

Trade-offs Analysis - Envelope vs Equipment and Renewable Energy Generation

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ABSTRACT

Total building performance compliance in residential energy codes that allows trading off improvements in heating, ventilation, and air conditioning (HVAC), service water heater (SWH) equipment or renewable energy for cutbacks in building envelope efficiency concerns many energy code stakeholders. The two main objections are “free ridership” and inequity of measure life. Many homes are already designed with high performance HVAC systems (typically condensing furnaces) and allowing the trade-off simply results in a less efficient building envelope. While a home’s enclosure typically lasts 40 or more years, HVAC and renewable energy generation may last less than half as long, thus efficient equipment with first year energy savings equal to that of an efficient building enclosure will have much lower savings over the life of a home. This concern is addressed somewhat in the International Energy Conservation Code (IECC) by including a “backstop” on envelope trade-offs. Regardless of improvements in mechanical equipment or the inclusion of renewable energy systems, the building envelope can be no worse than one that complies with the 2012 edition of the IECC. In this study, large scale building energy simulation has been conducted to systematically and quantitatively evaluate the potential impact of allowing unlimited trade-offs between HVAC improvements or renewable energy and building envelope components.

Introduction

Residential energy code provisions that allow trading off performance improvements in HVAC/SWH equipment or renewable energy generation from photovoltaic (PV) systems for lower stringency in building envelope efficiency have the potential to reduce long-term building efficiency in homes built to the IECC. Two of the main reasons for this are free ridership where credit is given for high efficiency equipment already widely used in the market and the failure to account for measure life in the code compliance framework (ICF 2013). While the home’s enclosure can last 40 or more years, HVAC/SWH and PV equipment have a much shorter lifetime, yet the trade-off value of each are based on first year energy savings only. The effects of energy waste by free ridership and lifecycle impacts can be substantial over the lifetime of today’s residential buildings.

On the other hand, the restriction of envelope efficiency reductions in trade-offs becomes increasingly difficult as the code gets more stringent to simultaneously encourage enhanced efficiency equipment (HVAC/SWH) and/or PV systems while maintaining compliance rules that limit the ability to view a home as an integrated system. There are benefits to allow trade-offs in code compliance. During the development of alternatives to the IECC energy code in Pennsylvania, Lau et al (2001) demonstrated that the trade-offs provide a degree of flexibility for builders that is not available without using the more complicated and costly performance-based compliance path. To achieve zero net energy (ZNE) building codes, Contoyannis et al (2020)

developed a simplified performance approach based on the detailed trade-offs for low-rise office buildings to achieve target performance levels.

This study outlines a straightforward but extensive simulation analysis to assess the potential impact of envelope efficiency trade-offs from enhanced efficiency equipment and/or PV systems when used in an unrestricted performance-style compliance analysis. The intent is to evaluate the potential degradation in envelope efficiency that could result from an energy code that allows unrestricted compliance trade-offs for enhanced equipment efficiency and/or PV systems. The current edition of the 2021 IECC code (IECC 2021) restricts envelope efficiency trade-offs because from an energy, resilience, comfort, and moisture standpoint, a robust thermal envelope is critical to make the house system work as intended. However, this study provides data to show the ramifications of allowing unrestricted envelope trade-offs when accounting for enhanced efficiency equipment and PV through performance-based code compliance.

Methodology

Overview of the Simulation and Analysis Approach

The study evaluates energy consumption of buildings for a series of scenarios of enhanced equipment efficiency and PV systems, and a series of degradations on the building envelope efficiency *either* by degrading the entire envelope to the suite of prescriptive requirements of the earlier editions of IECC codes from 2006 IECC to 2018 IECC (IECC 2006, IECC 2009, IECC 2021, IECC 2015, IECC 2018) *or* by relaxing the requirement of the individual envelope component (ceiling, above grade wall, window and air leakage) to successively lower efficiencies in isolation. The 2021 IECC code with federal minimum equipment efficiency requirements is used as the baseline for both the enhanced equipment efficiencies scenarios and the degraded envelope efficiencies scenarios. The reductions of energy consumption from the enhanced equipment efficiency scenarios and the increase of energy consumption from the degraded envelope scenarios, both over that of the 2021 IECC baseline, are compared to determine if a given envelope efficiency trade-off from a given enhanced equipment efficiency is allowed.

Large scale building energy simulation is conducted to evaluate the building energy consumption. Simulations are based on DOE's established cost effectiveness methodology for analyzing new versions of (or proposed changes to) the IECC (Taylor et al. 2015, Salcido et al., 2021a, b). The DOE's methodology evaluates the building energy consumption for each code scenario based on two prototype buildings (single-family (sf), low-rise multifamily (mf)) with variants of four foundation types (ventilated crawlspace, slab on grade, heated basement, unheated basement), and four system types (gas furnace, oil furnace and electric furnace, all with split central Air Conditioner (A/C), and electric heat pump). The evaluation is conducted through whole building energy simulations using a set of weather locations (18 for low-rise multifamily prototype and 19 for single family prototype) which represent all U.S. climate zones (CZ 1 to 8), moisture regimes (moist, dry, and marine), humidity designations (warm-humid, not warm humid), and tropical designations (tropical, non-tropical and semi-conditioned) defined by the IECC. For this analysis, only two system types are included—heat pump and gas furnace with A/C. Electric furnaces are excluded because the IECC's Total Building Performance compliance path sets an electric heat pump as the baseline for trade-offs in homes with an electric furnace; oil furnaces are excluded because they are relatively uncommon outside a few regions and there are no enhanced efficiency tiers defined by the Consortium for Energy

Efficiency (CEE) for oil fired equipment. *EnergyPlus* version 9.5 (DOE 2020) was used to conduct the building energy simulation.

