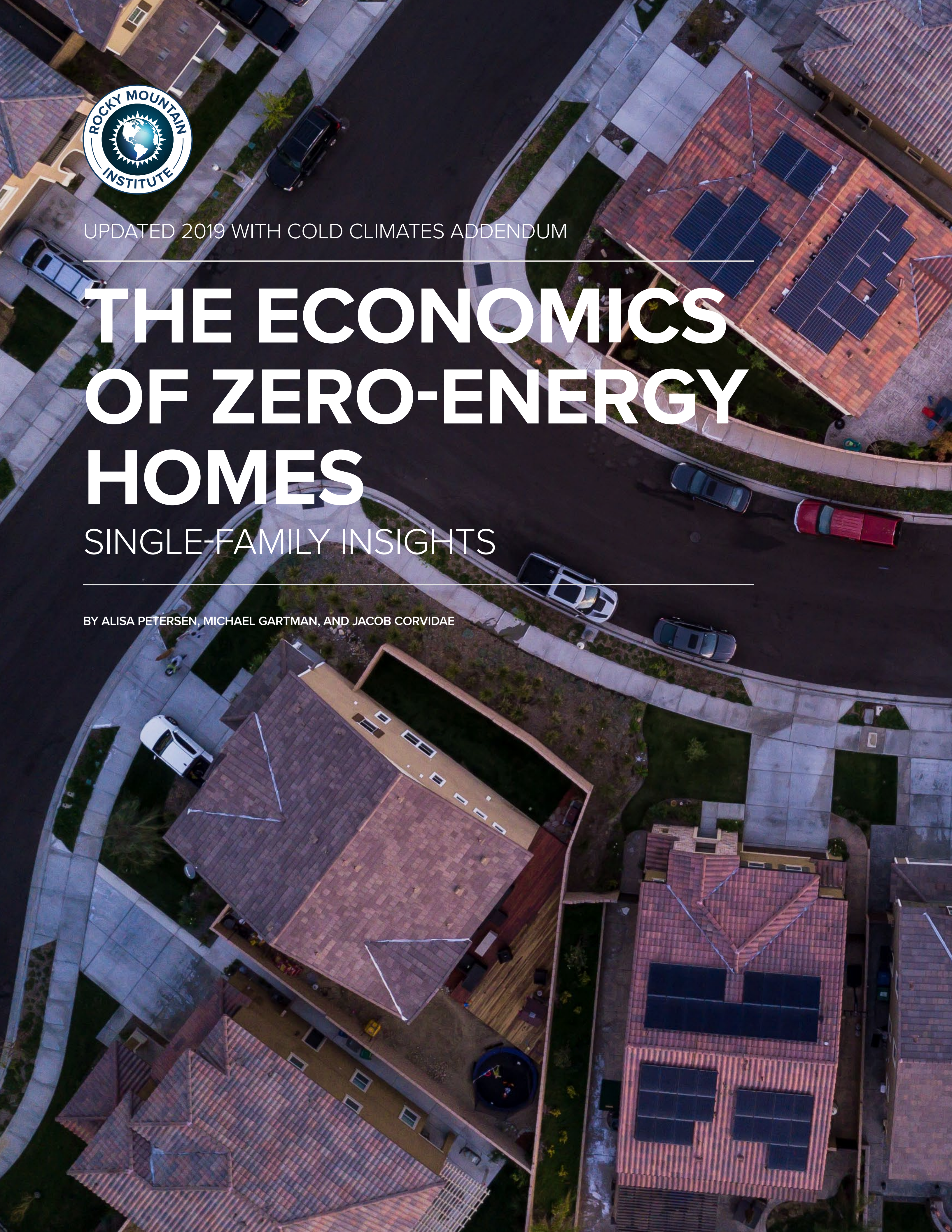

UPDATED 2019 WITH COLD CLIMATES ADDENDUM

THE ECONOMICS OF ZERO-ENERGY HOMES

SINGLE-FAMILY INSIGHTS

BY ALISA PETERSEN, MICHAEL GARTMAN, AND JACOB CORVIDAE

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ABOUT US

ABOUT ROCKY MOUNTAIN INSTITUTE

Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from fossil fuels to efficiency and renewables. RMI has offices in Basalt and Boulder, Colorado; New York City; Washington, D.C.; and Beijing.

