of-electricity/download

Rest is from: https://www.eia.gov/environment/emissions/co2\_vol\_mass.php

In line with that source, I assume that each heat pump will add to the \

grid and is not part of base demand, and so the marginal emissions from \

producing electricity from heat pumps will be constant at the value as it \

will come from natural gas generators (explanation of which is from here: \

https://willbrownsberger.com/how-green-will-the-power-be/

|

Average U Value of Houses Switching Into Sources[Heating and Cooling System]=

XIDZ(U Value Increase from Source Switching[Heating and Cooling System], Houses Switching Into Sources\

[Heating and Cooling System], :NA:)

~ kBTU / (sf \* F \* Year)

~ The average U value of houses switching into each source, for each source.

|

Average U Value by Heating and Cooling System[Heating and Cooling System]=

ZIDZ(Total U Value by Heating and Cooling System[Heating and Cooling System], Housing by Heating and Cooling System\

[Heating and Cooling System])

~ kBTU / (sf \* F \* Year)

~ The U value of the average house using each heating and cooling system.

|

Houses Switching Into Sources[Heating and Cooling System]=

SUM(Houses Switching Sources[Cohort!,Heating and Cooling System!,Retrofitting Status\

!,Heating and Cooling System])

~ Houses / Year

~ The number of houses switching into each Heating and Cooling System, \

cohort, and retrofitting group due to system switching.

|

Housing by Heating and Cooling System[Heating and Cooling System]=

SUM(Housing[Cohort!,Heating and Cooling System,Retrofitting Status!])

~ House

~ Number of houses by energy source across all cohorts.

|

U Value Increase from Source Switching[Heating and Cooling System]=

SUM(U Value Shift from Source Switching[Cohort!,Heating and Cooling System!,Heating and Cooling System\

,Retrofitting Status!])

~ kBTU\*House/(Year\*Year\*sf\*F)

~ The increase in total U value for each Heating and Cooling System from \

houses switching their heating and cooling systems.

|

Fractional Decrease in Code U=

0

~ 1 / Year [0,0.5,0.01]

~ Fractional decrease in code per year. Exogenous and set by policymakers in \

the real world. For initial paper, assume that code U is constant.

|

Heating Energy Use Under Alternatives[Cohort, Heat Pump Heating and Cooling, Not Open to Retrofitting\

, Heating and Cooling System]=

U Value by Grouping[Cohort,Heat Pump Heating and Cooling,Not Open to Retrofitting] \*\

Average Area[Cohort, Not Open to Retrofitting

] \* Heating Degree Days / Heating System Efficiency[Heating and Cooling System] ~~|

Heating Energy Use Under Alternatives[Cohort,Fossil Fuel Heating,Not Open to Retrofitting\

,Heating and Cooling System]=

U Value by Grouping[Cohort,Fossil Fuel Heating, Not Open to Retrofitting] \* Average Area\

[Cohort, Not Open to Retrofitting] \* Heating Degree Days / Heating System Efficiency\

[Heating and Cooling System] ~~|

Heating Energy Use Under Alternatives[Cohort,Heat Pump Heating and Cooling,Open to Retrofitting\

,Heating and Cooling System]=

MIN(U Value by Grouping[Cohort,Heat Pump Heating and Cooling,Open to Retrofitting], \

Optimal U Value for Existing Homes if no EEHIC Cap[Cohort,Heating and Cooling System\

]) \* Average Area[Cohort,Open to Retrofitting

] \* Heating Degree Days / Heating System Efficiency[Heating and Cooling System] ~~|

Heating Energy Use Under Alternatives[Cohort,Fossil Fuel Heating, Open to Retrofitting\

,Heating and Cooling System]=

MIN(U Value by Grouping[Cohort,Fossil Fuel Heating,Open to Retrofitting], Optimal U Value for Existing Homes if no EEHIC Cap\

[Cohort,Heating and Cooling System]) \* Average Area[Cohort,Open to Retrofitting

] \* Heating Degree Days / Heating System Efficiency[Heating and Cooling System]

~ kBTU / (House \* Year)

~ The heating energy use of each group, if they were to switch into another \

Heating and Cooling System. That is, when they switch, their area and U \

stays the same, but the energy system's efficiency may change, meaning \

that each grouping (the first "Heating and Cooling System" subscript) must \

consider their heating energy use under alternative systems (the second \

"Heating and Cooling System" subscript). Houses about to retrofit use the \

U value that they will retrofit too; using their current U-value that \

they'll retrofit away from is too short cited.

|

Total U Value by Heating and Cooling System[Heating and Cooling System]=

SUM(Total U Value[Cohort!,Heating and Cooling System,Retrofitting Status!])

~ House \* kBTU / (sf \* F \* Year)

~ The total U value by heating and cooling system

|

Optimal Energy Cost[Cohort, Heating and Cooling System, Retrofitting Status]=

Optimal Cooling Cost[Cohort,Heating and Cooling System,Retrofitting Status] + Optimal Heating Cost\

[Cohort,Heating and Cooling System,Retrofitting Status]

~ Dollar / (Year \* House)

~ Total energy cost if optimal U value is achieved.

|

Marginal Cooling Cost Reduction from Retrofitting[Cohort,Heating and Cooling System]=

Expected Cooling Energy Price \* Cooling Degree Days / Cooling System Efficiency[Heating and Cooling System\

]

~ Dollar \* F / (kBTU)

~ The marginal reduction in heating costs per square foot from retrofitting \

away one unit of U. Calculated as the derivative of total cooling energy \

costs with respect to U, where total cooling energy costs are Cooling \

Energy Price \* Cooling Energy Use Per Square Foot, and the latter is U \

value \* Area \* Cooling Temperature Differential (CDD) / Area.

|

Average Energy Use by Heating and Cooling System[Heating and Cooling System]=

ZIDZ(SUM(Energy Use by Grouping[Cohort!,Heating and Cooling System,Retrofitting Status\

!]), SUM(Housing[Cohort!,Heating and Cooling System,Retrofitting Status!]))

~ kBTU / (House \* Year)

~ The average energy use for each home by heating and cooling system.

|

System Switching SWITCH=

1

~ dmnl [0,1,1]

~ Switch for allowing houses to switch heating and cooling systems. If 1, \

they can switch.

|

Houses Switching Sources[Cohort, Heat Pump Heating and Cooling, Retrofitting Status, \

Heating and Cooling System]=

Fraction of Houses Switching[Cohort,Heat Pump Heating and Cooling, Retrofitting Status\

, Heating and Cooling System]\*

Houses Considering Switching System[Cohort,Heat Pump Heating and Cooling,Retrofitting Status\

] \* System Switching SWITCH ~~|

Houses Switching Sources[Cohort, Fossil Fuel Heating, Retrofitting Status , Heating and Cooling System\

]=

Fraction of Houses Switching[Cohort,Fossil Fuel Heating, Retrofitting Status ,Heating and Cooling System\

]\* Houses Considering Switching System

[Cohort,Fossil Fuel Heating,Retrofitting Status] \* System Switching SWITCH

~ House / Year

~ The number of houses switching Heating and Cooling Systems. The first \

heating and cooling system subscript is the system combination they're \

leaving, and the h & c system subscript is the combination they're \

entering.

|

Average EUI in All Housing=

Average Energy Use in All Housing / Average Area in All Housing

~ kBTU / (sf \* Year)

~ The average energy use intensity across all housing.

|

Energy Use by Grouping[Cohort,Heating and Cooling System,Retrofitting Status]=

Average Energy Use[Cohort,Heating and Cooling System,Retrofitting Status] \* Housing[\

Cohort,Heating and Cooling System,Retrofitting Status]

~ kBTU / Year

~ The total amount of energy used for heating and cooling in each group.

|

Average Energy Use in All Housing=

Total Energy Use / Total Housing Stock

~ kBTU / Year / House

~ The average energy use across all stocks.

|

Average EUI by Grouping[Cohort, Heating and Cooling System, Retrofitting Status]=

XIDZ(Average Energy Use[Cohort,Heating and Cooling System,Retrofitting Status], Average Area\

[Cohort,Retrofitting Status], :NA:)

~ kBTU / (sf \* Year)

~ The average energy use intensity by grouping

|

Total Energy Use=

SUM(Energy Use by Grouping[Cohort!,Heating and Cooling System!,Retrofitting Status!]\

)

~ kBTU / Year

~ The total energy use for all homes in the model.

|

Input 1=

1+STEP(Cooling Energy Price Step Height 1,INITIAL TIME + Step Time 1)+

(Energy Price Pulse Quantity 1/TIME STEP)\*PULSE(INITIAL TIME + Pulse Time 1,TIME STEP\

)+

RAMP(Energy Price Ramp Slope 1,INITIAL TIME + Ramp Start Time 1,INITIAL TIME + Ramp End Time 1\

)+(STEP(1, INITIAL TIME)\*(exp(Energy Price Exponential Growth Rate 1\*(Time - INITIAL TIME\

))-1))+

Sine Amplitude 1\*SIN(2\*3.14159\*(Time - INITIAL TIME)/Sine Period 1)+

STEP(1,INITIAL TIME + Noise Start Time 1)\*Autocorrelated Noise 1

~ Dimensionless

~ Input is a dimensionless variable which provides a variety of test input patterns, \

including a step,

pulse, sine wave, and random noise.

|

Autocorrelated Noise 1 = INTEG(Change in AC Noise 1,0)

~ Dimensionless

~ First-order autocorrelated noise. Provides a realistic noise input to models in \

which the next random shock depends in part on the previous shocks. The \

user can specify the correlation time. The mean is 0 and the standard \

deviation is specified

by the user.

|

Average Area[Cohort, Retrofitting Status]=

ZIDZ(Area[Cohort,Retrofitting Status], Housing by Cohort and Retrofitting Status[Cohort\

,Retrofitting Status])

~ sf / House

~ Average area by cohort and retrofitting status (assume it's the same \

across heating and cooling systems).

|

Average Cooling Cost[Cohort, Heating and Cooling System, Retrofitting Status]=

Expected Cooling Energy Price \* Average Cooling Energy Use[Cohort,Heating and Cooling System\

,Retrofitting Status]

~ Dollar / (Year \* House)

~ The average costs for keeping a home cool, by grouping.

|

Average Energy Cost[Cohort,Heating and Cooling System,Retrofitting Status]=

Average Cooling Cost[Cohort,Heating and Cooling System,Retrofitting Status] + Average Heating Cost\

[Cohort,Heating and Cooling System,Retrofitting Status]

~ Dollar / (Year \* House)

~ The average cost of both heating and cooling a home, by grouping.

|

Average Energy Use[Cohort, Heating and Cooling System, Retrofitting Status]=

Average Heating Energy Use[Cohort,Heating and Cooling System,Retrofitting Status] + \

Average Cooling Energy Use[Cohort,Heating and Cooling System,Retrofitting Status]

~ kBTU / (Year \* House)

~ Average energy use to both heat and cool a home.

|

Average Lifetime of Cooling Technology[Heat Pump Heating and Cooling]=

12.5 ~~|

Average Lifetime of Cooling Technology[Central AC Cooling]=

12.5 ~~|

Average Lifetime of Cooling Technology[Window AC Cooling]=

9 ~~|

Average Lifetime of Cooling Technology[No AC Cooling]=

:NA:

~ Years

~ The average lifetime of each cooling system.