Simulation results are evaluated by annual Energy Usage Intensity (EUI) in units of kBtu/ft²-yr which are aggregated to the climate zone level using DOE's established methodology. The site EUI reduction percentages of the enhanced equipment efficiency scenarios and the percentages EUI increase of the degraded envelope scenarios, both relative to the 2021 IECC baseline, are calculated and compared. Allowed trade-offs are revealed as those combinations of the enhanced equipment scenario and the degraded envelope scenario which do not lead to an increase in annual energy use relative to the 2021 IECC baseline. More details about the methodology and results can be found from (Salcido et al 2022),

Enhanced Equipment Efficiency and Renewables Scenarios

The enhanced efficiency equipment/PV part of the parametric suite includes an equipment baseline with equipment efficiencies set to federal minimum levels, plus two enhanced tiers based on recommendations from the CEE Residential Heating and Cooling Systems Initiative and Residential Water Heating Initiative.¹ The baseline contains no renewable energy generation PV and has a single alternative of a fixed PV capacity based on a study by the Pacific Northwest National Laboratory (PNNL) examining the feasibility of achieving zero energy buildings through building energy codes (Franconi et al. 2022). This results in one baseline and five enhanced efficiency equipment/PV scenarios as shown in [Table 1](#) and further defined in Table 2.

Degraded Envelope Efficiency Scenarios

The degradation of envelope efficiencies is characterized in two ways.

First, the envelope efficiencies are degraded to the levels of the prescriptive requirements of the previous IECC building energy code editions (2006 IECC to 2018 IECC). For these simulations, all building model inputs are set to match the 2021 IECC except for the following components which are set to match the requirements in the five preceding IECC code editions:

- Ceiling insulation R-value (hr·ft²·°F/Btu)
- Wall insulation R-values, cavity and continuous (hr·ft²·°F/Btu)
- Floor insulation R-value (hr·ft²·°F/Btu)
- Slab-edge R-value and depth (hr·ft²·°F/Btu, ft)
- Basement wall R-value (hr·ft²·°F/Btu)
- Fenestration U-factor (Btu/hr·ft²·°F)
- Fenestration SHGC (fraction)
- Envelope leakage ACH50 (air changes per hour at a 50-pascal pressure differential)

Secondly, the efficiencies of individual envelope components are sequentially degraded in isolation from other components. The specific degraded levels evaluated are shown in Tables 3-6 for ceiling insulation, above grade wall insulation, window U-factors and air leakage rates, respectively.

¹ <https://library.cee1.org/content/cee-residential-high-efficiency-central-air-conditioners-and-air-source-heat-pumps-specifica>

Cost Analysis

The energy simulation allows the possible trade-offs of envelope efficiency degradation with enhanced efficiency equipment/PV without an increase in overall annual net energy use. However, when considering energy and energy cost savings over the lifetime of the building, envelope measures would provide longer-lasting energy impacts due to their longer lifetimes. Envelope measures typically have a lifetime of 40 years or more while residential HVAC and SWH equipment are assumed to have a lifetime of 12-15 years on average based on the DOE cost effectiveness methodology (ICF 2013; Taylor et al. 2015, Salcido et al., 2021b). PV Panels have a rated lifetime of 25 years (Chowdhury et al. 2020). Based on the lifetime differences, enhanced efficiency equipment and PV systems will require replacement within the lifetime of any envelope component. In addition, there is no requirement that the replacement HVAC or PV system would have the same level of efficiency (as compared to minimum code requirements) as originally installed. The efficiency level of the replacement equipment is completely independent of the trade-offs made during the time of home construction.

In addition to evaluating the change in energy usage, this study also analyzes the change in energy cost and present values of energy cost of the envelope and the enhanced efficiency equipment/PV over the 2021 IECC baseline during the house's lifetime. The following 2020 national average residential fuel prices from the US Energy Information (EIA) are used for the analysis, including a price of: \$0.1323/kWh (EIA 2020a) for electricity and, \$0.94/therm for natural gas based on \$9.77/1,000 ft³ for natural gas and an average heat content of 1,037 Btu/ft³ for natural gas delivered to consumers in 2016 (EIA 2020b, 2020c).

The present values of the annual energy cost changes are based on a simple present value calculation with a discount rate of 3% over the lifetime (15 years for HVAC, 25 years for PV and 40 years for envelope). A few selected enhanced efficiency equipment/PV system scenarios are compared to the envelope degradation on the full code edition scenarios to determine which have higher impact. If the envelope degradation has less impact than a given enhanced equipment/PV scenario, it then represents an allowed trade-off.

Energy cost savings from PV assumes that electricity generated that can be utilized by the home offsets grid purchased electricity completely, while excess generation is assumed to be fed back into the grid via a net metering arrangement with the electric utility. Because net metering policies vary widely by state and utility, with some utilities reimbursing customers at the full retail rate and others providing no reimbursement for excess generation at all (DSIRE, 2021), this analysis takes a middle ground and credits excess generation at the national average wholesale electric price of \$0.048/kWh.

Results

Impact of Enhanced Efficiency Equipment and PV

Each of the five enhanced efficiency equipment/PV scenarios as well as the baseline scenario were analyzed. The whole-building annual energy usages were aggregated to each IECC climate zone level. While the code regulates only heating, cooling, fans, lighting, and water heating prescriptively, whole-building annual energy use is used in these comparisons to provide a common baseline for the PV scenarios. Each of the five enhanced efficiency equipment/PV scenarios were compared to the 2021 IECC baseline scenario to render a single *percent-*

reduction in site energy use value at the IECC climate zone level. Those results are shown in Table 7.

The percent-reduction in energy use values in Table 7 are the primary framework against which various envelope efficiency degradations can be compared to determine whether an energy code with an unrestricted trade-off mechanism would allow each envelope degradation to comply.