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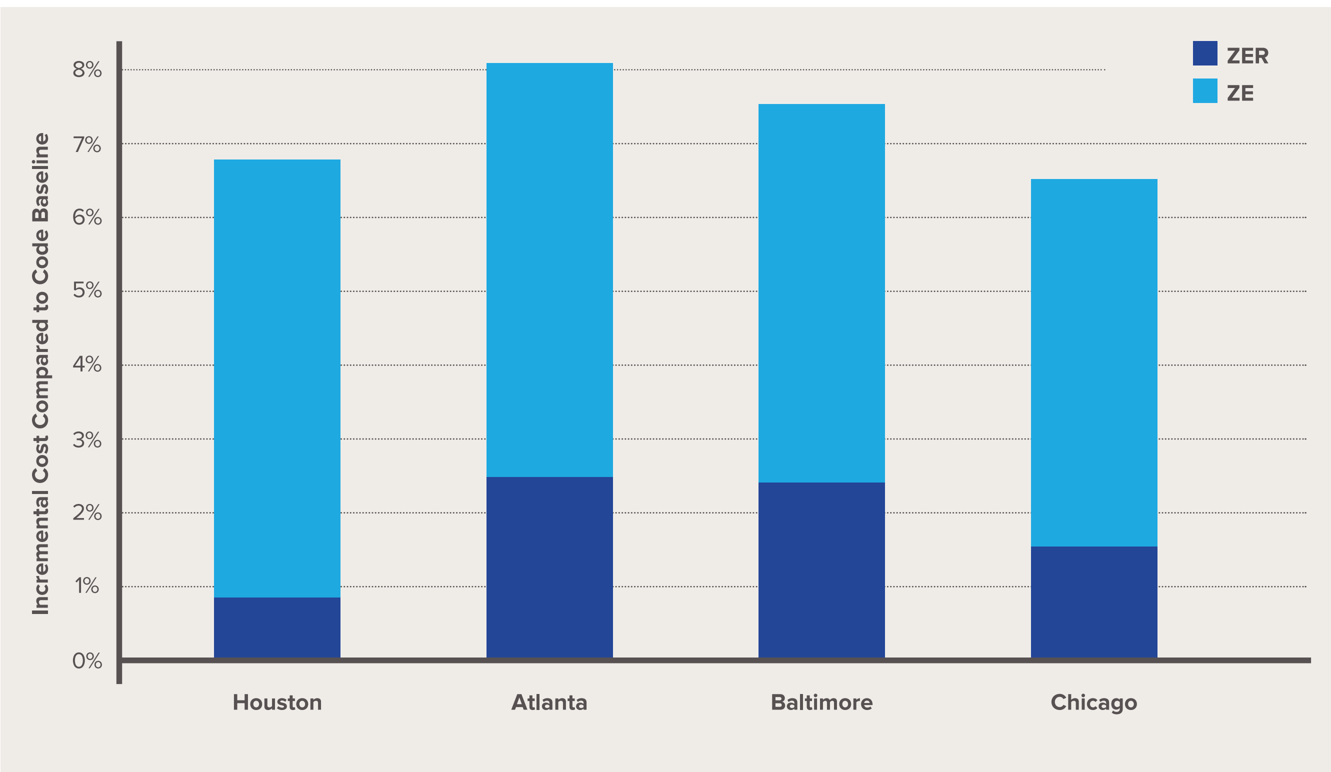
EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

Building new single-family homes to zero-energy (ZE) or zero-energy ready (ZER) home standards can save consumers thousands of dollars over the home's life cycle. ZE homes produce as much renewable energy as they consume over the course of a year, and ZER homes have similar levels of efficiency without on-site solar photovoltaics (PV). In addition, increasing market penetration of ZE homes can help cities meet their aggressive greenhouse gas emission goals while building a more future-proofed and energy-secure building stock.

Despite these benefits, ZE and ZER homes make up less than 1% of the residential market, partially due to outdated perceptions of the incremental cost for these offerings. This report demonstrates that the cost increase to build a ZE or ZER home is modest (with incremental costs of 6.7%–8.1% for ZE homes and 0.9%–2.5% for ZER homes as shown in Figure 1)—far less than consumers, builders, and policymakers may realize—and highlights methods builders and policymakers can use to drive increased market penetration.

FIGURE 1: INCREMENTAL COSTS FOR ZE AND ZER HOMES



Consumer Thresholds

Rocky Mountain Institute (RMI) compared the incremental costs of building ZE and ZER homes in four US locations against four key consumer cost thresholds that reflect the metrics that both homebuyers and builders use to make investment decisions:

- **Mortgage:** The anticipated energy savings over the life of the mortgage.
- **Resale:** The anticipated energy savings over 12 years (the typical length of time homeowners stay in a home).
- **Consumer Willingness to Pay (WTP):** The 4% first cost premium customers have stated they're willing to pay, according to consumer research.
- **First Cost:** The cost to build an identical home that meets local energy code.

When the incremental costs of building ZE and ZER homes are equal to or less than the cost thresholds, decision makers are more likely to bear the cost of investment in ZE or ZER homes. In many cases, the cost thresholds have already been achieved. Figure 2 and Figure 3, respectively, summarize the results for ZER and ZE homes compared against these cost thresholds.