Central AC data from: https://www.energy.gov/energysaver/central-air-conditioning

Window AC data from: \

https://www.consumerreports.org/air-conditioner/is-it-time-to-get-a-new-win\

dow-air-conditioner-a1532530762/

|

Noise Standard Deviation 1 = 0

~ Dimensionless

~ The standard deviation of the pink noise process.

|

Noise Start Time 1 = 5

~ Year

~ Start time for the random input.

|

Change in AC Noise 1 = (White Noise 1 - Autocorrelated Noise 1)/Noise Correlation Time 1

~ 1/Year

~ Change in the pink noise value; Pink noise is a first order exponential smoothing \

delay of the white

noise input.

|

Cooling Energy Price=

Initial Cooling Energy Price \* Input 1

~ Dollar / kBTU

~ Price of cooling a home (through air conditioning), subject to the test \

input.

|

Cooling Energy Price Step Height 1=

0

~ Dimensionless [0,2]

~ Height of step input to customer orders, as fraction of initial value.

|

Cooling Degree Days=

1029

~ F [426,426]

~ The difference between temperature setpoint (65 F) and outside temperature for \

heating. Typically called cooling degree days, but units are solely in \

terms of fahrenheit.

Data from degreedays.net, using the weather station for Norwood Memorial \

Airport, the closest weather station to the center of MA's population, \

Natick. Use set point of 65°F, in line with industry standard, as at that \

temperature little heating or cooling is necessary.

|

Optimal Heating Cost[Cohort, Heating and Cooling System, Retrofitting Status]=

Expected Heating Energy Price[Heating and Cooling System] \* Optimal Heating Energy Use\

[Cohort,Heating and Cooling System,Retrofitting Status]

~ Dollar / (Year \* House)

~ Average heating cost if U value is optimal.

|

Traditional Cooling:

Gas and Central AC, Gas and Window AC, Gas and No AC, Oil and Central AC, Oil and Window AC\

, Oil and No AC

~

~ |

U Value by Grouping[Cohort, Heating and Cooling System, Retrofitting Status]=

IF THEN ELSE(Housing[Cohort,Heating and Cooling System,Retrofitting Status] > 1e-12,\

Total U Value[Cohort,Heating and Cooling System,Retrofitting Status]/Housing[Cohort\

,Heating and Cooling System,Retrofitting Status], 0)

~ kBTU / (sf \* F \* Year)

~ The average U value in each home by cohort, heating/cooling system, etc.

|

Present Value of Operating Costs[Cohort,Heat Pump Heating and Cooling,Retrofitting Status\

,Heating and Cooling System]=

Present Value of Cooling Operating Costs[Cohort, Heat Pump Heating and Cooling,Retrofitting Status\

, Heating and Cooling System] + Present Value of Heating Operating Costs

[Cohort,Heat Pump Heating and Cooling,Retrofitting Status, Heating and Cooling System\

] ~~|

Present Value of Operating Costs[Cohort,Fossil Fuel Heating,Retrofitting Status,Heating and Cooling System\

]=

Present Value of Cooling Operating Costs[Cohort, Fossil Fuel Heating,Retrofitting Status\

, Heating and Cooling System] + Present Value of Heating Operating Costs

[Cohort, Fossil Fuel Heating,Retrofitting Status, Heating and Cooling System]

~ Dollar / (House) [0,?,1]

~ Operating costs of each heating and cooling technology, in the order: heat pump \

only, central AC, window AC (two units), no AC, gas, oil.

For window AC and no AC, this is includes the cost of the lack of comfort these \

technologies have. That is, it includes the amount of money that users of \

those technologies would pay each month to use central AC or heat pumps \

instead due to window ACs' noise or both technologies' inability to \

properly cool homes.

Rough data from:

Heat pump and central ac: https://carbonswitch.com/heat-pump-costs/

Window AC ( 70/year): https://applianceanalysts.com/window-ac-running-costs/

Gas: https://homeguide.com/costs/gas-furnace-prices

Oil: https://homeguide.com/costs/oil-furnace-cost

|

Energy Price Exponential Growth Rate 1=

0

~ 1/Year [-0.1,0.1,0.01]

~ The exogenous growth fraction for the test input.

|

Energy Price Pulse Quantity 1=

0

~ Dimensionless\*Year

~ Pulse value, as a fraction of the base value of Input.

For example, to pulse in a quantity equal to 50% of the current value of \

input, set to

.50.

|

Energy Price Ramp Slope 1=

0

~ 1/Year [-0.2,0.2,0.01]

~ Slope of the ramp input, as a fraction of the base value (per week).

|

Initial Cooling Energy Price=

0.062

~ Dollar / kBTU

~ The price to cool a home per BTU. This is the price of electricity as all \

cooling systems, as air conditioning systems, use electricity.

|

Heating Degree Days=

5026

~ F [6113,6113]

~ The difference between temperature setpoint (65 F) and outside temperature.

Data from degreedays.net, using the weather station for Norwood Memorial \

Airport, the closest weather station to the center of MA's population, \

Natick. In line with industry standard, use set point of 65°F, as \

that temperature little heating or cooling is needed.

|

Expected Cooling Energy Price=

SMOOTH3(Cooling Energy Price, Delay in Forming Expectations of Energy Price)

~ Dollar / kBTU

~ Energy price for one kBTU of cooling used to calculate optimal U value. \

Third order exponential smoothing of cooling energy price.

|

Retrofitting[Cohort,Heating and Cooling System]=

MAX(0, Housing[Cohort,Heating and Cooling System,Open to Retrofitting] \* (U Value by Grouping\

[Cohort,Heating and Cooling System

,Open to Retrofitting] - Optimal U Value for Existing Homes if no EEHIC Cap[Cohort,Heating and Cooling System\

]) / Retrofit Delay

)

~ House \* kBTU / (sf \* F\* Year) / Year

~ Energy use retrofitted away. If positive, this means that energy use is \

being retrofitted away.

|

Total Present Value of Cost[Cohort,Heat Pump Heating and Cooling,Retrofitting Status,\

Heating and Cooling System]=

Present Value of Operating Costs[Cohort,Heat Pump Heating and Cooling,Retrofitting Status\

,Heating and Cooling System] + Present Value Replacement Cost[Heating and Cooling System\

] + Cost of Bad Air Conditioning[Heating and Cooling System] ~~|

Total Present Value of Cost[Cohort, Fossil Fuel Heating,Retrofitting Status, Heating and Cooling System\

]=

Present Value of Operating Costs[Cohort,Fossil Fuel Heating,Retrofitting Status, Heating and Cooling System\

] + Present Value Replacement Cost[Heating and Cooling System] + Cost of Bad Air Conditioning\

[Heating and Cooling System]

~ Dollar / House

~ Total net present value of each heating and cooling combination. Assume \

that for systems with fossil fuel backups, the backup system is used so \

sparingly that its operating costs are negligible.

|

Optimal Energy Use[Cohort, Heating and Cooling System, Retrofitting Status]=

Optimal Cooling Energy Use[Cohort,Heating and Cooling System,Retrofitting Status] + \

Optimal Heating Energy Use[Cohort,Heating and Cooling System,Retrofitting Status]

~ kBTU / (House \* Year)

~ Average energy use to heat and cool per house if U is optimal.

|

Net Area Shift due to Retrofit Status Switching[Cohort]=

SUM(Net Area Shift by System[Cohort,Heating and Cooling System!])

~ sf / Year

~ Shift in area between energy sources due to houses switching sources.

|

Optimal Heating Energy Use[Cohort, Heating and Cooling System, Retrofitting Status]=

Optimal U Value for Existing Homes if no EEHIC Cap[Cohort,Heating and Cooling System\

] \* Average Area[Cohort,Retrofitting Status] \* Heating Degree Days / Heating System Efficiency\

[Heating and Cooling System]

~ kBTU / (House \* Year)

~ The energy used for heating, for the average household, if U is optimal. \

Calculated by setting efficiency times energy use equal to total heating \

temperature differential, multiplied by optimal U, and solving for energy \

use.

|

Sine Amplitude 1=0

~ Dimensionless

~ Amplitude of sine wave in customer orders (fraction of mean).

|

Sine Period 1=50

~ Year

~ Period of sine wave. Set initially to 50 weeks (1 year).

|

Step Time 1=

5

~ Year

~ Time for the step input.

|

Noise Correlation Time 1 = 4

~ Year

~ The correlation time constant for Pink Noise.

|

Pulse Time 1=5

~ Year

~ Time at which the pulse in Input occurs.

|

U Value Shift from Source Switching[Cohort, Heat Pump Heating and Cooling, Heating and Cooling System\

,Retrofitting Status]=

Houses Switching Sources[Cohort,Heat Pump Heating and Cooling, Retrofitting Status ,\

Heating and Cooling System] \* U Value by Grouping

[Cohort,Heat Pump Heating and Cooling,Retrofitting Status] ~~|

U Value Shift from Source Switching[Cohort,Fossil Fuel Heating,Heating and Cooling System\

,Retrofitting Status]=

Houses Switching Sources[Cohort,Fossil Fuel Heating, Retrofitting Status, Heating and Cooling System\

] \* U Value by Grouping

[Cohort,Fossil Fuel Heating,Retrofitting Status]

~ House \* kBTU / (Year \* F \* sf) / Year

~ The shift in total U value coming from switching sources.

|

Ramp Start Time 1=5

~ Year

~ Start time for the ramp input.

|

White Noise 1 = Noise Standard Deviation 1\*((24\*Noise Correlation Time 1/TIME STEP)^0.5\

\*(RANDOM 0 1() - 0.5

))

~ Dimensionless

~ White noise input to the pink noise process.

|

U Value of Retrofitting Homes[Cohort, Heating and Cooling System]=

U Value by Grouping[Cohort,Heating and Cooling System,Open to Retrofitting]

~ kBTU / (sf \* Year \* F)

~ The Average U Value of each home that is open to retrofitting.

|

Ramp End Time 1=1e+09

~ Year

~ End time for the ramp input.

|

Optimal Cooling Cost[Cohort,Heating and Cooling System,Retrofitting Status]=

Expected Cooling Energy Price \* Optimal Cooling Energy Use[Cohort,Heating and Cooling System\

,Retrofitting Status]

~ Dollar / (Year \* House)

~ The average cost of cooling, if homes have the optimal U value.

|

Net U Value Change from Retrofitting Home Shifts[Cohort,Heating and Cooling System]=

IF THEN ELSE(Net Change in Homes Retrofitting[Cohort,Heating and Cooling System] > 0\

, U Value by Grouping[Cohort,Heating and Cooling System

,Not Open to Retrofitting]\* Net Change in Homes Retrofitting[Cohort,Heating and Cooling System\

]

, U Value by Grouping[Cohort,Heating and Cooling System,Open to Retrofitting]\* Net Change in Homes Retrofitting\

[Cohort,

Heating and Cooling System])

~ House \* kBTU / (Year \* F \* sf) / Year

~ Net change in U value due to homes becoming open or not to retrofitting. \

If net change is positive, then homes are going from not being open to \

retrofitting to being open, meaning non-retrofitting homes' U value is \

flowing into the retrofitting homes' U value. If net change is negative, \

then houses becoming less likely to retrofit.

|

U Value Loss from Demolition[Cohort, Heating and Cooling System, Retrofitting Status]\

=

U Value by Grouping[Cohort,Heating and Cooling System,Retrofitting Status] \* Demolitions\

[Cohort,Heating and Cooling System

,Retrofitting Status]

~ House \* kBTU / (Year \* F \* sf) / Year

~ Homes' total energy use decrease from those homes being demolished.

|

Demolitions[Cohort,Heating and Cooling System,Retrofitting Status]=

Demolition Hazard Rate \* Housing[Cohort,Heating and Cooling System,Retrofitting Status\

] \* (1- No Turnover Switch)