Impact of Envelope Degradation – by Code Year

The full code envelope degradation scenarios reduce only the envelope efficiency requirements from the 2021 IECC baseline to the older editions of the IECC (2006 through 2018). Each of the envelope specifications based on IECC code editions was simulated with federal minimum efficiencies regulated by National Appliance Energy Conservation Act (NAECA) compliant baseline equipment without PV, and the whole-building annual energy usage was aggregated to each IECC climate zone level. Then, each of the five code edition envelope degradation scenarios was compared to the baseline scenario to render a single *percent-increase in energy use* value on the climate zone level as shown in Table 8.

The percent increase in energy use values based on the five code editions for each climate zone can be compared with the similar percent reduction in energy use values for the five enhanced efficiency equipment/PV scenarios in Table 7. If the absolute magnitude of the enhanced efficiency equipment/PV percent decrease in annual energy use value is greater than the magnitude of the code edition envelope percent increase in annual energy use value, then envelope degradation to the level of that energy code edition would be allowed under the IECC Total Building Performance path.

Table 9 combines the information in Tables 7 and 8 to provide a code compliance assessment for each combination of envelope degradation by energy code edition and enhanced efficiency equipment/PV scenario. If an enhanced efficiency equipment/PV scenario saves more annual energy use than is lost by degrading the envelope for each earlier code edition, the combination of the enhanced efficiency equipment/PV scenario and the envelope degradation scenario is an allowed trade-off. For all not allowed trade-offs, the cells are highlighted in light grey.

All enhanced efficiency equipment/PV scenarios (except climate zone 4) allow the envelope of any residential building to be degraded down to the 2012 IECC level. In climates zones 1, 2 and 3, the PV scenario and the higher tiers of equipment efficiency/PV scenarios allow envelope degradation to the 2009 IECC level, and in climate zones 1 and 2, the PV scenario and the higher tiers of equipment efficiency/PV scenarios allow envelope degradation to the 2006 IECC level.

Impact of Envelope Degradation – by Building Component

Each level of degradation on the individual envelope components as specified in Tables 3 to 6 was simulated with NAECA compliant baseline equipment without PV, and the whole-building annual energy usages were aggregated to the IECC climate zone level. Next, each of the component-specific envelope degradations was compared to the baseline 2021 IECC scenario to render a single percent increase in energy use for each climate zone. The percent increase in energy use, by climate zone, of each level of the individual envelope component are presented in Tables 10 to 13 for ceiling, above-grade wall, fenestration U-factor, and air leakage, respectively.

The percent reduction of the enhanced equipment efficiency/PV scenarios by climate zone, as listed in Table 7, are also included in these tables. If the absolute magnitude of the enhanced equipment efficiency/PV percent reduction is greater than the magnitude of the envelope degradation percent increase, that component insulation degradation would be allowed under the IECC Total Building Performance path.

Ceiling Insulation Degradation. Ceiling insulation is a critical component in the overall envelope thermal efficiency and helps regulate the home's internal temperature. DOE suggests that ceiling insulation should not go below a minimum of R-30 for optimal efficiency and comfort (Energy.Gov, 2022).

The results shown in Table 10 indicate that all enhanced equipment efficiency/PV scenarios will allow ceiling insulation to be degraded to R-11 or R-19 insulation depending on climate zone except to trade off the degradation level 2 (R-19) with the Tier 1 equipment in climate zone 3.

Above Grade Wall Insulation Degradation. Above grade wall insulation is another large contributor to building loads and regulator of comfort for any home. Wall insulation properly installed provides a large thermal break from ambient conditions over the entire wall area. Insulation can be housed completely in the stud cavity, or outside the cavities, or a combination to meet the energy code requirements.

Table 11 shows the allowed trade-offs of degraded wall insulation with the enhanced equipment efficiency/PV scenario by climate zones.

For climate zones 1 & 2, the wall insulation is allowed to be degraded from R-13 to R-11 in general and even to R-0 for the Tier 2 equipment efficiency / PV scenario. For climate zone 3, the wall insulation is allowed to be degraded from R-20 to R-13 if traded off with the enhanced efficiency scenarios with PV. For climate zones 4 to 8, the wall insulation can be allowed to be degraded from R-20+5ci to R-11 or R-13.

Fenestration U-Factor Degradation. Homes with high-performance windows are more comfortable and consume less energy than homes with traditional windows.² These windows have a lower U-factor, and thus greater thermal resistance and typically have lower air leakage rates. Reducing the performance of windows due to trade-offs with enhanced equipment efficiency/PV systems will not increase annual energy use dramatically but can influence occupant comfort.

Table 12 highlights the levels of degradation for fenestration U-factors leading to allowed trade-offs with enhanced equipment efficiency/PV scenarios by climate zones. The results show that the enhanced efficiency equipment/PV scenarios will allow the fenestration U-Factors to be increased to the levels of a single pane window (U-Factor of 1.2 W/(m²K)) in climate zones 2-4³. Climate zones 5 through 7 allow a U-Factor degradation to 0.65 while windows U-factors in climate zone 8 can reach 0.50. Increases in U-factor to this extent will compromise comfort around the areas of the windows.⁴

² <https://basc.pnnl.gov/building-science-measures/high-performance-window-system>

³ Climate zone 1 does not have a prescriptive fenestration U-factor requirement.

⁴ <https://www.energy.gov/energysaver/update-or-replace-windows>

Envelope Air Leakages Degradation. Building a tight thermal envelope is a cost-effective method to reduce energy use for heating and cooling.⁵ Air leakage can come from numerous small openings in the envelope such as electrical and plumbing penetrations, window frames, joints, etc. Allowing higher levels of air leakage into the home can result in substantial increase in energy use for both heating and cooling depending on climate zone as well as compromised comfort.

Table 13 highlights the allowed trade-offs on degraded air leakage requirement with enhanced equipment efficiency/PV scenarios by climate zones.

In climate zones 1 through 4, air leakage at 7 or 8 ACH50 can pass energy code with the enhanced equipment efficiency trade-offs under the IECC Total Building Performance path. Climate zones 5 through 8 would pass at 5 ACH50 which is the maximum allowed envelope leakage for the 2021 IECC.