FIGURE 2: INCREMENTAL COSTS FOR ZER HOMES COMPARED AGAINST COST THRESHOLDS

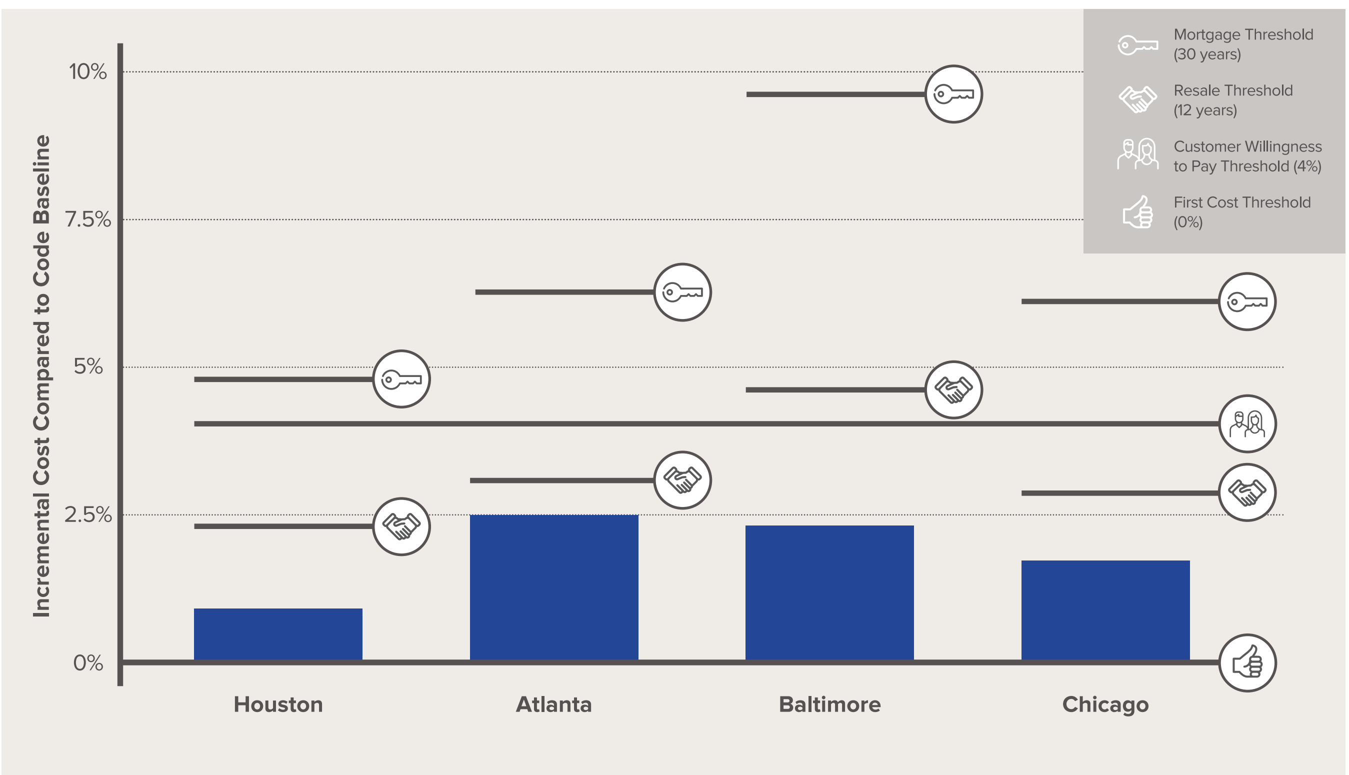
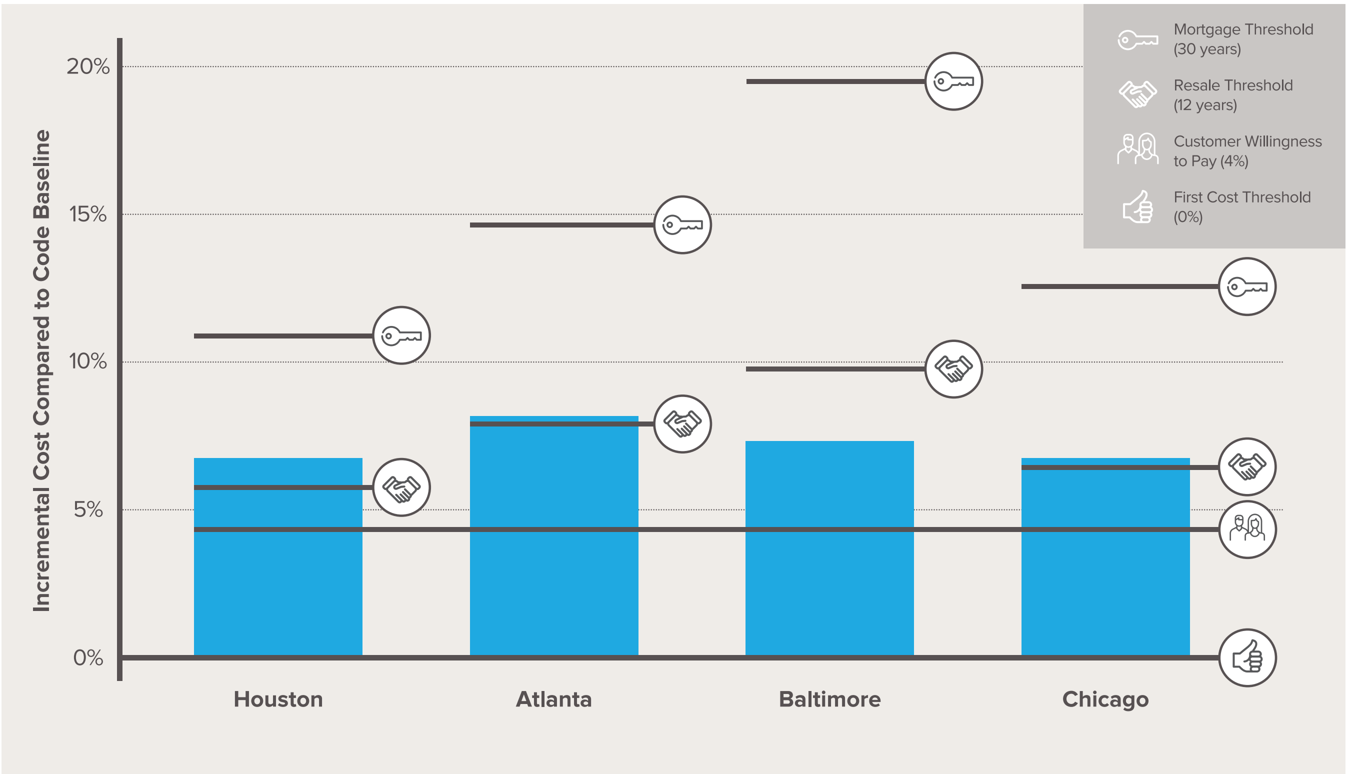


FIGURE 3: INCREMENTAL COSTS FOR ZE HOMES COMPARED AGAINST COST THRESHOLDS



Actions for Builders and Policymakers

Builders can use the recommendations provided in this report to fine-tune home designs and construction processes to minimize incremental costs. This report also outlines key actions that policymakers can take to drive increased adoption of ZE and ZER homes in their jurisdictions. Both builders and policymakers are essential to driving progress in this industry.