~ House / Year

~ Homes that are destroyed every year.

|

Housing by Retrofitting Status[Retrofitting Status]=

SUM(Housing by Cohort and Retrofitting Status[Cohort!,Retrofitting Status])

~ House

~ Amount of housing by retrofitting status, across all cohorts and systems.

|

No Turnover Switch=

0

~ dmnl [0,1,1]

~ Switch for having no turnover in housing stock-- i.e., no housing \

demolitions or constructions.

|

Fraction Retrofitting=

Housing by Retrofitting Status[Open to Retrofitting] / (Housing by Retrofitting Status\

[Not Open to Retrofitting] + Housing by Retrofitting Status[Open to Retrofitting])

~ dmnl

~ Proportion of housing that is open to retrofitting, across all cohorts and \

systems.

|

Affinity of Heating and Cooling Systems[Cohort,Heat Pump Heating and Cooling,Retrofitting Status\

,Heating and Cooling System]=

IF THEN ELSE(Cost of Switching Heating and Cooling Systems[Cohort, Heat Pump Heating and Cooling\

, Retrofitting Status, Heating and Cooling System] <>

0,

exp(-Sensitivity of Affinity to Cost \* Cost of Switching Heating and Cooling Systems\

[Cohort,Heat Pump Heating and Cooling, Retrofitting Status, Heating and Cooling System\

] / Reference Lifetime Cost of Heating and Cooling Systems), 0) ~~|

Affinity of Heating and Cooling Systems[Cohort,Fossil Fuel Heating,Retrofitting Status\

,Heating and Cooling System]=

IF THEN ELSE(Cost of Switching Heating and Cooling Systems[Cohort,Fossil Fuel Heating\

, Retrofitting Status , Heating and Cooling System] <> 0, exp(-Sensitivity of Affinity to Cost

\* Cost of Switching Heating and Cooling Systems[Cohort,Fossil Fuel Heating, Retrofitting Status\

, Heating and Cooling System] / Reference Lifetime Cost of Heating and Cooling Systems

), 0)

~ dmnl

~ The affinity of switching from each heating and cooling combination to \

each other one. If the model assumes that no one switches from one \

combination to another, as indicated by zero in the cost variable, then \

the affinity is zero.

|

Oil and Window or No AC:

Oil and Window AC, Oil and No AC

~

~ |

Gas and Window or No AC:

Gas and Window AC, Gas and No AC

~

~ |

Window AC Cooling:

Gas and Window AC, Oil and Window AC

~

~ |

No AC Cooling:

Gas and No AC, Oil and No AC

~

~ |

Oil Heating:

Oil and Central AC, Oil and Window AC, Oil and No AC

~

~ |

Central AC Cooling:

Gas and Central AC, Oil and Central AC

~

~ |

Gas Heating:

Gas and Central AC, Gas and Window AC, Gas and No AC

~

~ |

Reference Lifetime Cost of Heating and Cooling Systems=

30000

~ Dollar / House [10000,30000]

~ The reference value of lifetime heating and cooling combinations when \

people calculate affinity of each combo. Hand calibrated to roughly match \

heat pump sales in \

https://www.masssave.com/en/about/news-and-events/news/mass-save-sponsors-a\

nnounce-record-number-of-heat-pump-installations-across-massachusetts

|

Heating:

Heat Pump, Gas, Oil

~

~ |

Discount Rate=

0.05

~ 1 / Year [0.03,0.11,0.01]

~ Discount rate for discounting energy savings cash flows.

Average and bounds from demand-side discount rate from MassDEP's analysis \

of pathways for net zero (pg. 103): \

https://www.mass.gov/doc/energy-pathways-for-deep-decarbonization-report/do\

wnloadhttps://www.mass.gov/doc/energy-pathways-for-deep-decarbonization-rep\

ort/download

|

Average Lifetime of Heating Technology[Heat Pump Heating and Cooling]=

12.5 ~~|

Average Lifetime of Heating Technology[Gas Heating]=

20 ~~|

Average Lifetime of Heating Technology[Oil Heating]=

20

~ Year

~ The average lifetime of each heating system.

Heat pump data from: https://glascohvac.com/heating/heat-pumps/long-heat-pump-last/

Gas data from: \

https://www.carrier.com/residential/en/us/products/furnaces/how-long-does-a\

-furnaces-last/

Oil data from: \

https://modernize.com/hvac/heating-repair-installation/furnace/oil

|

Sensitivity of Affinity to Cost=

10

~ dmnl [0,10,0.2]

~ Sensitivity of affinity to each heating and cooling combination having higher cost. \

The higher this, the fewer houses will convert to more expensive \

combinations.

Calculated by hand calibration-- value ensures that amount of heat pumps \

sold 2020 - 2024 begins at about 10K and goes to about 20K in 2024, in \

accordance with MassSave data from \

https://www.masssave.com/en/about/news-and-events/news/mass-save-sponsors-a\

nnounce-record-number-of-heat-pump-installations-across-massachusetts

|

Technology:

Heat Pump, Central AC, Window AC, No AC, Gas, Oil

~

~ The individual technologies used to heat or cool homes.

|

Total Initial Housing Starts=

0.5

~ Houses / Year [0,1000,0.5]

~ Total number of houses that are built per year, across all systems.

|

Total U Value by Cohort[Cohort]=

SUM(Total U Value[Cohort,Heating and Cooling System!,Retrofitting Status!])

~ House \* kBTU / (sf \* F \* Year)

~ Total U Value within each cohort.

|

Total U Value Across All Groupings=

SUM(Total U Value by Cohort[Cohort!])

~ House \* kBTU / (sf \* F \* Year)

~ Total U value across all groupings of households.

|

U Value Retrofitted Away= INTEG (

SUM(Retrofitting[Cohort!,Heating and Cooling System!]),

0)

~ House \* kBTU / (Year \* F \* sf)

~ Total amount of U value that has been retrofitted away.

|

Retrofitting Across Cohorts and Systems=

SUM(Retrofitting[Cohort!,Heating and Cooling System!])

~ House \* kBTU / ( Year \* Year \* sf \* F)

~ The total amount of retrofits across all cohorts and heating/cooling \

systems.

|

Houses Retrofitting[Cohort, Heating and Cooling System]=

Housing[Cohort, Heating and Cooling System, Open to Retrofitting]

~ Houses

~ Total amount of houses retrofitting in each cohort and heating and cooling \

system.

|

Indicated Homes Retrofitting[Cohort, Heating and Cooling System]=

Indicated Fraction of Homes Retrofitting[Cohort,Heating and Cooling System] \* Housing by Cohort and Heating and Cooling System\

[Cohort,Heating and Cooling System]

~ House

~ Number of homes that, once delays are taken into account, will be open to \

retrofitting.

|

Housing by Cohort and Heating and Cooling System[Cohort, Heating and Cooling System]=

SUM(Housing[Cohort,Heating and Cooling System,Retrofitting Status!])

~ Houses

~ Housing by heating and cooling system and cohort, irrespective of retrofit \

status.

|

Housing[Cohort,Heating and Cooling System,Not Open to Retrofitting]= INTEG (

Housing Starts[Cohort,Heating and Cooling System] -Net Change in Homes Retrofitting[\

Cohort,Heating and Cooling System]-

Demolitions[Cohort,Heating and Cooling System,Not Open to Retrofitting]+ SUM(Houses Switching Sources\

[Cohort, Heating and Cooling System

!, Not Open to Retrofitting , Heating and Cooling System]) - SUM(Houses Switching Sources\

[Cohort, Heating and Cooling System

, Not Open to Retrofitting , Heating and Cooling System!]),

Initial Homes Not Retrofitting[Cohort,Heating and Cooling System]) ~~|

Housing[Cohort,Heating and Cooling System,Open to Retrofitting]= INTEG (

Net Change in Homes Retrofitting[Cohort,Heating and Cooling System]-Demolitions[Cohort\

,Heating and Cooling System,Open to Retrofitting

] + SUM(Houses Switching Sources[Cohort, Heating and Cooling System!, Open to Retrofitting\

, Heating and Cooling System])

- SUM(Houses Switching Sources[Cohort, Heating and Cooling System, Open to Retrofitting\

, Heating and Cooling System!]),

Initial Homes Retrofitting[Cohort,Heating and Cooling System])

~ House

~ Houses, divided into those open to retrofitting (i.e., they will retrofit \

if their U is not equal to optimal) and those who are not.

|

Total U Value[Cohort,Heating and Cooling System,Not Open to Retrofitting]= INTEG (

Increase in U Value from Housing Starts[Cohort,Heating and Cooling System]-Net U Value Change from Retrofitting Home Shifts

[Cohort,Heating and Cooling System]

-U Value Loss from Demolition[Cohort,Heating and Cooling System,Not Open to Retrofitting\

] + SUM(U Value Shift from Source Switching

[Cohort, Heating and Cooling System!, Heating and Cooling System, Not Open to Retrofitting\

]) - SUM(U Value Shift from Source Switching

[Cohort, Heating and Cooling System, Heating and Cooling System!, Not Open to Retrofitting\

]),

Initial U Value[Cohort,Heating and Cooling System,Not Open to Retrofitting]) ~~|

Total U Value[Cohort,Heating and Cooling System,Open to Retrofitting]= INTEG (

Net U Value Change from Retrofitting Home Shifts[Cohort,Heating and Cooling System]-\

U Value Loss from Demolition[Cohort,Heating and Cooling System

,Open to Retrofitting] + SUM(U Value Shift from Source Switching[Cohort, Heating and Cooling System\

!, Heating and Cooling System

, Open to Retrofitting]) - SUM(U Value Shift from Source Switching[Cohort, Heating and Cooling System\

, Heating and Cooling System

!, Open to Retrofitting]) - Retrofitting[Cohort,Heating and Cooling System],

Initial U Value[Cohort,Heating and Cooling System,Open to Retrofitting])

~ House \* kBTU / (Year \* F \* sf) [0,?]

~ Total U-value of homes. Note that that is not a physical quantity, as the \

U-value of individual homes is not additive.

|

Indicated Fraction of Homes Retrofitting[Cohort, Heating and Cooling System]=

Affinity of Retrofitting[Cohort,Heating and Cooling System] / (Affinity of Retrofitting\

[Cohort,Heating and Cooling System] + Affinity of Not Retrofitting[Cohort,Heating and Cooling System\

])

~ dmnl

~ Proportion of households which are open to retrofitting to the optimum U. \

This is not necessarily all households, because the optimal U does not \

take into account fixed costs in retrofit costs, and so for a portion (or \

all) of them, retrofit costs > energy savings, and so not all (or any) \

households will retrofit. This also does not indicate households which are \

actively retrofitting, because if average U is already equal to optimum U \

then houses which are open to retrofitting have already retrofitted.

|

Total Cost of Ownership of Retrofitted Homes[Cohort, Heating and Cooling System]=

Amoritized Subsidized Retrofit Cost[Cohort,Heating and Cooling System] + Average Energy Costs if Retrofitted\

[Cohort, Heating and Cooling System]

~ Dollar / (House \* Year)

~ The total cost of ownership of owning a home that has been retrofitted to \

the optimal U.

|

Net Age Shift by System[Cohort, Heating and Cooling System]=

IF THEN ELSE(Net Change in Homes Retrofitting[Cohort,Heating and Cooling System] > 0\

, Average Age[Cohort,Not Open to Retrofitting] \* Net Change in Homes Retrofitting[Cohort\

,Heating and Cooling System], Average Age[Cohort, Open to Retrofitting] \* Net Change in Homes Retrofitting\

[Cohort,Heating and Cooling System])

~ Year \* House / Year

~ The shift in age from switching retrofit system, by cohort and by heating \

and cooling system.

|

Net Age Shift from Retrofitting Status Shifting[Cohort]=

SUM(Net Age Shift by System[Cohort,Heating and Cooling System!])