Cost Analysis

Table 14 and Figure 1 illustrate, through a few selective cases (Salcido et al 2022), that while the annual energy change (kBtu) and annual energy cost change (\$) from those of the 2021 IECC baseline for the envelope degradation and high efficiency equipment/PV measures can be roughly equal, the lifetime energy change (kBtu) and the present values of lifetime energy cost changes (\$) are much larger for the envelope degradation scenarios than the enhanced equipment efficiency and PV scenarios due to the longer lifetimes of the former. In these cases, the trade-offs from a degraded envelope combined with enhanced equipment efficiency/PV led to an adverse impact over the life of the buildings.

Conclusions and Discussion

This report illustrates that performance-based compliance allowing unrestricted envelope trade-offs with high efficiency HVAC/SWH and PV generation can result in significant envelope degradation. While the delta in first year energy costs between the measures is minimal, homeowners would see larger impact on lifetime energy and present value of energy costs from the envelope measures due to their longer lifetime. Therefore, it is important to not gauge the effectiveness of enhanced efficiency equipment or envelope measures based solely on first costs or first year energy costs but by the lifetime value of the measure.

Given the results of this trade-off analysis and the consequences from envelope efficiency degradation on comfort, energy use and persistent cost savings for the homeowner, it is imperative that energy codes continue to require a minimum level of envelope efficiency that cannot be traded with enhanced efficiency equipment and/or PV systems.

If full trade-offs between the thermal envelope and enhanced equipment efficiency/PV systems are allowed by code, installed costs of the envelope and equipment become the only determining factor in choosing where the building efficiency is implemented. Lifetime costs or savings are not factored into the value engineering of components. As a result, costs or efficiency of replacements and measure lifetimes are not part of the equation. Over the life of the home, HVAC equipment with average lifetime of 15 years will be replaced several times while insulation with a lifetime of 40 years, if installed correctly and adequately, may never need replacing. There is no requirement that a high efficiency HVAC system would not be replaced

⁵ <https://www.energy.gov/energysaver/air-sealing-your-home>

with a federal minimum efficiency equipment, thus losing the efficiency benefit from the original equipment with a less efficient envelope. It is imperative that envelop efficiency backstops remain in energy codes for performance-based compliance in order to maintain the most cost-effective envelope measures for efficiency in place. As an alternative, performance-based compliance path in the code could consider the lifetime savings in performance-based tradeoff analyses instead of annual savings (Thornton et al. 2015, Jonlin et al, 2016).

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Table 1. High Efficiency Equipment/PV Scenarios

Equipment Scenarios	Equipment Efficiencies	Renewable (PV) Capacity
NAECA baseline	Federal minimums	No PV
EQ1	CEE Tier 1	No PV
EQ2	CEE Tier 3 if available, else Tier 2	No PV
PV	Federal minimums	1500 Watts/mf unit, 4000 Watts/sf
EQ1PV	CEE Tier 1	1500 Watts/mf unit, 4000 Watts/sf
EQ2PV	CEE Tier 3 if available, else Tier 2	1500 Watts/mf unit, 4000 Watts/sf

Table 2. HVAC and SHW Efficiency Tiers

Metric	Federal Minimum	Equipment Tier 1 (EQ1)	Equipment Tier 2 (EQ2)
Heat Pump HSPF	8.2	8.5	9.5
Heat Pump SEER	14	15	18
Split Central Air Conditioner SEER	13	16	18
Gas Furnace AFUE	80%	92%	97%
Electric Storage Water Heater EF	0.93	0.93	3
Gas Storage Water Heater EF	0.59	0.59	0.82

Table 3. Ceiling Insulation R-Value Degradation Levels

Climate Zone	Baseline	Level 1	Level 2	Level 3	Level 4
1	30	19	11	0	—
2	49	30	19	0	—
3	49	30	19	0	—
4	60	49	30	19	0
5	60	49	30	19	0
6	60	49	30	19	0
7	60	49	30	19	0
8	60	49	30	19	0

Table 4. Above Grade Wall Insulation R-Value Degradation Levels

Climate Zone	Baseline	Level 1	Level 2	Level 3	Level 4
1	13	11	0	—	—
2	13	11	0	—	—
3	20	13	11	0	—
4	20+5ci	13	11	0	—
5	20+5ci	20	13	11	0
6	20+5ci	20	13	11	0
7	20+5ci	20	19	13	0
8	20+5ci	20	19	13	0

Table 5. Window U-Factor Degradation Levels

Climate Zone	Baseline	Level 1	Level 2	Level 3	Level 4
1	—	—	—	—	—
2	0.4	0.5	0.65	1.2	—
3	0.3	0.4	0.5	0.65	1.2
4	0.3	0.4	0.5	0.65	1.2

5	0.3	0.4	0.5	0.65	1.2
6	0.3	0.4	0.5	0.65	1.2
7	0.3	0.4	0.5	0.65	1.2
8	0.3	0.4	0.5	0.65	1.2

Table 6. Air Leakage (ACH50) Degradation Levels

Climate Zone	Baseline	Level 1	Level 2	Level 3	Level 4
1	5	7	8	—	—
2	5	7	8	—	—
3	3	5	7	8	—
4	3	5	7	8	—
5	3	5	7	8	—
6	3	5	7	8	—
7	3	5	7	8	—
8	3	5	7	8	—

Table 7. Percent Reduction in Energy Use for High Efficiency Equipment/PV Scenarios from the Federal Minimum Efficiencies

Climate Zone	EQ1	EQ2	PV	EQ1PV	EQ2PV
1	-2.5	-6.4	-30.4	-32.9	-36.8
2	-3.1	-6.2	-29.0	-32.1	-35.2
3	-2.8	-5.3	-29.5	-32.3	-34.8
4	-3.9	-6.4	-19.0	-22.8	-25.3
5	-5.9	-8.2	-15.3	-21.3	-23.6
6	-6.4	-8.8	-12.1	-18.5	-20.9
7	-6.0	-8.3	-10.9	-16.8	-19.1
8	-6.3	-8.6	-7.1	-13.4	-15.7