For the cases in which the cost thresholds are not met, it is important to remember that costs of building ZE and ZER homes continue to decline, with a projected incremental cost for ZE homes of 3%–5% by 2030. Although our analysis yielded concrete recommendations for cost-optimal ZE home designs, a variety of other solutions are available and may be specified based on local conditions or consumer priorities. This analysis also focused on all-electric solutions; we did not analyze natural gas options.

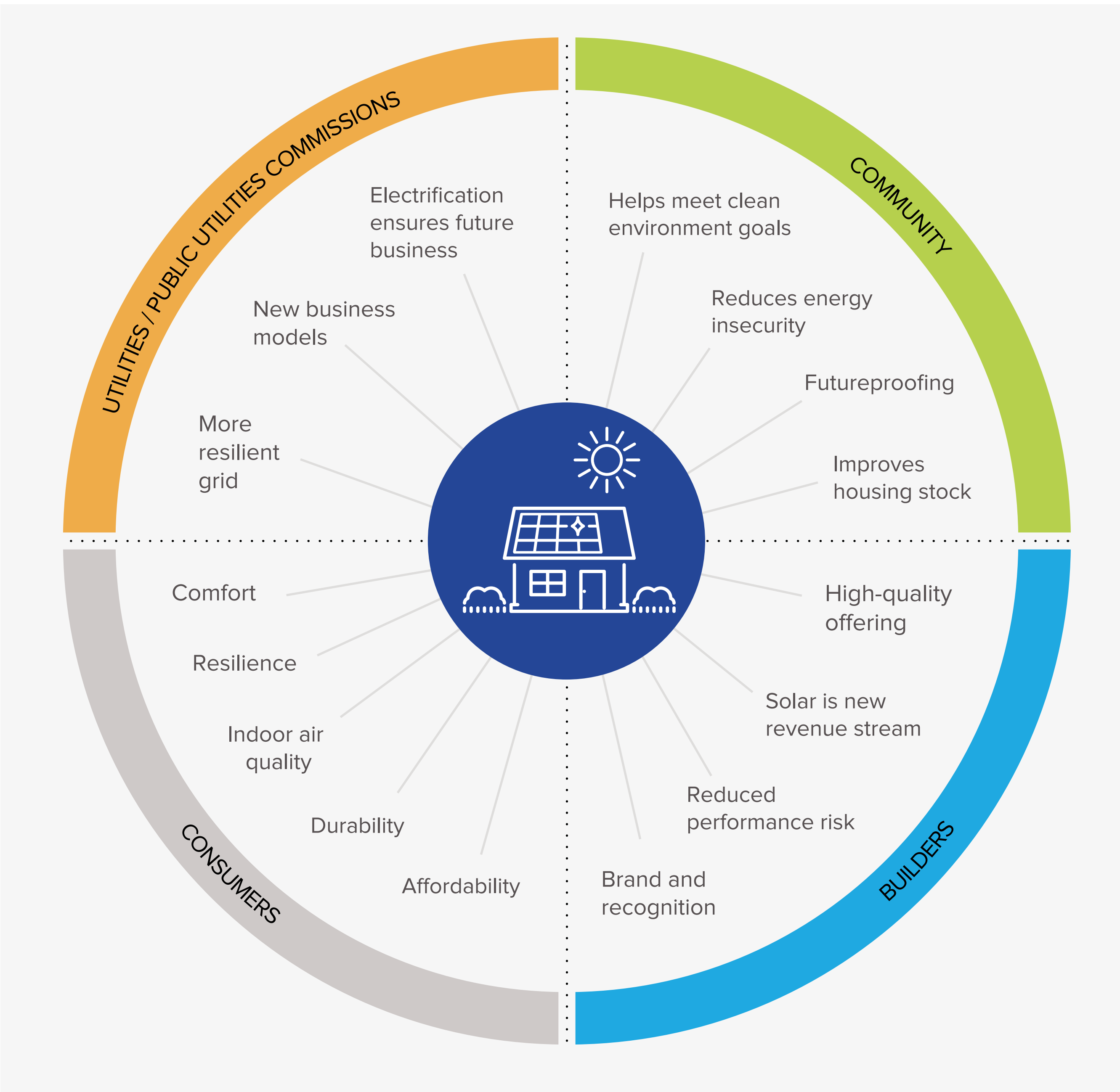
01

THE COST BARRIER FOR ZE HOMES

THE COST BARRIER FOR ZE HOMES

The energy performance of highly efficient ZE and ZER homes can provide myriad benefits to homeowners, builders, utilities, and communities at large, as documented in a growing body of evidence.[1] Figure 4 provides a summary of these benefits across key stakeholder groups.