~ House \* Year / Year

~ Shift in age within each cohort due to houses becoming open or closed to \

retrofitting.

|

Fossil Fuel Heating:

Gas and Central AC, Gas and Window AC, Gas and No AC, Oil and Central AC, Oil and Window AC\

, Oil and No AC

~

~ |

Fraction Retrofitting by System and Cohort[Cohort, Heating and Cooling System]=

ZIDZ(Housing[Cohort,Heating and Cooling System,Open to Retrofitting], SUM(Housing[Cohort\

,Heating and Cooling System,Retrofitting Status!]))

~ dmnl

~ The fraction of houses that are retrofitting, by heating/cooling system \

and cohort.

|

Optimal U Across All Housing=

SUM(Optimal U Value for Existing Homes if no EEHIC Cap[Cohort!,Heating and Cooling System\

!] \* Housing[Cohort!,Heating and Cooling System!,Retrofitting Status!] / Total Housing Stock\

)

~ kBTU / (sf \* F \* Year)

~ The average optimal U value across all cohorts and all energy sources. \

Weigh optimal U by share of housing so that houses which haven't been \

built yet don't factor into the average.

|

Fraction Retrofitting by Cohort[Cohort]=

ZIDZ(SUM(Housing[Cohort,Heating and Cooling System!,Open to Retrofitting]), SUM(Housing\

[Cohort,Heating and Cooling System!,Retrofitting Status!]))

~ dmnl

~ Fraction that are retrofitting, only by cohort.

|

Initial Area[Cohort]=

10

~ sf

~ Total initial area across all houses, by cohort (assuming that average \

area is the same across systems). Determined by RECS 2020 data, current \

value is a placeholder.

|

Housing by Cohort and Retrofitting Status[Cohort, Retrofitting Status]=

SUM(Housing[Cohort,Heating and Cooling System!,Retrofitting Status])

~ House

~ Amount of housing by retrofit status and cohort.

|

Average Time To Consider Switching=

15

~ Year [1,30,1]

~ The average time it takes for a house to consider switching their heating \

and cooling system.

|

Houses Considering Switching System[Cohort, Heating and Cooling System, Retrofitting Status\

]=

Housing[Cohort,Heating and Cooling System,Retrofitting Status] / Average Time To Consider Switching

~ Houses / Year

~ The number of houses per year considering switching their heating and \

cooling system.

|

Net Change in Homes Retrofitting[Cohort,Heating and Cooling System]=

(Indicated Homes Retrofitting[Cohort,Heating and Cooling System] - Housing[Cohort,Heating and Cooling System\

,Open to Retrofitting]) / Time to Decide to Retrofit

~ Houses / Year

~ Homes that are in the process of deciding to retrofit.

|

Time to Decide to Retrofit=

3

~ Year [0.5,10,0.5]

~ Time to decide to retrofit.

|

Demolition Hazard Rate=

0.01

~ 1 / Year [0,1,0.01]

~ Proportion of homes demolished every year. Value is assumed to be equal \

across both retrofitting and non-retrofitting homes. Heuristically chosen \

so total housing stock grows at net 1%/year.

|

Retrofitting Status:

Not Open to Retrofitting, Open to Retrofitting

~

~ |

Retrofit Delay=

2

~ Year [0.0833,10,0.08333]

~ Time to retrofit. Assumed to be on average six months.

|

Total Initial Homes=

20

~ Houses [0,4e+06,100000]

~ Total number of houses, including those retrofitting or not. Number taken \

from Census's list of households in MA in 2022: \

https://www.census.gov/quickfacts/fact/table/MA/PST045222

|

Housing by Cohort[Cohort]=

SUM(Housing[Cohort,Heating and Cooling System!, Retrofitting Status!])

~ House

~ Number of houses per cohort

|

Affinity of Not Retrofitting[Cohort,Heating and Cooling System]=

exp(-Sensitivity of Retrofits to Cost \* Perceived Cost of Not Retrofitting[Cohort,Heating and Cooling System\

] / Reference Retrofit Cost)

~ dmnl

~ The affinity of not retrofitting; the utility or NPV of not retrofitting \

is just retrofit costs - energy costs saved.

|

Amoritization Period=

20

~ Year [5,30,1]

~ Time period over which incurred retrofit cost is amoritized; should be \

related to lifetime of a home.

|

Weight on Upfront Cost=

0.5

~ dmnl [0,1,0.05]

~ How much homeowners weigh upfront (amoritized) costs of retrofits as \

opposed to the total cost of ownership due to being more perceptive of \

short-term costs.

|

Perceived Cost of Not Retrofitting[Cohort,Heating and Cooling System]=

(1 - Weight on Upfront Cost) \* Total Cost of Ownership of Average Home[Cohort,Heating and Cooling System\

]

~ Dollar / (House \* Year)

~ Homeowners' perceived cost (or negation of the utility) for not \

retrofitting their home further, taking into homeowners weighupfront \

retrofit costs higher.

|

Total Cost of Ownership of Average Home[Cohort, Heating and Cooling System]=

Average Energy Costs for Retrofitting Home[Cohort,Heating and Cooling System]

~ Dollar / (Year \* House)

~ Total cost of ownership of a house without any further retrofit costs, \

i.e., at current energy use. Equivalent to energy costs because no \

retrofit costs are incurred.

|

Perceived Cost of Retrofitting[Cohort, Heating and Cooling System]=

(1 - Weight on Upfront Cost) \* Total Cost of Ownership of Retrofitted Homes[Cohort,Heating and Cooling System\

] + Weight on Upfront Cost \* Amoritized Subsidized Retrofit Cost[Cohort,Heating and Cooling System\

]

~ Dollar / (House \* Year)

~ Homeowners' perceived costs (or negation of their utility) for \

retrofitting their home, taking into account higher costs have less utilty \

and homeowners weigh upfront retrofit costs higher.

|

Reference Retrofit Cost=

8740

~ Dollar / (House \* Year) [500,20000,10]

~ Perceived cost of home heating to which households compare the perceived cost of \

retrofitting to when deciding to retrofit.

Taken from average retrofit cost in Less et al. (2021)'s dataset, shown on \

page 17: \

https://eta-publications.lbl.gov/sites/default/files/final\_walker\_-\_the\_cos\

t\_of\_decarbonization\_and\_energy.pdf

|

Sensitivity of Retrofits to Cost=

10

~ dmnl [0,100,1]

~ Sensitivity of affinity (and fraction of houses retrofitting) to NPV of \

retrofitting.

|

Retrofit Cost:

Existing Housing, New Housing

~

~ |

Heat Pump Heating and Cooling:

Heat Pump Only, Heat Pump and Gas, Heat Pump and Oil

~

~ Houses that use heat pumps as their primary source for both heating and \

cooling.

|

Heating and Cooling System:

Heat Pump Only, Heat Pump and Gas, Heat Pump and Oil, Gas and Central AC, Gas and Window AC\

, Gas and No AC, Oil and Central AC, Oil and Window AC, Oil and No AC

~

~ |

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

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\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*~

|

Code U= INTEG (

-Decrease in Code U,

Initial Code U Value)

~ kBTU / (sf \* Year \* F)

~ U of house that is built to standard code.

For initial paper, assume that it's constant at a level in between average \

U and optimal U.

|

Optimal U for New Homes[Cohort, Heating and Cooling System]=

((Expected Reference Marginal Cost / (Marginal Cost Reductions from Retrofitting[Cohort\

,Heating and Cooling System]/ Discount Rate

)) ^ (1/Sensitivity of Marginal Cost to U Value

)) \* Reference U Value \* (1 - Expected MassSave Proportional Subsidy Rate for Retrofits\

)

~ kBTU / (sf \* Year \* F)

~ The optimal U for houses being built, taking into account energy savings \

and construction costs. Calculated in a similar manner to the optimal U \

for existing homes.

|

Decrease in Code U=

Code U \* Fractional Decrease in Code U

~ kBTU / (sf \* Year \* F) / Year

~ The change in code U from policy.

|

U Value of Housing Starts[Cohort,Heating and Cooling System]=

IF THEN ELSE(Additional Cost of Building to U Value[Cohort,Heating and Cooling System\

] < 0 :AND: Optimal U for New Homes[Cohort,Heating and Cooling System] < Code U, Optimal U for New Homes\

[Cohort,Heating and Cooling System], Code U)

~ kBTU / (Year \* F \* sf)

~ Equal to optimal U Value if it is lower than code U value and it is \

cheaper to build to lower U value. Otherwise, developers just build to \

code.

|

Increase in U Value from Housing Starts[Cohort, Heating and Cooling System]=

Housing Starts[Cohort,Heating and Cooling System] \* U Value of Housing Starts[Cohort\

,Heating and Cooling System]

~ House \* kBTU / (Year \* F \* sf) / Year

~ New U value from new homes being built.

|

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

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\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*~

|

Cost of Switching Heating and Cooling Systems[Cohort, Heat Pump Only, Retrofitting Status\

, Heating and Cooling System] :EXCEPT: [Cohort, Heat Pump Only, Retrofitting Status\

, Heat Pump Only], [Cohort, Heat Pump Only, Retrofitting Status, Gas and Central AC\

], [Cohort, Heat Pump Only, Retrofitting Status, Oil and Central AC]=

0 ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Heat Pump Only, Retrofitting Status\

, Heat Pump Only]=

Total Present Value of Cost[Cohort,Heat Pump Only,Retrofitting Status,Heat Pump Only\

] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Heat Pump Only, Retrofitting Status\

, Gas and Central AC]=

Total Present Value of Cost[Cohort,Heat Pump Only,Retrofitting Status,Gas and Central AC\

]+ Cost of Cooling System Replacement[Gas and Central AC] + Cost of Heating System Replacement\

[Gas and Central AC] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Heat Pump and Gas, Retrofitting Status\

, Heating and Cooling System] :EXCEPT: [Cohort, Heat Pump and Gas, Retrofitting Status\

, Heat Pump Only], [Cohort, Heat Pump and Gas, Retrofitting Status, Heat Pump and Gas

], [Cohort, Heat Pump and Gas, Retrofitting Status, Gas and Central AC]=

0 ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Heat Pump and Gas, Retrofitting Status\

, Heat Pump and Gas]=

Total Present Value of Cost[Cohort, Heat Pump and Gas, Retrofitting Status, Heat Pump and Gas\

] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Heat Pump and Gas, Retrofitting Status\

, Gas and Central AC]=

Total Present Value of Cost[Cohort, Heat Pump and Gas, Retrofitting Status, Gas and Central AC\

] + Cost of Cooling System Replacement[Gas and Central AC] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Gas and Central AC, Retrofitting Status\

, Heating and Cooling System] :EXCEPT: [Cohort, Gas and Central AC, Retrofitting Status\

, Heat Pump Only], [Cohort, Gas and Central AC, Retrofitting Status, Heat Pump and Gas\

], [Cohort, Gas and Central AC, Retrofitting Status, Gas and Central AC]=

0 ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Gas and Central AC, Retrofitting Status\

, Heat Pump Only]=

Total Present Value of Cost[Cohort, Gas and Central AC, Retrofitting Status, Heat Pump Only\

] + Cost of Heating System Replacement[Heat Pump Only] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Gas and Central AC, Retrofitting Status\

, Heat Pump and Gas]=

Cost of Heating System Replacement[Heat Pump and Gas] + Total Present Value of Cost[\