Table 8. Percent Increase in Energy Use from IECC editions from 2021 IECC baseline

Climate Zone	2018 IECC	2015 IECC	2012 IECC	2009 IECC	2006 IECC
1	0.0	0.0	0.0	7.7	13.4
2	0.4	0.4	0.4	9.7	16.8
3	1.5	2.2	2.2	25.5	35.5
4	4.2	5.4	5.4	36.1	48.4
5	4.1	5.0	5.0	34.4	46.4
6	0.4	1.4	1.4	38.7	53.4
7	0.4	1.5	1.5	40.5	54.9
8	0.4	1.5	1.5	41.6	56.9

Table 9. Envelope Trade-off of Older IECC Editions with Equipment/PV Scenarios

Equipment/PV Scenario	CZ	HVAC/PV	2018 IECC	2015 IECC	2012 IECC	2009 IECC	2006 IECC
		A	A	A	A	A	A
EQ1	1	-2.5	0.0	0.0	0.0	7.7	13.4
	2	-3.1	0.4	0.4	0.4	9.7	16.8
	3	-2.8	1.5	2.2	2.2	25.5	35.5
	4	-3.9	4.2	5.4	5.4	36.1	48.4
	5	-5.9	4.1	5.0	5.0	34.4	46.4
	6	-6.4	0.4	1.4	1.4	38.7	53.4

Equipment/PV Scenario	CZ	HVAC/PV	2018 IECC	2015 IECC	2012 IECC	2009 IECC	2006 IECC
		A	A	A	A	A	A
EQ2	7	-6.0	0.4	1.5	1.5	40.5	54.9
	8	-6.3	0.4	1.5	1.5	41.6	56.9
	1	-6.4	0.0	0.0	0.0	7.7	13.4
	2	-6.2	0.4	0.4	0.4	9.7	16.8
	3	-5.3	1.5	2.2	2.2	25.5	35.5
	4	-6.4	4.2	5.4	5.4	36.1	48.4
	5	-8.2	4.1	5.0	5.0	34.4	46.4
	6	-8.8	0.4	1.4	1.4	38.7	53.4
PV	7	-8.3	0.4	1.5	1.5	40.5	54.9
	8	-8.6	0.4	1.5	1.5	41.6	56.9
	1	-30.4	0.0	0.0	0.0	7.7	13.4
	2	-29.0	0.4	0.4	0.4	9.7	16.8
	3	-29.5	1.5	2.2	2.2	25.5	35.5
	4	-19.0	4.2	5.4	5.4	36.1	48.4
	5	-15.3	4.1	5.0	5.0	34.4	46.4
	6	-12.1	0.4	1.4	1.4	38.7	53.4
EO1PV	7	-10.9	0.4	1.5	1.5	40.5	54.9
	8	-7.1	0.4	1.5	1.5	41.6	56.9
	1	-32.9	0.0	0.0	0.0	7.7	13.4
	2	-32.1	0.4	0.4	0.4	9.7	16.8
	3	-32.3	1.5	2.2	2.2	25.5	35.5
	4	-22.8	4.2	5.4	5.4	36.1	48.4
	5	-21.3	4.1	5.0	5.0	34.4	46.4
	6	-18.5	0.4	1.4	1.4	38.7	53.4
EQ2PV	7	-16.8	0.4	1.5	1.5	40.5	54.9
	8	-13.4	0.4	1.5	1.5	41.6	56.9
	1	-36.8	0.0	0.0	0.0	7.7	13.4
	2	-35.2	0.4	0.4	0.4	9.7	16.8
	3	-34.8	1.5	2.2	2.2	25.5	35.5
	4	-25.3	4.2	5.4	5.4	36.1	48.4
	5	-23.6	4.1	5.0	5.0	34.4	46.4
	6	-20.9	0.4	1.4	1.4	38.7	53.4
	7	-19.1	0.4	1.5	1.5	40.5	54.9
	8	-15.7	0.4	1.5	1.5	41.6	56.9

A: percent change in EUI relative to the 2021 IECC baseline

Table 10. Ceiling Insulation Degradation Trade-off with Equipment/PV Scenarios

Equipment/PV Scenario	CZ	HVAC/PV		Degradation		Degradation		Degradation		Degradation	
		A	B	A	B	A	B	A	B	A	B
EQ1	1	30	-2.5	19	0.5	11	1.8	0	12.2	—	—
	2	49	-3.1	30	0.9	19	2.1	0	24.2	—	—
	3	49	-2.8	30	1.2	19	3.1	0	38.7	—	—
	4	60	-3.9	49	0.4	30	1.8	19	4.1	0	53.2
	5	60	-5.9	49	0.5	30	2.2	19	5.1	0	65.4
	6	60	-6.4	49	0.5	30	2.3	19	5.1	0	68.9
	7	60	-6.0	49	0.5	30	2.5	19	5.7	0	75.5
	8	60	-6.3	49	0.5	30	2.5	19	5.7	0	70.4
EO2	1	30	-6.4	19	0.5	11	1.8	0	12.2	—	—
	2	49	-6.2	30	0.9	19	2.1	0	24.2	—	—
	3	49	-5.3	30	1.2	19	3.1	0	38.7	—	—
	4	60	-6.4	49	0.4	30	1.8	19	4.1	0	53.2
	5	60	-8.2	49	0.5	30	2.2	19	5.1	0	65.4
	6	60	-8.8	49	0.5	30	2.3	19	5.1	0	68.9