FIGURE 4: BENEFITS OF ZE HOMES

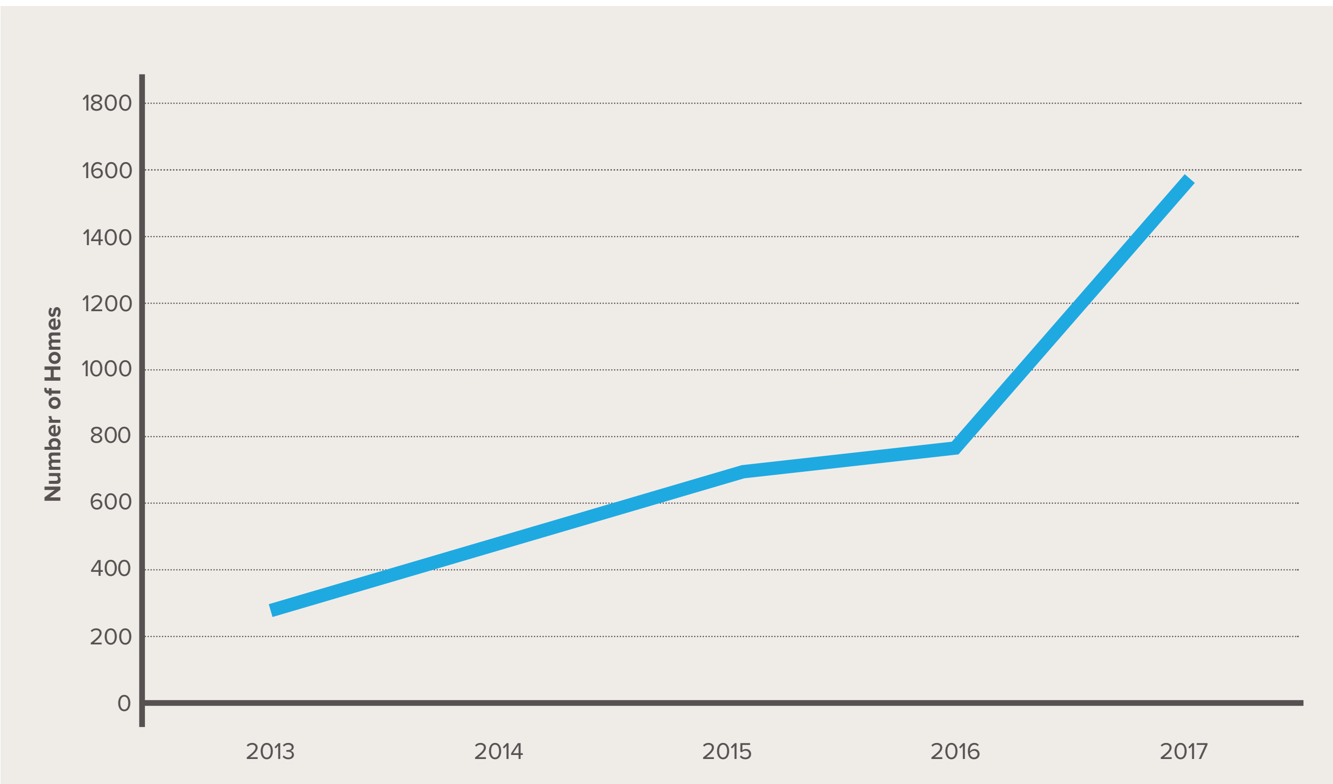


Yet, most stakeholders never consider the opportunity that ZE and ZER homes represent due to outdated perceptions of the price tag these benefits carry: A National Association of Home Builders (NAHB) 2017 survey found that 81% of single-family home builders either don't know how much more it will cost to build a green home or thought green home building would add more than 5% to the cost, while 58% think consumers are willing to pay less than a 5% premium for a green home.[2] Consumer research yields a similar result for home buyers. These perceptions are preventing or disincentivizing stakeholders from acting in their own long-term interests.

While ZE and ZER single-family homes still comprise less than 0.1% of the current US residential housing stock,[3] the market for these homes is growing rapidly: Net Zero Energy Coalition reported an astounding 60% market growth from 2016 to 2017,[4] while DOE's Zero Energy Ready Home (ZERH) program reported 104% growth in certified projects over the same time period (see Figure 5). Additionally, DOE's ZERH program has forecasted 1,150 certified homes in 2018, nearly doubling the number of certified homes for the third straight year.

This report attempts to further accelerate that growth by addressing outdated cost perceptions and showing

FIGURE 5: ZERO ENERGY READY HOMES CERTIFIED EACH YEAR[5]



that the superior long-term performance of ZE and ZER homes deserves consideration from a variety of stakeholders. The following pages identify the current incremental cost of ZE and ZER homes, describe best practices for builders to minimize costs, shed light on dropping cost trends, and provide policymakers with recommendations for how to promote growth of ZE homes in their cities.

This report is focused on single-family homes. A similar report focused on multifamily housing will be produced at a later date.

What Is Zero Energy? What Is Zero Energy Ready?

A ZE home is a highly efficient home that produces as much renewable energy as it consumes over the course of the year. This report defines a ZER home as a home that could be certified under the DOE ZERH program. DOE defines a ZER home as "a high-performance home so energy efficient all or most annual energy consumption can be offset with renewable energy." A home builder may choose to pursue ZER instead of ZE if there is excessive roof shading (e.g., trees, urban locations), unconducive roof design for solar PV (e.g., orientation, complexity), budget constraints requiring a lower up-front cost, or preference to wait until solar prices drop further before purchasing. Although not all buildings can be built to ZE standards, all buildings can be built to ZER standards. ZER helps "futureproof" homes against changing expectations and allows for other renewable energy solutions, such as community solar programs, utility renewable power purchase options, and purchase of carbon offsets. The DOE ZERH program requires independent verification to ensure that homes will perform as intended, and it offers easy-to-follow guidance for builders that are new to building ZER homes.