Cohort, Gas and Central AC, Retrofitting Status, Heat Pump and Gas] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Gas and Central AC, Retrofitting Status\

, Gas and Central AC]=

Total Present Value of Cost[Cohort, Gas and Central AC, Retrofitting Status, Gas and Central AC\

] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Gas and Window or No AC, Retrofitting Status\

, Heating and Cooling System] :EXCEPT: [Cohort, Gas and Window or No AC, Retrofitting Status\

, Heat Pump Only], [Cohort, Gas and Window or No AC, Retrofitting Status, Heat Pump and Gas\

], [Cohort, Gas and Window or No AC, Retrofitting Status, Gas and Central AC]=

0 ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Gas and Window or No AC, Retrofitting Status\

, Heat Pump Only]=

Cost of Heating System Replacement[Heat Pump Only] + Total Present Value of Cost[Cohort\

, Gas and Window or No AC, Retrofitting Status, Heat Pump Only] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Gas and Window or No AC, Retrofitting Status\

, Heat Pump and Gas]=

Cost of Heating System Replacement[Heat Pump Only] + Total Present Value of Cost[Cohort\

, Gas and Window or No AC, Retrofitting Status, Heat Pump and Gas] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Gas and Window or No AC, Retrofitting Status\

, Gas and Central AC]=

Cost of Cooling System Replacement[Gas and Central AC] + Total Present Value of Cost\

[Cohort, Gas and Window or No AC, Retrofitting Status, Gas and Central AC] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Heat Pump and Gas, Retrofitting Status\

, Heat Pump Only]=

Total Present Value of Cost[Cohort, Heat Pump and Gas, Retrofitting Status, Heat Pump Only\

] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Heat Pump Only, Retrofitting Status\

, Oil and Central AC]=

Cost of Heating System Replacement[Oil and Central AC] + Cost of Cooling System Replacement\

[Oil and Central AC] + Total Present Value of Cost[

Cohort, Heat Pump Only, Retrofitting Status, Oil and Central AC] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Oil and Central AC, Retrofitting Status\

, Heating and Cooling System] :EXCEPT: [Cohort, Oil and Central AC, Retrofitting Status\

, Heat Pump Only], [Cohort, Oil and Central AC, Retrofitting Status, Gas and Central AC\

], [Cohort, Oil and Central AC, Retrofitting Status, Heat Pump and Oil], [Cohort, Oil and Central AC\

, Retrofitting Status, Oil and Central AC]=

0 ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Oil and Central AC, Retrofitting Status\

, Heat Pump Only]=

Cost of Heating System Replacement[Heat Pump Only] + Total Present Value of Cost[Cohort\

, Oil and Central AC, Retrofitting Status, Heat Pump Only] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Oil and Central AC, Retrofitting Status\

, Gas and Central AC]=

Cost of Heating System Replacement[Gas and Central AC] + Total Present Value of Cost\

[Cohort, Oil and Central AC, Retrofitting Status, Gas and Central AC] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Oil and Central AC, Retrofitting Status\

, Heat Pump and Oil]=

Cost of Heating System Replacement[Heat Pump and Oil] + Total Present Value of Cost[\

Cohort, Oil and Central AC, Retrofitting Status, Heat Pump and Oil] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Oil and Central AC, Retrofitting Status\

, Oil and Central AC]=

Total Present Value of Cost[Cohort, Oil and Central AC, Retrofitting Status, Oil and Central AC\

] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Oil and Window or No AC, Retrofitting Status\

, Heating and Cooling System] :EXCEPT: [Cohort,Oil and Window or No AC, Retrofitting Status\

, Heat Pump Only], [Cohort, Oil and Window or No AC, Retrofitting Status, Gas and Central AC\

], [Cohort

, Oil and Window or No AC, Retrofitting Status, Heat Pump and Oil], [Cohort, Oil and Window or No AC

, Retrofitting Status, Oil and Central AC]=

0 ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Oil and Window or No AC, Retrofitting Status\

, Heat Pump Only]=

Cost of Heating System Replacement[Heat Pump Only] + Total Present Value of Cost[Cohort\

, Oil and Window or No AC, Retrofitting Status, Heat Pump Only] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Oil and Window or No AC, Retrofitting Status\

, Gas and Central AC]=

Cost of Heating System Replacement[Gas and Central AC] + Cost of Cooling System Replacement\

[Gas and Central AC] + Total Present Value of Cost[

Cohort, Oil and Window or No AC, Retrofitting Status, Gas and Central AC] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Oil and Window or No AC, Retrofitting Status\

, Heat Pump and Oil]=

Cost of Heating System Replacement[Heat Pump and Oil] + Total Present Value of Cost[\

Cohort, Oil and Window or No AC, Retrofitting Status, Heat Pump and Oil] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Oil and Window or No AC, Retrofitting Status\

, Oil and Central AC]=

Cost of Cooling System Replacement[Oil and Central AC] + Total Present Value of Cost\

[Cohort, Oil and Window or No AC, Retrofitting Status, Oil and Central AC] ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Heat Pump and Oil, Retrofitting Status\

, Heating and Cooling System] :EXCEPT: [Cohort, Heat Pump and Oil

, Retrofitting Status, Heat Pump Only], [Cohort,Heat Pump and Oil, Retrofitting Status\

, Heat Pump and Gas], [Cohort,Heat Pump and Oil

, Retrofitting Status, Oil and Central AC], [Cohort, Heat Pump and Oil, Retrofitting Status\

, Heat Pump and Oil]=

0 ~~|

Cost of Switching Heating and Cooling Systems[Cohort, Heat Pump and Oil, Retrofitting Status\

, Heat Pump Only]=

Total Present Value of Cost[Cohort,Heat Pump Only, Retrofitting Status, Heat Pump Only\

] ~~|

Cost of Switching Heating and Cooling Systems[Cohort,Heat Pump and Oil, Retrofitting Status\

, Heat Pump and Gas]=

Cost of Heating System Replacement[Gas and Central AC] + Total Present Value of Cost\

[Cohort,Heat Pump and Oil, Retrofitting Status, Heat Pump and Gas] ~~|

Cost of Switching Heating and Cooling Systems[Cohort,Heat Pump and Oil, Retrofitting Status\

, Oil and Central AC]=

Cost of Cooling System Replacement[Oil and Central AC] + Total Present Value of Cost\

[Cohort,Heat Pump and Oil, Retrofitting Status, Oil and Central AC] ~~|

Cost of Switching Heating and Cooling Systems[Cohort,Heat Pump and Oil, Retrofitting Status\

, Heat Pump and Oil]=

Total Present Value of Cost[Cohort,Heat Pump and Oil, Retrofitting Status, Heat Pump and Oil\

]

~ Dollar / House

~ Affinities of each heating and cooling combination based on which heating \

and cooling combination houses have. This the numerator of a logit \

function. Assumes that retirement of systems is not determined by age, and \

so homes considering to switch heating systems do not have to replace \

their current one-- but they do have to purchase a system they currently \

do not have. The cost is determined by present cost of operating (i.e., \

opeating a system for infinite horizon, as it's included in sale price), \

in addition to current replacement costs if house does not have a system \

they're switching into. Any switches we assume are not possible we list as \

being 0.

|

Initial U Value[Cohort,Heating and Cooling System,Retrofitting Status] :EXCEPT: \

[Preexisting Cohorts,

Heating and Cooling System, Retrofitting Status

]=

0 ~~|

Initial U Value[Preexisting Cohorts,Heating and Cooling System,Retrofitting Status]=

Initial Average U Value[Preexisting Cohorts] \* Housing[Preexisting Cohorts,Heating and Cooling System

, Retrofitting Status]

~ House \* kBTU / (Year \* F \* sf)

~ Initial U value of cohorts; must be zero for cohorts not yet built.

|

Additional Cost of Building to U Value[Cohort,Heating and Cooling System]=

((1 - Expected MassSave Proportional Subsidy Rate for Retrofits) \* Expected Reference Marginal Cost\

/ (1 - Sensitivity of Marginal Cost to U Value

) )\*

(((Reference U Value / Code U) ^ Sensitivity of Marginal Cost to U Value) \* Code U \

-

((Reference U Value / Optimal U for New Homes[Cohort,Heating and Cooling System]) ^ \

(Sensitivity of Marginal Cost to U Value)) \* Optimal U for New Homes[Cohort,Heating and Cooling System\

]) -Expected Lump Sum Subsidy Intensity[New Housing]

~ Dollar / sf

~ Assuming optimal U is lower than code U, additional cost of building to \

optimal U instead of code u. If this cost is negative and optimal U < code \

U, then building to optimal U is cheaper than building to code. Lump sum \

subsidies are assumed to only apply to houses that are built to be more \

energy efficient than code. Calculated using the same method as \

unsubsidized retrofit costs.

|

Amoritized Subsidized Retrofit Cost[Cohort, Heating and Cooling System]=

Subsidized Retrofit Cost[Cohort,Heating and Cooling System] / Amoritization Period

~ Dollar / (House \* Year)

~ The incurred total retrofit cost amoritized over the specified \

amoritization period.

|

Expected Lump Sum Subsidy Intensity[Retrofit Cost]=

HOMES Expected Lower Lump Sum Subsidy / Average Area of Housing Starts

~ Dollar / sf

~ Lump sum subsidy for retrofits per square foot.

|

Expected MassSave Proportional Subsidy Rate for Retrofits=

SMOOTH3(Implemented MassSave Subsidy Proportional Rate for Retrofits, Delay in Changing Subsidy Expectations\

) \* Proportional Subsidy Switch for Retrofits

~ dmnl

~ Expected proportional subsidy rate that lowers subsidized retrofit costs, \

taking into account information delays.

|

HOMES Implemented Lower Subsidy=

IF THEN ELSE(Time >= HOMES Subsidy Implementation Year :AND: Time <= HOMES Subsidy Final Year\

, HOMES Lower Subsidy Amount, 0)

~ Dollar / House

~ Lump sum subsidy that is actually implemented. Equal to zero before \

implementation year and to lump sum subsidy after implementation year.

|

HOMES Expected Lower Lump Sum Subsidy=

SMOOTH3(HOMES Implemented Lower Subsidy, Delay in Changing Subsidy Expectations)

~ Dollar / House

~ Expected lump sum subsidy that lowers subsidized retrofit costs, taking \

into account information delays.

|

Subsidized Retrofit Cost[Cohort,Heating and Cooling System]=

Unsubsidized Retrofit Cost[Cohort, Heating and Cooling System] - Expected Subsidy for Retrofits\

[Cohort,Heating and Cooling System

,Open to Retrofitting] + Soft Costs of Retrofitting

~ Dollar /House

~ The total retrofit cost, net of any subsidies for existing homes. Hassle \

costs are added here because subsidies cannot subsidize those directly.

|

MassSave Expected Subsidy for Retrofits[Cohort,Heating and Cooling System,Retrofitting Status\

]=

MIN(Proportional Subsidy Switch for Retrofits \* Expected MassSave Proportional Subsidy Rate for Retrofits\

\* Unsubsidized Retrofit Cost Intensity[Cohort,

Heating and Cooling System] \* Average Area[Cohort,Retrofitting Status], Expected MassSave Maximum Subsidy for Retrofits

)

~ Dollar / House

~ The proportional subsidy offered against the retrofit cost intensity from \

MassSave, taking into account whether it has gone into effect.

|

Expected Subsidy for Retrofits[Cohort,Heating and Cooling System,Retrofitting Status]\

=

IF THEN ELSE(Energy Savings[Cohort,Heating and Cooling System] >= HOMES Cut Off for Savings\