Equipment/PV Scenario	CZ	HVAC/PV		Degradation		Degradation		Degradation		Degradation	
		A	B	A	B	A	B	A	B	A	B
	7	60	-8.3	49	0.5	30	2.5	19	5.7	0	75.5
	8	60	-8.6	49	0.5	30	2.5	19	5.7	0	70.4
PV	1	30	-30.4	19	0.5	11	1.8	0	12.2	—	—
	2	49	-29.0	30	0.9	19	2.1	0	24.2	—	—
	3	49	-29.5	30	1.2	19	3.1	0	38.7	—	—
	4	60	-19.0	49	0.4	30	1.8	19	4.1	0	53.2
	5	60	-15.3	49	0.5	30	2.2	19	5.1	0	65.4
	6	60	-12.1	49	0.5	30	2.3	19	5.1	0	68.9
	7	60	-10.9	49	0.5	30	2.5	19	5.7	0	75.5
	8	60	-7.1	49	0.5	30	2.5	19	5.7	0	70.4
EQ1PV	1	30	-32.9	19	0.5	11	1.8	0	12.2	—	—
	2	49	-32.1	30	0.9	19	2.1	0	24.2	—	—
	3	49	-32.3	30	1.2	19	3.1	0	38.7	—	—
	4	60	-22.8	49	0.4	30	1.8	19	4.1	0	53.2
	5	60	-21.3	49	0.5	30	2.2	19	5.1	0	65.4
	6	60	-18.5	49	0.5	30	2.3	19	5.1	0	68.9
	7	60	-16.8	49	0.5	30	2.5	19	5.7	0	75.5
	8	60	-13.4	49	0.5	30	2.5	19	5.7	0	70.4
EO2PV	1	30	-36.8	19	0.5	11	1.8	0	12.2	—	—
	2	49	-35.2	30	0.9	19	2.1	0	24.2	—	—
	3	49	-34.8	30	1.2	19	3.1	0	38.7	—	—
	4	60	-25.3	49	0.4	30	1.8	19	4.1	0	53.2
	5	60	-23.6	49	0.5	30	2.2	19	5.1	0	65.4
	6	60	-20.9	49	0.5	30	2.3	19	5.1	0	68.9
	7	60	-19.1	49	0.5	30	2.5	19	5.7	0	75.5
	8	60	-15.7	49	0.5	30	2.5	19	5.7	0	70.4

A: R-value of the ceiling insulation

B: percent change in EUI relative to the 2021 IECC baseline

Cells in grey show trade-off scenarios which would result in an EUI lower than the 2021 IECC baseline

Table 11. Wall Insulation Degradation Trade-off with Equipment/PV Scenarios

Equipment/ PV Scenario	CZ	HVAC/PV		Degradation Level 1		Degradation Level 2		Degradation Level 3		Degradation Level 4	
		A	B	A	B	A	B	A	B	A	B
EQ1	1	13	-2.5	11	0.4	0	17.1	—	—	—	—
	2	13	-3.1	11	0.7	0	28.7	—	—	—	—
	3	20	-2.8	13	5.4	11	6.3	0	47.4	—	—
	4	20+5ci	-3.9	20	9.3	11	10.6	0	63.9	—	—
	5	20+5ci	-5.9	20	3.6	13	11.7	11	13.3	0	79.6
	6	20+5ci	-6.4	20	3.7	13	11.7	11	13.4	0	81.1
	7	20+5ci	-6.0	20	4.1	19	5.5	13	13.3	0	91.4
	8	20+5ci	-6.3	20	4.5	19	5.9	13	14.2	0	93.4
EQ2	1	13	-6.4	11	0.4	0	17.1	—	—	—	—
	2	13	-6.2	11	0.7	0	28.7	—	—	—	—
	3	20	-5.3	13	5.4	11	6.3	0	47.4	—	—
	4	20+5ci	-6.4	20	9.3	11	10.6	0	63.9	—	—
	5	20+5ci	-8.2	20	3.6	13	11.7	11	13.3	0	79.6
	6	20+5ci	-8.8	20	3.7	13	11.7	11	13.4	0	81.1
	7	20+5ci	-8.3	20	4.1	19	5.5	13	13.3	0	91.4
	8	20+5ci	-8.6	20	4.5	19	5.9	13	14.2	0	93.4
PV	1	13	-30.4	11	0.4	0	17.1	—	—	—	—
	2	13	-29.0	11	0.7	0	28.7	—	—	—	—
	3	20	-29.5	13	5.4	11	6.3	0	47.4	—	—
	4	20+5ci	-19.0	20	9.3	11	10.6	0	63.9	—	—
	5	20+5ci	-15.3	20	3.6	13	11.7	11	13.3	0	79.6

Equipment/ PV Scenario	CZ	HVAC/PV		Degradation Level 1		Degradation Level 2		Degradation Level 3		Degradation Level 4	
		A	B	A	B	A	B	A	B	A	B
	6	20+5ci	-12.1	20	3.7	13	11.7	11	13.4	0	81.1
	7	20+5ci	-10.9	20	4.1	19	5.5	13	13.3	0	91.4
	8	20+5ci	-7.1	20	4.5	19	5.9	13	14.2	0	93.4
EO1PV	1	13	-32.9	11	0.4	0	17.1	—	—	—	—
	2	13	-32.1	11	0.7	0	28.7	—	—	—	—
	3	20	-32.3	13	5.4	11	6.3	0	47.4	—	—
	4	20+5ci	-22.8	20	9.3	11	10.6	0	63.9	—	—
	5	20+5ci	-21.3	20	3.6	13	11.7	11	13.3	0	79.6
	6	20+5ci	-18.5	20	3.7	13	11.7	11	13.4	0	81.1
	7	20+5ci	-16.8	20	4.1	19	5.5	13	13.3	0	91.4
	8	20+5ci	-13.4	20	4.5	19	5.9	13	14.2	0	93.4
EQ2PV	1	13	-36.8	11	0.4	0	17.1	—	—	—	—
	2	13	-35.2	11	0.7	0	28.7	—	—	—	—
	3	20	-34.8	13	5.4	11	6.3	0	47.4	—	—
	4	20+5ci	-25.3	20	9.3	11	10.6	0	63.9	—	—
	5	20+5ci	-23.6	20	3.6	13	11.7	11	13.3	0	79.6
	6	20+5ci	-20.9	20	3.7	13	11.7	11	13.4	0	81.1
	7	20+5ci	-19.1	20	4.1	19	5.5	13	13.3	0	91.4
	8	20+5ci	-15.7	20	4.5	19	5.9	13	14.2	0	93.4