Although ZE homes don't need to be all electric (this is not a requirement of the DOE ZERH program), this report focuses on completely electric ZE homes. Natural gas, fuel oil, and propane in residences currently account for one-tenth of total US carbon emissions and cannot be directly offset using renewables.[6] Further, RMI's research and analysis have found that in many cases electrification of space and water heating in new construction homes reduces homeowner costs over the lifetime of the appliances when compared with fossil fuels.[7] This focus also reflects the industry trend of electrifying building components as related technology matures: most notably, 43% of new homes now use air source heat pumps (ASHPs) for heating and cooling, compared with 10% of all existing homes as of 2015.[8]

Note that a wide range of terminology exists for these super-efficient building definitions. ZE homes are commonly referred to as net-zero energy homes; ZER homes are similarly referred to as net-zero energy ready homes. Net-zero carbon homes share very similar features but may not be identical to a ZE home. This report uses the terms "zero energy" and "zero-energy ready" to align with DOE-adopted terminology.

Introducing Cost Thresholds

Many prospective homebuyers don't factor in long-term costs associated with homeownership, such as utility bills, maintenance, and future value. Although some consumers might be willing to overlook sticker price because they understand the added benefits of a ZE home, this is not typical. Therefore, to increase market penetration, ZE and ZER homes need to be financially appealing to the broader market.

RMI centered the analysis in this report upon four "cost thresholds" that reflect metrics that both homebuyers and builders use to make investment decisions. When these cost thresholds are achieved (as some already have been), these decision makers are more likely to bear the cost of investment in ZE or ZER homes. The cost thresholds considered are:

- **Mortgage Threshold:** This threshold compares the incremental cost to build a ZE and ZER home (compared with an identical home that meets local energy code efficiency standards) to the net-present value of the anticipated energy savings over the life of the mortgage (**30 years** is most common).[9] This threshold might be desirable to long-term consumers who have no intention of moving and are likely interested in owning a ZE home for more than just financial reasons. Another way of thinking about this threshold is using net monthly cash flow: if the monthly mortgage payment increase is less than or equal to the monthly energy bill savings, then the mortgage threshold has been achieved.[10]

- **Resale Threshold:** This threshold compares the incremental cost to build a ZE and ZER home (compared with an identical home that meets local energy code) with the net-present value of the anticipated energy savings over the typical length a homeowner is expected to stay in the home (which is **12 years**).[11]

- **Consumer Willingness to Pay Threshold:** This threshold compares the incremental cost to build a ZE and ZER home (compared with an identical home that meets local energy code) with the first cost premium customers have stated they're willing to pay in consumer research. According to the latest NAHB research, 42% of consumers are willing to pay a **4% premium for a green home**, and 51% of consumers are willing to pay a 4% premium for a ZE home, according to an Opinion Dynamics survey performed in California.[12] Another study by NAHB found that consumers would be willing to spend an average of $10,732 more for every $1,000 in annual energy savings, which roughly translates to a **3.9% incremental cost**.[13] Although none of these consumer WTP metrics perfectly represents how much more consumers nationally would be willing to pay for a ZE home, combined they point to a similar threshold that people would be willing to pay for a ZE home—roughly a 4% premium.

- **First Cost Threshold:** This threshold compares the incremental cost to build a ZE and ZER home with an identical home that meets local energy code. If the first cost threshold is achieved, a ZE and ZER home will **cost the same** as a code-compliant home. If this threshold is achieved, the cost barrier to ZE and ZER homes has been eliminated.

Policymakers can use these cost thresholds to inform ZE programs and determine the level of incentives or cost reduction strategies required to overcome the first cost objection. Builders can use these cost thresholds to set targets for cost reduction in their ZE and ZER homes. This can help support their net profits by reducing costs and increasing the pool of customers they can serve with ZE and ZER homes.

02

THE CURRENT COST OF ZE HOMES

THE CURRENT COST OF ZE HOMES

RMI's techno-economic analysis confirmed that ZE homes have already passed the mortgage and some resale thresholds and that ZER homes have already passed the mortgage, resale, and consumer WTP thresholds in most US markets. To determine the current state of ZER and ZE home costs, RMI analyzed a typical single-family home in four cities (Houston, Atlanta, Baltimore, and Chicago) representing International Energy Conservation Code (IECC) climate zones 2–5, where 90% of new construction homes are being built.[14] These locations collectively represent an array of utility rates, labor costs, and solar resources, providing a diverse look at ZE costs across the country. The updated version of this report now also includes an addendum covering findings for climate zones 6 and 7.

RMI used BEopt, a free software tool developed by the National Renewable Energy Laboratory (NREL) to complete this analysis. BEopt can model various energy efficiency measure packages to find the "optimal" ZE package at the lowest cost.[15] Embedded in BEopt is a measure database that is set up to easily model certain envelope, lighting, large appliance, heating and cooling equipment, and hot water energy conservation measures (ECMs). The measure database has costs associated with each ECM using the National Residential Efficiency Measures Database (NREMD); these costs were updated or verified using RSMeans data; American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) data; National Institute of Standards and Technology (NIST) data; Electric Power Research Institute (EPRI) data; manufacturer cost quotes; and other available resources. The cost resource used for each ECM can be found in Appendix A.

RMI derived the baseline home cost from RSMeans and altered cost by location using RSMeans city-specific location factors. We also created a baseline model in BEopt to determine baseline energy consumption and baseline costs associated with energy-related equipment. We then compared the cost-optimized ZE home with the baseline BEopt home cost to determine incremental cost of energy-related equipment. Each baseline model was the same 2,200-square-foot, three-bedroom, two-bathroom home with a two-car garage but envelope and HVAC properties were climate zone-specific to the levels required by IECC 2009 energy code. Because the home was modeled to mimic typical construction, passive design strategies, such as optimized window placement, were not considered. **IECC 2009 energy code was selected as the baseline code** because that is the most common code in the United States,[16] and most cities with an energy code that isn't IECC 2009 have a more aggressive code, which would result in even smaller incremental costs to achieve ZE or ZER homes. Additionally, one goal of this analysis is to be able to scale the results from the four-city analysis throughout the United States. ZE and ZER home costs vary widely based on location. Labor and material rates, climate zones, utility rates, and building energy codes all play a role in determining the incremental cost to construct a ZE and ZER home. Appendix B summarizes how these results can be used to approximate the cost of ZE and ZER homes in 50 other cities as well as a methodology to use the results to approximate the cost in additional cities. Additional details about the assumptions that went into the baseline building models can be found in Appendix A. The results from the four-city analysis are summarized in Table 1.