, HOMES Expected Higher Subsidy, HOMES Expected Lower Lump Sum Subsidy) + MassSave Expected Subsidy for Retrofits\

[Cohort,Heating and Cooling System,Retrofitting Status] + EEHIC Expected Subsidy for Retrofits\

[Cohort,Heating and Cooling System,Retrofitting Status]

~ Dollar / House

~ Total subsidy offered against retrofit cost across both lump sum and \

proportional subsidy.

|

Implemented MassSave Maximum Subsidy for Retrofits=

IF THEN ELSE(Time >= Proportional MassSave Subsidy Implementation Year for Retrofits\

:AND: Time <= MassSave Subsidy for Retrofits Final Year, MassSave Maximum Subsidy for Retrofits

, 0)

~ Dollar / House

~ Maximum proportional subsidy that is actually implemented. Equal to zero \

before implementation year and to maximum proportional subsidy after \

implementation year.

|

Implemented MassSave Subsidy Proportional Rate for Retrofits=

IF THEN ELSE(Time >= Proportional MassSave Subsidy Implementation Year for Retrofits\

:AND: MassSave Subsidy for Retrofits Final Year >= Time, Mass Save Proportional Subsidy Rate for Retrofits

, 0)

~ dmnl

~ The implemented proportional subsidy rate from the state, taking into \

account whether a proportional subsidy has been implemented. Equal to zero \

before implementation year and proportional subsidy discount afterwards.

|

Marginal Cost Reductions from Retrofitting[Cohort, Heating and Cooling System]=

Marginal Cooling Cost Reduction from Retrofitting[Cohort,Heating and Cooling System]\

+ Marginal Heating Cost Reduction from Retrofitting[Cohort,Heating and Cooling System\

]

~ Dollar \* F / kBTU

~ Total cost reductions from retrofitting away one unit of U value for \

existing homes, including reductions in both heating and cooling costs.

|

Average Energy Costs for Retrofitting Home[Cohort, Heating and Cooling System]=

Average Energy Cost[Cohort,Heating and Cooling System,Open to Retrofitting]

~ Dollar / Year / House

~ Heating costs for each home open to retrofitting, annually, if no further \

retrofit measures are undertaken.

|

Expected Heating Energy Price[Heating and Cooling System]=

SMOOTH3(Heating Energy Price[Heating and Cooling System], Delay in Forming Expectations of Energy Price\

)

~ Dollar / kBTU

~ Energy price for one kBTU of heating used to calculate optimal U value. \

Third order exponential smoothing of heating energy price.

|

HOMES Lower Subsidy Amount=

2000

~ Dollar / House [0,8000,1]

~ The lump sum subsidy given for retrofits that save less than 35% of their energy \

from the Home Owner Managing Energy Savings tax credit.

Source: \

https://www.nrdc.org/bio/lauren-urbanek/theres-no-better-time-consider-home\

-energy-upgrades#: \

:text=The%20HOMES%20Rebate%20Program%20provides,or%20from%20measured%20ener\

gy%20savings.

|

Mass Save Proportional Subsidy Rate for Retrofits=

0.75

~ dmnl [0,1,0.05]

~ Proportion of total retrofit cost that will be credited as part of a proportional \

subsidy. Theoretically, this can vary between current housing and housing \

under construction.

Based off Mass Save data: \

https://www.masssave.com/en/residential/rebates-and-incentives/insulation-a\

nd-windows/insulation-and-air-sealing

|

Expected Fixed Cost=

SMOOTH(Fixed Cost, Delay in Forming Expectations of Retrofit Costs)

~ Dollar / House

~ Fixed cost used in calculating optimal EUI. Third order exponential \

smoothing of fixed cost.

|

Proportional Subsidy Switch for Retrofits=

1

~ dmnl [0,1,1]

~ Turns proportional subsidy's effect on retrofit cost on/off.

|

Expected MassSave Maximum Subsidy for Retrofits=

SMOOTH3(Implemented MassSave Maximum Subsidy for Retrofits, Delay in Changing Subsidy Expectations\

)

~ Dollar / House

~ Expected maximum proportional subsidy that lowers subsidized retrofit \

costs, taking into account information delays.

|

Delay in Forming Expectations of Energy Price=

1

~ Year [0,?]

~ Delay in perceiving changes in energy price.

|

Delay in Forming Expectations of Retrofit Costs=

1.5

~ Year [0,?]

~ Delay in perceiving changes in fixed retrofit cost and reference marginal \

cost. Assumed to be the same for both types of costs.

|

Expected Reference Marginal Cost=

SMOOTH(Reference Marginal Cost, Delay in Forming Expectations of Retrofit Costs)

~ (Dollar / sf) / (kBTU / (sf \* Year \* F))

~ Reference marginal cost used in calculating optimal U value. Third order \

exponential smoothing of reference marginal cost.

|

Delay in Changing Subsidy Expectations=

0.5

~ Year [0,?]

~ Delay in perceiving any changes to subsidies. Assumed to be the same for \

both subsidies.

|

HOMES Subsidy Implementation Year=

2025

~ Year [2010,2050,1]

~ The year in which the lump sum subsidy will activate.

|

MassSave Maximum Subsidy for Retrofits=

1e+07

~ Dollar / House [0,?]

~ The maximum proportional subsidy that will be offered, regardless of that subsidy's \

discount. For instance, if the proportional subsidy is 50% but the maximum \

is $1000, then for a retrofit project that costs $3000 only a $1000 \

subsidy will be given.

If very large, then no maximum subsidy given.

|

Proportional MassSave Subsidy Implementation Year for Retrofits=

2020

~ Year [2010,2050]

~ Time at which the proportional subsidy will take effect.

|

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.recovered housingagingchain v9

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|

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

.housingagingchain v9

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*~

|

Reference U Value=

0.006

~ kBTU / (sf \* Year \* F) [0.001,0.01,0.001]

~ Reference U Value to ensure base of exponent in marginally optimal U value is \

dimensionless. This must be equal to or greater than code U value.

Value taken as the average of U values of single family homes in MA in \

2020 for our sample.

|

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*

.housingagingchain v8

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*~

|

Area[Cohort,Not Open to Retrofitting] :EXCEPT: [Preexisting Cohorts\

, Not Open to Retrofitting]= INTEG (

Area of New Homes[Cohort] - Net Area Shift due to Retrofit Status Switching[Cohort]\

- Area Removal[Cohort,Not Open to Retrofitting],

Initial Area[Cohort] \* (1- Fraction Retrofitting by Cohort[Cohort])) ~~|

Area[Preexisting Cohorts,Not Open to Retrofitting]= INTEG (

-Net Area Shift due to Retrofit Status Switching[Preexisting Cohorts] - Area Removal\

[Preexisting Cohorts,Not Open to Retrofitting],

Initial Area[Preexisting Cohorts] \* (1 - Fraction Retrofitting by Cohort[Preexisting Cohorts\

])) ~~|

Area[Cohort, Open to Retrofitting] :EXCEPT: [Preexisting Cohorts, Open to Retrofitting\

]= INTEG (

Net Area Shift due to Retrofit Status Switching[Cohort] -Area Removal[Cohort, Open to Retrofitting\

],

Initial Area[Cohort] \* Fraction Retrofitting by Cohort[Cohort]) ~~|

Area[Preexisting Cohorts,Open to Retrofitting]= INTEG (

Net Area Shift due to Retrofit Status Switching[Preexisting Cohorts]-Area Removal[Preexisting Cohorts\

,Open to Retrofitting],

Initial Area[Preexisting Cohorts]\* Fraction Retrofitting by Cohort[Preexisting Cohorts\

])

~ sf

~ "Total" Area for each cohort of housing . This is determined by the \

inflows and outflows into and out of each cohort, multiplied by the \

average energy use intensity in each cohort.

|

Active Cohort Indicator[Cohort] :EXCEPT: [Preexisting Cohorts]=

IF THEN ELSE(INTEGER((Time - INITIAL TIME)/Cohort Duration)+1 = Cohort - ELMCOUNT(Preexisting Cohorts\

), 1 , 0 ) ~~|

Active Cohort Indicator[Preexisting Cohorts]=

0

~ dmnl

~ The model tracks housing by age, with a cohort representing all housing \

built between years t0 to t0+D, where t0 is the initial time and D is the \

width of each cohort (Cohort Duration). If Cohort Duration is 5 years, \

then the first cohort C1 accumulates all new housing built from t0 to \

t0+D, the second cohort, C2, accumulates all new housing built from t0+D \

to t0+2D, and the ith cohort accumulates all new housing built from t0 + \

iD to t0 + (i+1)D. Note that the INTEGER function rounds (t - t0)/D down, \

which requires adding 1 to activate the cohort with number corresponding \

to the value-if-true in the IF THEN ELSE function.

|

Initial Age[Cohort, Retrofitting Status] :EXCEPT: [Preexisting Cohorts, Retrofitting Status\

]= INITIAL(

0) ~~|

Initial Age[Preexisting Cohorts, Retrofitting Status]=

(Cohort Duration \* (ELMCOUNT(Preexisting Cohorts) - Preexisting Cohorts + 1)) \* Housing by Cohort and Retrofitting Status\

[Preexisting Cohorts,Retrofitting Status]

~ House \* Year

~ The initial age of each cohort. For cohorts built during the model's run, \

this is zero. For each pre-existing cohort, this is the length of each \

cohort multiplied by how many cohorts separate the pre-existing cohort \

from the beginning of the model. For example, if there are two \

pre-existing cohorts each with length 5, the first cohort at the beginning \

of the run is already ten years old on average.

|

Average Area in All Housing=

ZIDZ(Total Area, Total Housing Stock)

~ sf/ House

~ The average are of all houses, regardless of what group they're in.

|

Area of New Homes[Cohort]=

Average Area of Housing Starts \* SUM(Housing Starts[Cohort,Heating and Cooling System\

!])