A: R-value of the ceiling insulation

B: percent change in EUI relative to the 2021 IECC baseline

Cells in grey show trade-off scenarios which would result in an EUI lower than the 2021 IECC baseline

Table 12. Fenestration U-Factor Degradation Trade-off with Equipment/PV Scenarios

Equipment/PV Scenario	CZ	HVAC/PV		Degradation Level 1		Degradation Level 2		Degradation Level 3		Degradation Level 4	
		A	B	A	B	A	B	A	B	A	B
EQ1	1	0.5	-2.5	0.5	—	—	—	—	—	—	—
	2	0.4	-3.1	0.5	1.1	0.65	2.8	1.2	6.7	—	—
	3	0.3	-2.8	0.4	2.5	0.5	4.8	0.65	8.1	1.2	15.4
	4	0.3	-3.9	0.4	3.9	0.5	7.6	0.65	12.7	1.2	23.8
	5	0.3	-5.9	0.4	4.6	0.5	9.0	0.65	14.9	1.2	27.6
	6	0.3	-6.4	0.4	4.8	0.5	9.3	0.65	15.3	1.2	28.3
	7	0.3	-6.0	0.4	5.3	0.5	10.2	0.65	16.7	1.2	30.6
	8	0.3	-6.3	0.4	5.5	0.5	10.5	0.65	17.2	1.2	31.1
EQ2	1	0.5	-6.4	0.5	—	—	—	—	—	—	—
	2	0.4	-6.2	0.5	1.1	0.65	2.8	1.2	6.7	—	—
	3	0.3	-5.3	0.4	2.5	0.5	4.8	0.65	8.1	1.2	15.4
	4	0.3	-6.4	0.4	3.9	0.5	7.6	0.65	12.7	1.2	23.8
	5	0.3	-8.2	0.4	4.6	0.5	9.0	0.65	14.9	1.2	27.6
	6	0.3	-8.8	0.4	4.8	0.5	9.3	0.65	15.3	1.2	28.3
	7	0.3	-8.3	0.4	5.3	0.5	10.2	0.65	16.7	1.2	30.6
	8	0.3	-8.6	0.4	5.5	0.5	10.5	0.65	17.2	1.2	31.1
PV	1	0.5	-30.4	0.5	—	—	—	—	—	—	—
	2	0.4	-29.0	0.5	1.1	0.65	2.8	1.2	6.7	—	—
	3	0.3	-29.5	0.4	2.5	0.5	4.8	0.65	8.1	1.2	15.4
	4	0.3	-19.0	0.4	3.9	0.5	7.6	0.65	12.7	1.2	23.8
	5	0.3	-15.3	0.4	4.6	0.5	9.0	0.65	14.9	1.2	27.6
	6	0.3	-12.1	0.4	4.8	0.5	9.3	0.65	15.3	1.2	28.3
	7	0.3	-10.9	0.4	5.3	0.5	10.2	0.65	16.7	1.2	30.6
	8	0.3	-7.1	0.4	5.5	0.5	10.5	0.65	17.2	1.2	31.1
EO1PV	1	0.5	-32.9	0.5	—	—	—	—	—	—	—
	2	0.4	-32.1	0.5	1.1	0.65	2.8	1.2	6.7	—	—

Equipment/PV Scenario	CZ	HVAC/PV		Degradation Level 1		Degradation Level 2		Degradation Level 3		Degradation Level 4	
		A	B	A	B	A	B	A	B	A	B
	3	0.3	-32.3	0.4	2.5	0.5	4.8	0.65	8.1	1.2	15.4
	4	0.3	-22.8	0.4	3.9	0.5	7.6	0.65	12.7	1.2	23.8
	5	0.3	-21.3	0.4	4.6	0.5	9.0	0.65	14.9	1.2	27.6
	6	0.3	-18.5	0.4	4.8	0.5	9.3	0.65	15.3	1.2	28.3
	7	0.3	-16.8	0.4	5.3	0.5	10.2	0.65	16.7	1.2	30.6
	8	0.3	-13.4	0.4	5.5	0.5	10.5	0.65	17.2	1.2	31.1
EQ2PV	1	0.5	-36.8	0.5	—	—	—	—	—	—	—
	2	0.4	-35.2	0.5	1.1	0.65	2.8	1.2	6.7	—	—
	3	0.3	-34.8	0.4	2.5	0.5	4.8	0.65	8.1	1.2	15.4
	4	0.3	-25.3	0.4	3.9	0.5	7.6	0.65	12.7	1.2	23.8
	5	0.3	-23.6	0.4	4.6	0.5	9.0	0.65	14.9	1.2	27.6
	6	0.3	-20.9	0.4	4.8	0.5	9.3	0.65	15.3	1.2	28.3
	7	0.3	-19.1	0.4	5.3	0.5	10.2	0.65	16.7	1.2	30.6
	8	0.3	-15.7	0.4	5.5	0.5	10.5	0.65	17.2	1.2	31.1

A: R-value of the ceiling insulation

B: percent change in EUI relative to the 2021 IECC baseline

Cells in grey show trade-off scenarios which would result in an EUI lower than the 2021 IECC baseline