TABLE 1: RESULTS FROM THE BEOPT ANALYSIS

	CZ2	CZ3	CZ4	CZ5
Modeled City	Houston, TX	Atlanta, GA	Baltimore, MD	Chicago, IL
Utility Energy Rate ($/kWh)	$0.096	$0.121	$0.147	$0.122
Baseline Energy Use Intensity (kBtu/sf/yr)	22.0	23.6	26.9	33.1
Proposed Energy Use Intensity (kBtu/sf/yr)	13.0	13.3	13.8	16.0
Solar PV Size (kW)	6.5	6.2	6.8	8.4
Baseline Cost ($)	$228,479	$242,243	$253,254	$346,848
Incremental Cost for ZER Homes($)	$2,065	$6,094	$5,993	$5,368
Incremental Cost for ZER Homes (%)	0.9%	2.5%	2.4%	1.5%
Incremental Cost for ZE Homes ($)	$21,240	$25,314	$24,693	$30,736
Incremental Cost for ZE Homes (%)	9.3%	10.4%	9.8%	8.9%
Incremental Cost for ZE Homes with ITC ($)	$15,488	$19,548	$19,083	$23,125
Incremental Cost for ZE Homes with ITC (%)	6.8%	8.1%	7.5%	6.7%

ZE homes have an average 7.3% cost premium and ZER homes have an average 1.8% cost premium compared with code baseline efficiency homes, based on the techno-economic analysis performed by RMI and summarized in Table 1. This is the cost to builders and does not include the cost of land. Incremental increases for ZE homes for developers and home buyers will be a smaller percentage of the total cost.

ZER Cost Thresholds Snapshot

The maximum incremental cost to meet each cost threshold was calculated and compared with the current incremental cost to build ZER homes. Figure 6 summarizes the results. Houston has the lowest mortgage and resale thresholds because it has the lowest utility rates, as Table 1 shows. The city also has a lower incremental cost because it doesn't require significant envelope upgrades beyond IECC 2009.

FIGURE 6: SUMMARY OF ZER HOME COST THRESHOLD ACHIEVEMENT

	Houston (CZ2)	Atlanta (CZ3)	Baltimore (CZ4)	Chicago (CZ5)
ZER Incremental Cost	$2,065	$6,094	$5,993	$5,368
Mortgage Threshold (30 years)	✔ $10,980	✔ $15,563	✔ $23,305	✔ $20,619
Resale Threshold (12 years)	✔ $5,576	✔ $7,903	✔ $11,835	✔ $10,472
Customer Willingness to Pay Threshold (4%)	✔ $9,139	✔ $9,690	✔ $10,130	✔ $13,874
First Cost Threshold (0%)	✖ $0	✖ $0	✖ $0	✖ $0

ZER homes are consistently less expensive than the mortgage, resale, and consumer WTP thresholds. Surprisingly, these homes almost meet the first cost threshold; on average, they only cost 1.8% more than a code-compliant home.

ZE Cost Thresholds Snapshot

The maximum incremental cost to meet each cost threshold was calculated and compared with the current incremental cost to build ZE homes. Figure 7 summarizes the results.

ZE homes consistently passed the mortgage threshold and are close to passing the resale threshold. This analysis includes the solar Investment Tax Credit (ITC), a federal tax credit that reduces solar cost by 30% until 2019. This tax credit is in the process of being phased out; the impact of this phaseout is addressed in the "Solar PV Installed Costs" section of the report.

FIGURE 7: SUMMARY OF ZE HOME COST THRESHOLD ACHIEVEMENT

	Houston (CZ2)	Atlanta (CZ3)	Baltimore (CZ4)	Chicago (CZ5)
ZE Incremental Cost	$15,488	$19,548	$19,083	$23,125
Mortgage Threshold (30 years)	✓ $26,715	✓ $35,927	✓ $49,118	✓ $45,414
Resale Threshold (12 years)	✗ $13,567	✗ $18,245	✓ $24,945	✗ $23,063
Customer Willingness to Pay Threshold (4%)	✗ $9,139	✗ $9,690	✗ $10,130	✗ $13,874
First Cost Threshold (0%)	✗ $0	✗ $0	✗ $0	✗ $0

How Does Builder Expertise Affect Cost?

Builder expertise and experience with ZE homes play a large role in the incremental cost to build a ZE home. Builders new to ZE homes might initially see higher costs than the costs highlighted above, but new ZE builders should be able to achieve these costs or lower as they optimize technical solutions and get crews acclimated to these approaches. This learning curve will likely be much steeper for minimum code builders compared with ENERGY STAR builders, but all builders should rapidly find opportunities for cost reductions from systems integration and optimization often only gained with experience. A recent NAHB study showed that builders that build majority green homes think green homes have less than a 4% incremental cost to build, whereas builders that have only a small green building portfolio typically think it has a 10% incremental cost.[17] When builders are first starting to build ZE homes, there is a large learning curve. The typical subcontractors they work with might not be familiar with the new technology, selection of the cost-optimal package may take a few iterations, and builders need to integrate completely new processes into their design, such as the Home Energy Rating System (HERS) rater.