~ sf / Year

~ The total Area added by the construction of new homes, by cohort.

|

Preexisting Cohorts:

Before 1950, From 1950 to 1959, From 1960 to 1969, From 1970 to 1979, From 1980 to 1989\

, From 1990 to 1999, From 2000 to 2009, From 2010 to 2020

~

~ |

Area Removal[Cohort,Retrofitting Status]=

Average Area[Cohort,Retrofitting Status] \* SUM(Demolitions[Cohort,Heating and Cooling System\

!,Retrofitting Status])

~ sf /Year

~ Total area lost as houses are destroyed, scrapped, etc.

|

Net Area Shift by System[Cohort,Heating and Cooling System]=

IF THEN ELSE(Net Change in Homes Retrofitting[Cohort,Heating and Cooling System] > 0\

, Average Area[Cohort,Not Open to Retrofitting

] \* Net Change in Homes Retrofitting[Cohort,Heating and Cooling System], Average Area\

[Cohort,Open to Retrofitting] \* Net Change in Homes Retrofitting

[Cohort,Heating and Cooling System])

~ sf / Year

~ The shift in area from switching retrofit status, by heating and cooling \

system in addition to cohort.

|

Average Energy Costs if Retrofitted[Cohort, Heating and Cooling System]=

Optimal Energy Cost[Cohort,Heating and Cooling System,Open to Retrofitting]

~ Dollar/(Year\*House)

~ Energy costs per year for each retrofitting house if homes retrofit to the \

optimal U value.

|

Unsubsidized Retrofit Cost[Cohort, Heating and Cooling System]=

Unsubsidized Retrofit Cost Intensity[Cohort,Heating and Cooling System] \* Average Area\

[Cohort,Open to Retrofitting]

~ Dollar / House

~ Total retrofit cost without taking into account subsidies.

|

Age Removal[Cohort, Retrofitting Status]=

SUM(Demolitions[Cohort,Heating and Cooling System!,Retrofitting Status]) \* Average Age\

[Cohort,Retrofitting Status]

~ House \* Year /Year

~ Total age lost as houses are destroyed, scrapped, etc.

|

Aging[Cohort,Retrofitting Status]=

Aging per Year \* SUM(Housing[Cohort,Heating and Cooling System!,Retrofitting Status]\

)

~ House \* Year / Year

~ Amount of years added to the housing stocks' total age per year. Because \

houses age 1 year per year, this is simply 1 multplied by the number of \

houses per cohort.

|

Total Age[Cohort, Not Open to Retrofitting]= INTEG (

Aging[Cohort, Not Open to Retrofitting]- Net Age Shift from Retrofitting Status Shifting\

[Cohort]- Age Removal[Cohort,Not Open to Retrofitting],

Initial Age[Cohort,Not Open to Retrofitting]) ~~|

Total Age[Cohort,Open to Retrofitting]= INTEG (

Net Age Shift from Retrofitting Status Shifting[Cohort]+Aging[Cohort, Open to Retrofitting\

]-Age Removal[Cohort,Open to Retrofitting],

Initial Age[Cohort,Open to Retrofitting])

~ House \* Year

~ "Total" age for each cohort of housing.

|

Average Age[Cohort, Retrofitting Status]=

ZIDZ(Total Age[Cohort,Retrofitting Status], Housing by Cohort and Retrofitting Status\

[Cohort,Retrofitting Status])

~ Year

~ The age per house in each cohort and energy source. Assumes that age is \

constant across heating and cooling systems within each cohort and \

retrofitting status.

|

Average Age in All Housing=

ZIDZ(SUM(Total Age[Cohort!,Retrofitting Status!]), Total Housing Stock)

~ Year

~ Average age of houses, regardless of cohort

|

Energy Price Exponential Growth Rate=

0

~ 1/Year [-0.1,0.1,0.01]

~ The exogenous growth fraction for the test input.

|

Aging per Year=

1

~ Year / Year

~ Number of years a house ages per year (which must be one), used to ensure \

dimensional consistency and make the model clearer

|

Autocorrelated Noise 0 = INTEG(Change in AC Noise 0,0)

~ Dimensionless

~ First-order autocorrelated noise. Provides a realistic noise input to models in \

which the next random shock depends in part on the previous shocks. The \

user can specify the correlation time. The mean is 0 and the standard \

deviation is specified

by the user.

|

Sine Period 0=50

~ Year

~ Period of sine wave in customer demand. Set initially to 50 weeks (1 \

year).

|

Energy Price Ramp Slope=

0

~ 1/Year [-0.2,0.2,0.01]

~ Slope of the ramp input, as a fraction of the base value (per week).

|

Energy Price Step Height=

0

~ Dimensionless [0,2]

~ Height of step input to customer orders, as fraction of initial value.

|

Pulse Time 0=5

~ Year

~ Time at which the pulse in Input occurs.

|

Change in AC Noise 0 = (White Noise 0 - Autocorrelated Noise 0)/Noise Correlation Time 0

~ 1/Year

~ Change in the pink noise value; Pink noise is a first order exponential smoothing \

delay of the white

noise input.

|

Noise Standard Deviation 0 = 0

~ Dimensionless

~ The standard deviation of the pink noise process.

|

Noise Start Time 0 = 5

~ Year

~ Start time for the random input.

|

Input 0=

1+STEP(Energy Price Step Height,INITIAL TIME + Step Time 0)+

(Energy Price Pulse Quantity/TIME STEP)\*PULSE(INITIAL TIME + Pulse Time 0,TIME STEP)\

+

RAMP(Energy Price Ramp Slope,INITIAL TIME + Ramp Start Time 0,INITIAL TIME + Ramp End Time 0\

)+(STEP(1, INITIAL TIME)\*(exp(Energy Price Exponential Growth Rate\*(Time - INITIAL TIME\

))-1))+

Sine Amplitude 0\*SIN(2\*3.14159\*(Time - INITIAL TIME)/Sine Period 0)+

STEP(1,INITIAL TIME + Noise Start Time 0)\*Autocorrelated Noise 0

~ Dimensionless

~ Input is a dimensionless variable which provides a variety of test input patterns, \

including a step,

pulse, sine wave, and random noise.

|

Ramp End Time 0=1e+09

~ Year

~ End time for the ramp input.

|

Step Time 0=

5

~ Year

~ Time for the step input.

|

Sine Amplitude 0=0

~ Dimensionless

~ Amplitude of sine wave in customer orders (fraction of mean).

|

White Noise 0 = Noise Standard Deviation 0\*((24\*Noise Correlation Time 0/TIME STEP)^0.5\

\*(RANDOM 0 1() - 0.5

))

~ Dimensionless

~ White noise input to the pink noise process.

|

Energy Price Pulse Quantity=

0

~ Dimensionless\*Year

~ The quantity to be injected to customer orders, as a fraction of the base value of \

Input.

For example, to pulse in a quantity equal to 50% of the current value of \

input, set to

.50.

|

Ramp Start Time 0=5

~ Year

~ Start time for the ramp input.

|

Noise Correlation Time 0 = 4

~ Year

~ The correlation time constant for Pink Noise.

|

Autocorrelated Noise = INTEG(Change in AC Noise,0)

~ Dimensionless

~ First-order autocorrelated noise. Provides a realistic noise input to models in \

which the next random shock depends in part on the previous shocks. The \

user can specify the correlation time. The mean is 0 and the standard \

deviation is specified

by the user.

|

Change in AC Noise = (White Noise - Autocorrelated Noise)/Noise Correlation Time

~ 1/Year

~ Change in the pink noise value; Pink noise is a first order exponential smoothing \

delay of the white

noise input.

|

Cohort Duration=

10

~ Year [1,20,1]

~ The width (duration) of each cohort.

|

Housing Starts Exponential Growth Rate=

0

~ 1/Year [-0.1,0.1,0.01]

~ The exogenous growth fraction for the test input.

|

Ramp Start Time=5

~ Year

~ Start time for the ramp input.

|

Input=

1+STEP(Housing Starts Step Height,INITIAL TIME + Step Time)+

(Housing Starts Pulse Quantity/TIME STEP)\*PULSE(INITIAL TIME + Pulse Time,TIME STEP)\

+

RAMP(Housing Starts Ramp Slope,INITIAL TIME + Ramp Start Time,INITIAL TIME + Ramp End Time\

)+(STEP(1, INITIAL TIME)\*(exp(Housing Starts Exponential Growth Rate\*(Time - INITIAL TIME\

))-1))+

Sine Amplitude\*SIN(2\*3.14159\*(Time - INITIAL TIME)/Sine Period)+

STEP(1,INITIAL TIME + Noise Start Time)\*Autocorrelated Noise

~ Dimensionless

~ Input is a dimensionless variable which provides a variety of test input patterns, \

including a step,

pulse, sine wave, and random noise.

|

Noise Correlation Time = 4

~ Year

~ The correlation time constant for Pink Noise.

|

Noise Standard Deviation = 0

~ Dimensionless

~ The standard deviation of the pink noise process.

|

Noise Start Time = 5

~ Year

~ Start time for the random input.

|

Housing Starts Pulse Quantity=

0

~ Dimensionless\*Year

~ The quantity to be injected to customer orders, as a fraction of the base value of \

Input.

For example, to pulse in a quantity equal to 50% of the current value of \

input, set to

.50.

|

Pulse Time=5

~ Year

~ Time at which the pulse in Input occurs.

|

Ramp End Time=1e+09

~ Year

~ End time for the ramp input.

|

Step Time=

5

~ Year

~ Time for the step input.

|

Housing Starts Ramp Slope=

0

~ 1/Year [-0.2,0.2,0.01]

~ Slope of the ramp input, as a fraction of the base value (per week).

|

White Noise = Noise Standard Deviation\*((24\*Noise Correlation Time/TIME STEP)^0.5\*(RANDOM 0 1\

() - 0.5

))

~ Dimensionless

~ White noise input to the pink noise process.

|

Sine Amplitude=0

~ Dimensionless

~ Amplitude of sine wave in customer orders (fraction of mean).

|

Sine Period=50

~ Year

~ Period of sine wave in customer demand. Set initially to 50 weeks (1 \

year).

|

Housing Starts Step Height=

0

~ Dimensionless [0,2]

~ Height of step input to customer orders, as fraction of initial value.

|

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|

Initial Homes Retrofitting[Cohort, Heating and Cooling System] :EXCEPT: [Preexisting Cohorts\

, Heating and Cooling System

]=

0 ~~|

Initial Homes Retrofitting[Preexisting Cohorts, Heating and Cooling System]=

Initial Fraction of Homes Retrofitting \* Initial Housing[Preexisting Cohorts,Heating and Cooling System\

]

~ Houses

~ Homes that are open to retrofitting initially.

|

Unsubsidized Retrofit Cost Intensity[Cohort, Heating and Cooling System]=

MAX(IF THEN ELSE( U Value of Retrofitting Homes[Cohort,Heating and Cooling System] >\

1e-06 ,

(Expected Reference Marginal Cost \* Reference U Value/ (-Sensitivity of Marginal Cost to U Value

+ 1)) \*

(((Reference U Value / U Value of Retrofitting Homes[Cohort,Heating and Cooling System\

]) ^ Sensitivity of Marginal Cost to U Value

-1)-

((Reference U Value / Optimal U Value for Existing Homes[Cohort,Heating and Cooling System\

]) ^ (Sensitivity of Marginal Cost to U Value

-1))) + Fixed Cost per Unit Area[Cohort],

0),

0)

~ Dollar / sf

~ Total cost of retrofit per square foot when the marginally optimal amount of U value \

is retrofitted away.

Calculated as definite integral of marginal cost of retrofitting, which, at a given \

U, is Reference MC \* (Ref. U / U Value) ^ Sensitivity. The total retrofit \

function is then found by taking the finite integral of the marginal cost \

function from the indicated optimal U value to the original U value and \

adding the fixed cost. This cost can be theoretically negative, but if so \

no retrofitting will take place as the retrofitting outflow is nonnegative.