Table 13. Air Leakage Degradation Trade-off with Equipment/PV Scenarios

Equipment/PV Scenario	CZ	HVAC/PV		Degradation Level 1		Degradation Level 2		Degradation Level 3		Degradation Level 4	
		A	B	A	B	A	B	A	B	A	B
EQ1	1	5	-2.5	7	1.5	8	2.2	—	—	—	—
	2	5	-3.1	7	2.3	8	3.4	—	—	—	—
	3	3	-2.8	5	4.6	7	9.3	8	11.7	—	—
	4	3	-3.9	5	8.7	7	17.4	8	21.8	—	—
	5	3	-5.9	5	10.3	7	20.7	8	25.8	—	—
	6	3	-6.4	5	12.5	7	24.7	8	30.8	—	—
	7	3	-6.0	5	12.6	7	25.0	8	31.2	—	—
	8	3	-6.3	5	12.4	7	25.1	8	31.5	—	—
EQ2	1	5	-6.4	7	1.5	8	2.2	—	—	—	—
	2	5	-6.2	7	2.3	8	3.4	—	—	—	—
	3	3	-5.3	5	4.6	7	9.3	8	11.7	—	—
	4	3	-6.4	5	8.7	7	17.4	8	21.8	—	—
	5	3	-8.2	5	10.3	7	20.7	8	25.8	—	—
	6	3	-8.8	5	12.5	7	24.7	8	30.8	—	—
	7	3	-8.3	5	12.6	7	25.0	8	31.2	—	—
	8	3	-8.6	5	12.4	7	25.1	8	31.5	—	—
PV	1	5	-30.4	7	1.5	8	2.2	—	—	—	—
	2	5	-29.0	7	2.3	8	3.4	—	—	—	—
	3	3	-29.5	5	4.6	7	9.3	8	11.7	—	—
	4	3	-19.0	5	8.7	7	17.4	8	21.8	—	—
	5	3	-15.3	5	10.3	7	20.7	8	25.8	—	—
	6	3	-12.1	5	12.5	7	24.7	8	30.8	—	—
	7	3	-10.9	5	12.6	7	25.0	8	31.2	—	—
	8	3	-7.1	5	12.4	7	25.1	8	31.5	—	—
EO1PV	1	5	-32.9	7	1.5	8	2.2	—	—	—	—
	2	5	-32.1	7	2.3	8	3.4	—	—	—	—
	3	3	-32.3	5	4.6	7	9.3	8	11.7	—	—
	4	3	-22.8	5	8.7	7	17.4	8	21.8	—	—
	5	3	-21.3	5	10.3	7	20.7	8	25.8	—	—
	6	3	-18.5	5	12.5	7	24.7	8	30.8	—	—
	7	3	-16.8	5	12.6	7	25.0	8	31.2	—	—

	8	3	-13.4	5	12.4	7	25.1	8	31.5	—	—
EQ2PV	1	5	-36.8	7	1.5	8	2.2	—	—	—	—
	2	5	-35.2	7	2.3	8	3.4	—	—	—	—
	3	3	-34.8	5	4.6	7	9.3	8	11.7	—	—
	4	3	-25.3	5	8.7	7	17.4	8	21.8	—	—
	5	3	-23.6	5	10.3	7	20.7	8	25.8	—	—
	6	3	-20.9	5	12.5	7	24.7	8	30.8	—	—
	7	3	-19.1	5	12.6	7	25.0	8	31.2	—	—
	8	3	-15.7	5	12.4	7	25.1	8	31.5	—	—

A: R-value of the ceiling insulation

B: percent change in EUI relative to the 2021 IECC baseline

Cells in grey show trade-off scenarios which would result in an EUI lower than the 2021 IECC baseline

Table 14. Cost Analysis of High Efficiency Equipment/PV vs Envelope Measures

	EQ1	EQ2	PV	EQ1PV	EQ2PV
Climate Zone	CZ 5	CZ 4	CZ 3	CZ 3	CZ 3
IECC-Edition	2012-IECC	2012-IECC	2009-IECC	2009-IECC	2009-IECC
Annual Percent Change In Energy Use					
A	-5.90	-6.40	-29.50	-32.30	-34.80
B	5.90	6.40	29.50	32.30	34.80
Annual Energy Change (kBtu/dwelling unit)					
A	-5,421	-4,409	-16,920	-18,524	-19,927
B	5,421	4,409	16,920	18,524	19,927
Lifetime Energy Savings (kBtu/dwelling unit)					
A	-81,365	-66,138	-422,993	-418,158	-456,974
B	216,946	176,368	676,788	740,973	797,068
Annual Energy Cost Change (\$/dwelling unit)					
A	(\$80)	(\$85)	(\$403)	(\$416)	(\$442)
B	\$78	\$81	\$401	\$439	\$473
Present Value of Lifetime Energy Cost Change (\$/dwelling unit)					
A	(\$959)	(\$1,032)	(\$7,024)	(\$6,861)	(\$7,272)
B	\$1,812	\$1,880	\$9,277	\$10,157	\$10,926

A: Enhanced Equipment Efficiency/PV Scenario

B: The IECC Edition for the Degraded Envelope

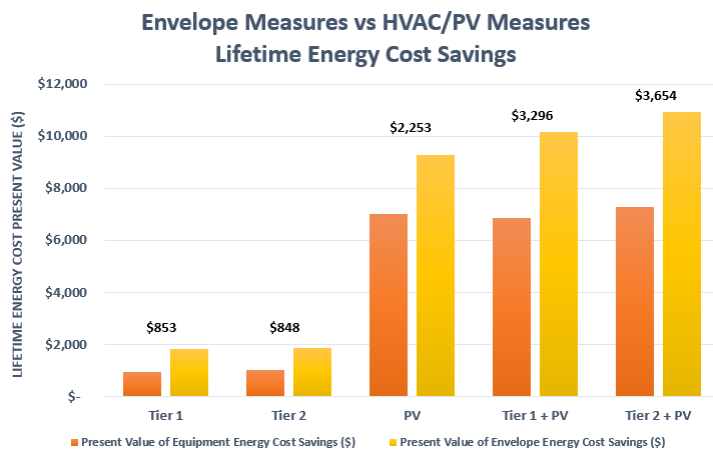


Figure 1 Present Value of Lifetime Energy Cost Change (\$/dwelling unit) of a few selected cases.