The "if" statement ensures there are no retrofit costs when there are no \

houses in a cohort. U value must be greater than 1e-6 as this is the \

threshold for ZIDZ used in calculating average U.

|

Present Value of Cooling Operating Costs[Cohort, Heat Pump Heating and Cooling, Retrofitting Status\

, Heating and Cooling System] :EXCEPT: [Cohort, Heat Pump Heating and Cooling, Retrofitting Status\

, No AC Cooling]=

(Expected Cooling Energy Price \* Cooling Energy Use Under Alternatives[Cohort,Heat Pump Heating and Cooling\

,Retrofitting Status,Heating and Cooling System] / Discount Rate)

\* (1 - exp(-Discount Rate \*Average Lifetime of Cooling Technology[Heating and Cooling System\

])) ~~|

Present Value of Cooling Operating Costs[Cohort, Traditional Cooling, Retrofitting Status\

, Heating and Cooling System] :EXCEPT: [Cohort, Traditional Cooling, Retrofitting Status\

, No AC Cooling]=

(Expected Cooling Energy Price \* Cooling Energy Use Under Alternatives[Cohort,Traditional Cooling\

,Retrofitting Status,Heating and Cooling System] /

Discount Rate)

\* (1 - exp(-Discount Rate \*Average Lifetime of Cooling Technology[Heating and Cooling System\

])) ~~|

Present Value of Cooling Operating Costs[Cohort,Heating and Cooling System,Retrofitting Status\

,No AC Cooling]=

0

~ Dollars / (House)

~ The present value of cost to operate a cooling system, from the \

perspective of a house with one heating and cooling system (first H & C \

subscript) to another (the second). The operating cost is just the energy \

price times usage for cooling. Assumes constant operating costs and \

discount rate, with costs ending at the end of the average lifetime.

|

Initial Homes Not Retrofitting[Cohort, Heating and Cooling System] :EXCEPT: [Preexisting Cohorts\

, Heating and Cooling System

]=

0 ~~|

Initial Homes Not Retrofitting[ Preexisting Cohorts, Heating and Cooling System]=

(1 - Initial Fraction of Homes Retrofitting) \* Initial Housing[Preexisting Cohorts,Heating and Cooling System\

]

~ House

~ Initial homes not open to retrofitting.

|

Fraction of Houses Switching[Cohort,Heat Pump Heating and Cooling, Retrofitting Status\

, Heating and Cooling System]=

Affinity of Heating and Cooling Systems[Cohort,Heat Pump Heating and Cooling,Retrofitting Status\

,Heating and Cooling System] / SUM(Affinity of Heating and Cooling Systems[Cohort,Heat Pump Heating and Cooling\

, Retrofitting Status, Heating and Cooling System!]) ~~|

Fraction of Houses Switching[Cohort, Gas Heating, Retrofitting Status , Heating and Cooling System\

]=

Affinity of Heating and Cooling Systems[Cohort,Gas Heating,Retrofitting Status,Heating and Cooling System\

] / SUM(Affinity of Heating and Cooling Systems[Cohort,Gas Heating,Retrofitting Status\

,Heating and Cooling System!]) ~~|

Fraction of Houses Switching[Cohort, Oil Heating, Retrofitting Status , Heating and Cooling System\

]=

Affinity of Heating and Cooling Systems[Cohort,Oil Heating,Retrofitting Status,Heating and Cooling System\

] / SUM(Affinity of Heating and Cooling Systems

[Cohort, Oil Heating, Retrofitting Status , Heating and Cooling System!])

~ dmnl

~ Fraction of houses considering switching switching from one to another. We \

also model "switching" from one system to the same system, as we keep \

track of total heat pump sales.

|

Marginal Heating Cost Reduction from Retrofitting[Cohort, Heating and Cooling System]\

=

Expected Heating Energy Price[Heating and Cooling System] \* Heating Degree Days / Heating System Efficiency\

[Heating and Cooling System]

~ Dollar \* F / (kBTU)

~ The marginal reduction in heating costs per square foot from retrofitting \

away one unit of U, for existing housing. Calculated as the derivative of \

total heating energy costs with respect to U, where total heating energy \

costs are Heating Energy Price \* Heating Energy Use Per Square Foot, and \

the latter is U value \* Area \* Heating Temperature Differential (HDD) / \

efficiency / Area.

|

Fixed Cost per Unit Area[Cohort]=

ZIDZ(Expected Fixed Cost, Average Area[Cohort,Open to Retrofitting])

~ Dollar / sf

~ The fixed cost (which is constant) per square foot for an average house \

that is open to retrofitting.

|

Average Heating Cost[Cohort, Heating and Cooling System, Retrofitting Status]=

Expected Heating Energy Price[Heating and Cooling System] \* Average Heating Energy Use\

[Cohort,Heating and Cooling System,Retrofitting Status

]

~ Dollar / (Year \* House)

~ The costs per year to heat one house.

|

Present Value of Heating Operating Costs[Cohort, Heat Pump Heating and Cooling, Retrofitting Status\

, Heating and Cooling System]=

(Expected Heating Energy Price[Heating and Cooling System] \* Heating Energy Use Under Alternatives\

[Cohort,Heat Pump Heating and Cooling,Retrofitting Status,Heating and Cooling System\

] / Discount Rate)

\* (1 - exp(-Discount Rate \* Average Lifetime of Heating Technology[Heating and Cooling System\

])) ~~|

Present Value of Heating Operating Costs[Cohort, Fossil Fuel Heating, Retrofitting Status\

, Heating and Cooling System]=

(Expected Heating Energy Price[Heating and Cooling System] \* Heating Energy Use Under Alternatives\

[Cohort,Fossil Fuel Heating,Retrofitting Status,Heating and Cooling System] / Discount Rate\

)

\* (1 - exp(-Discount Rate \* Average Lifetime of Heating Technology[Heating and Cooling System\

]))

~ Dollar / (House)

~ The present value of cost to operate a heating system, from the \

perspective of a house with one heating and cooling system (first H & C \

subscript) to another (the second). The operating cost is just the energy \

price times usage for cooling. Assumes constant operating costs and \

continuous discount rate, with costs ending at the end of the average \

lifetime.

|

Heating Energy Price[Heating and Cooling System]=

Initial Heating Energy Price[Heating and Cooling System]\* Input 0

~ Dollar / (kBTU)

~ The price to heat a home (which in this model we assume can only have one \

size) 1 kBTU, multiplied by the test input.

|

Fixed Cost=

0

~ Dollar / House [0,50000,100]

~ Fixed cost of retrofitting, due to permitting, finding contractors, etc. This is not \

taken into account in the marginal cost of retrofitting, and this model \

assumes that households have not yet paid a fixed cost when deciding to \

retrofit. This cost only applies to existing housing.

Set this equal to 0, because almost all costs for retrofits seem to be \

variable (except for permitting, which isn't usually used), and there's no \

data to suggest otherwise.

|

Initial Heating Energy Price[Heat Pump Heating and Cooling]=

0.062 ~~|

Initial Heating Energy Price[Gas Heating]=

0.0142 ~~|

Initial Heating Energy Price[Oil Heating]=

0.017

~ Dollar / (kBTU)

~ Price of energy used in each technology: heat pump, central AC, window AC, no AC, \

gas, and oil. For heat pumps and air conditioners, this is electricity.

Data from (using annual 2020 data for MA):

electricity: \

https://www.eia.gov/electricity/data/browser/#/topic/7?agg=1,0&geo=vvvvvvvv\

vvvvo&endsec=8&freq=M&start=200101&ctype=linechart&ltype=pin&rtype=s&pin=&r\

se=0&maptype=0,

natural gas:https://www.eia.gov/dnav/ng/ng\_pri\_sum\_a\_EPG0\_PRS\_DMcf\_a.htm

heating oil: https://www.eia.gov/petroleum/heatingoilpropane/

|

Sensitivity of Marginal Cost to U Value=

3.25

~ dmnl [1,10,0.05]

~ Measures the sensitivity of marginal retrofit costs as a function of optimal U \

value. In particular, marginal Retrofit Cost is equal to Constant \* (U \

Value retrofitted away ^ Convexity). This must be greater than 1.

This is taken from pg. 69 of Caswell (2022), where she calculates the \

total retrofit cost curve as a function of percent savings as having an \

exponent of 2.25. Because this is the total retrofit cost curve, the \

exponent for the marginal cost is -2.25 - 1. Because percent savings is \

inversely proportional to U, the exponent in the total cost curve will be \

the negation of 2.25, which is ensured in the marginal cost curve \

formulation in other variables.

|

Reference Marginal Cost=

12.88

~ Dollar / sf / (kBTU / (sf \* Year \* F)) [2,20,0.01]

~ The marginal cost of retrofitting at the reference EUI. In particular, the marginal \

cost of retrofitting at some EUI is Reference U \*( (Reference U / U) ^ \

Sensitivity )

This was calculated by setting sensitivity of marginal cost equal to 1.25, and \

finding the MC where a 31% reduction in U value from the reference costs a \

total of 4.95 / (1 - 0.21) dollars per square foot. The sensitivity value \

is explained in the sensitivity variable. Less et al. (2021, pg. 17-18) \

note that in their project database, the median cost per square foot for \

retrofits after subsidies was $4.95, while subsidies accounted for 21% of \

the total project cost for the median project. The median cost reduced \

energy use by 28% - 33% (of which I took the average), and I use the lower \

bound value to account for the fact that energy savings may occur not only \

due to increase in U value.

Obviously all of this is extraordinarily rough.

Less et al. (2021): \

https://eta-publications.lbl.gov/sites/default/files/final\_walker\_-\_the\_cos\

t\_of\_decarbonization\_and\_energy.pdf

|

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|

Optimal U Value for Existing Homes if no EEHIC Cap[Cohort, Heating and Cooling System\

]=

Reference U Value \* (Expected Reference Marginal Cost \* (1 - Expected MassSave Proportional Subsidy Rate for Retrofits\

) \* (1-Expected EEHIC Proportional Subsidy Rate for Retrofits)/Lifetime Marginal Cost Reductions from Retrofitting\

[Cohort,Heating and Cooling System])^(1/Sensitivity of Marginal Cost to U Value)

~ kBTU / (sf \* F \* Year)

~ Optimal U Value to retrofit to should achieve if fixed costs are not taken into \

consideration (e.g., if fixed costs have already been paid) for existing \

houses). This takes into account the proportional subsidy but not the lump \

sum. Effect of proportional subsidies are multiplied instead of added, \

i.e., (1 - subsidy1)(1-subsidy2) instead of (1 - subsidy1 - subsidy2), \

because costs from state programs are subtracted when calculating federal \

subsidy in MA (https://www.masssave.com/inflation-reduction-act, "How do \

Mass Save rebates factor into the calculation of tax credits?")

Expression is derived from the marginal energy savings from retrofitting being \

Energy Price and marginal cost of retrofitting being Reference MC \* (1/(U/ \

Reference U))^Sensitivity and then solving for optimal retrofit when \

marginal savings equal marginal cost.

This is the optimal U value if there were no cap on the Energy Efficiency \

Home Improvement Credit, i.e., no discontinuity the marginal cost curve.

|

Average U Value in All Housing=

ZIDZ(Total U Value Across All Groupings, Total Housing Stock)

~ kBTU / (sf \* F \* Year)

~ The average U Value over the entire housing stock, not disaggregated by \

any groupings.

|

Total Housing Stock=

SUM(Housing[Cohort!,Heating and Cooling System!,Retrofitting Status!])

~ House

~ Total number of houses across all cohorts, heating/cooling systems, and \

retrofitting status.

|

Affinity of Retrofitting[Cohort,Heating and Cooling System]=

exp(-Sensitivity of Retrofits to Cost \* Perceived Cost of Retrofitting[Cohort,Heating and Cooling System\

] / Reference Retrofit Cost)

~ dmnl

~ Affinity of retrofitting, where utility value is equal to its NPV.

|

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|

Initial Housing Starts[Heating and Cooling System]=

Total Initial Housing Starts / ELMCOUNT(Heating and Cooling System)

~ House/Year

~ Initial value of housing starts, initialized at 10 total houses.

|

Cohort:

Before 1950, From 1950 to 1959, From 1960 to 1969, From 1970 to 1979, From 1980 to 1989\

, From 1990 to 1999, From 2000 to 2009, From 2010 to 2020, From 2021 to 2030, From 2031 to 2040\

, From 2041 to 2050

~

~ |

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.Control

\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*\*~

Simulation Control Parameters

|

FINAL TIME = 2050

~ Year

~ The final time for the simulation.

|

INITIAL TIME = 2020

~ Year

~ The initial time for the simulation.

|

SAVEPER =

TIME STEP

~ Year [0,?]

~ The frequency with which output is stored.

|

TIME STEP = 0.03125

~ Year [0,?]

~ The time step for the simulation.

|