Could Local Incentives Help Achieve Cost Parity?

This analysis conservatively assumes no local incentives. Where efficiency incentives are available, ZER homes may already have a lower cost than standard construction. For example, in Chicago, Commonwealth Edison offers incentives for appliances, smart thermostats, mini splits, and hot water heat pumps, for a combined incentive of $1,450. These incentives bring ZER homes even closer to cost parity with only a 1.1% incremental cost compared with a code baseline home. For local incentives to help increase market penetration of ZE buildings, incentives will need to be effectively communicated to builders and easy to use.

Could a Solar PPA or Lease Help ZE Homes Achieve Cost Parity?

Although this analysis assumes outright purchasing of solar PV, financing options could offset most or all PV first costs and spread them over the life of the system. Because third-party solar providers offer power purchase agreements (PPAs) and solar leases, homeowners can use these financing vehicles to capture the Modified Accelerated Cost Recovery System (MACRS) tax credit, which is normally available only to businesses.[18] In some locations, PPA providers can offer contracts that provide homeowners with cheaper electricity rates than those available through utilities, allowing consumers to purchase ZE homes at ZER prices.[19] Policymakers can encourage businesses to offer PPAs and loans by working with utilities to offer favorable interconnection and net-metering policies and local financial incentives and by providing clarity around any legal or regulatory requirements for third-party solar ownership models.

The Added Cost of Ensuring Indoor Air Quality

ZE and ZER homes have better indoor air quality than most residential homes on the market because they require mechanical ventilation, which means that fresh air entering the home isn't dependent on occupants opening windows or high levels of infiltration. Having good indoor air quality reduces the risk of mold, asthma symptoms, moisture, radon, carbon monoxide, and toxic chemicals.[20] Better indoor air quality can reduce eye irritation, allergies, headaches, and respiratory problems. To qualify for the ZER certification, a home must also be certified under the US Environmental Protection Agency (EPA) Indoor airPLUS program, which adds an estimated $1,000 to the incremental cost.[21] This would have a minor effect on the incremental cost. For example, this would increase the ZER cost in Chicago from 1.5% to 1.8%. This added cost comes from requirements such as radon-resistant construction in EPA Radon Zone 1; supplemental dehumidification in hot/humid climates; low-formaldehyde wood products and adhesives; corrosion-proof rodent screens; low-volatile organic compound (low-VOC) interior paints, finishes, and carpets; home ventilation before occupancy; and equipment manuals. This program also improves pest management in the home, which reduces residue from pests that can trigger allergy and asthma attacks. Although Indoor airPLUS certification is required to qualify for the DOE ZERH program, this cost was not included in the cost thresholds report because a home can become ZE without being certified.

Are ZE Homes More Resilient?

ZE homes can provide an added resilience value to homeowners if the right components are in place. However, solar PV alone doesn't help with resilience currently because most grid-tied solar PV systems are designed to turn off during a power outage. One low-cost solution to this challenge is a secure power supply inverter, which allows solar PV systems to supply energy to ZE homes during grid outages at an added cost of only **$350 to $400**.[22] The technology does have some restrictions: It will only provide power when the solar PV system is producing energy, and it can only supply a set amount of power. This low-cost solution would help during a natural disaster, but it would still leave ZE homes without power at night and wouldn't support 100% of typical energy usage in the home.

An even more robust resiliency solution is to add an energy storage system, which can store energy produced by a solar PV system to be used even when the sun isn't shining. Energy storage systems provide resilience to homeowners and stability to the electricity grid and can even insulate homeowners against changes to utility rate structures (such as time of use, demand charges, or elimination of net metering). An energy storage system adds **$7,900 to $14,600** to the total ZE package before incentives[23]—but, like solar, costs are dropping rapidly. An energy storage system would allow the home to move away from zero energy and toward zero carbon and resilience.

Policymakers should include energy storage and secure power supplies in conversations about ZE policies to ensure a solution that minimizes grid costs and improves reliability. Although energy storage is rarely economical in residential applications under current conditions (due to a lack of demand charges or time-of-use rates), new utility business models often emphasize these strategies. Policymakers should work with utilities to ensure that future efforts to address grid volatility incorporate incentives and rate structures that support energy storage solutions. Builders and policymakers should also consider the Insurance Institute for Business & Home Safety FORTIFIED Home program for regionally specific design strategies to help fend against natural hazards.

Builders can also work with their local utility to help promote resilient ZE homes. Mandalay Homes, one of the largest ZE home builders in the United States, is building 3,000 ZE homes in Arizona with solar PV and energy storage and is coordinating with the local utility to set up a plan for the utility to pay homeowners to use the stored power.[24]

03

COST-OPTIMAL BUILDING PRACTICES FOR ZER

COST-OPTIMAL BUILDING PRACTICES FOR ZER

There is no "one-size-fits-all" solution for constructing a cost-optimized ZER home. A truly cost-optimized design is influenced by not only local climate but also site constraints, local labor rates, utility tariffs, and existing financial incentives. However, our analysis revealed several universal insights that can provide guidance for builders and policymakers alike.

HVAC: Heat Pumps Are an Essential Opportunity

Until recently, heat pumps have primarily been relegated to the milder winter climates of the southeastern United States due to an inability to operate in subfreezing temperatures. However, technological advancements have now yielded hundreds of models that can operate efficiently in temperatures as low as 5°F, with some units performing down to -12°F,[25] allowing year-round performance even in the cold climate of Chicago.[26] These systems now represent an essential component for ZE and ZER homes.

A range of options exists for builders specifying heat pump HVAC systems:

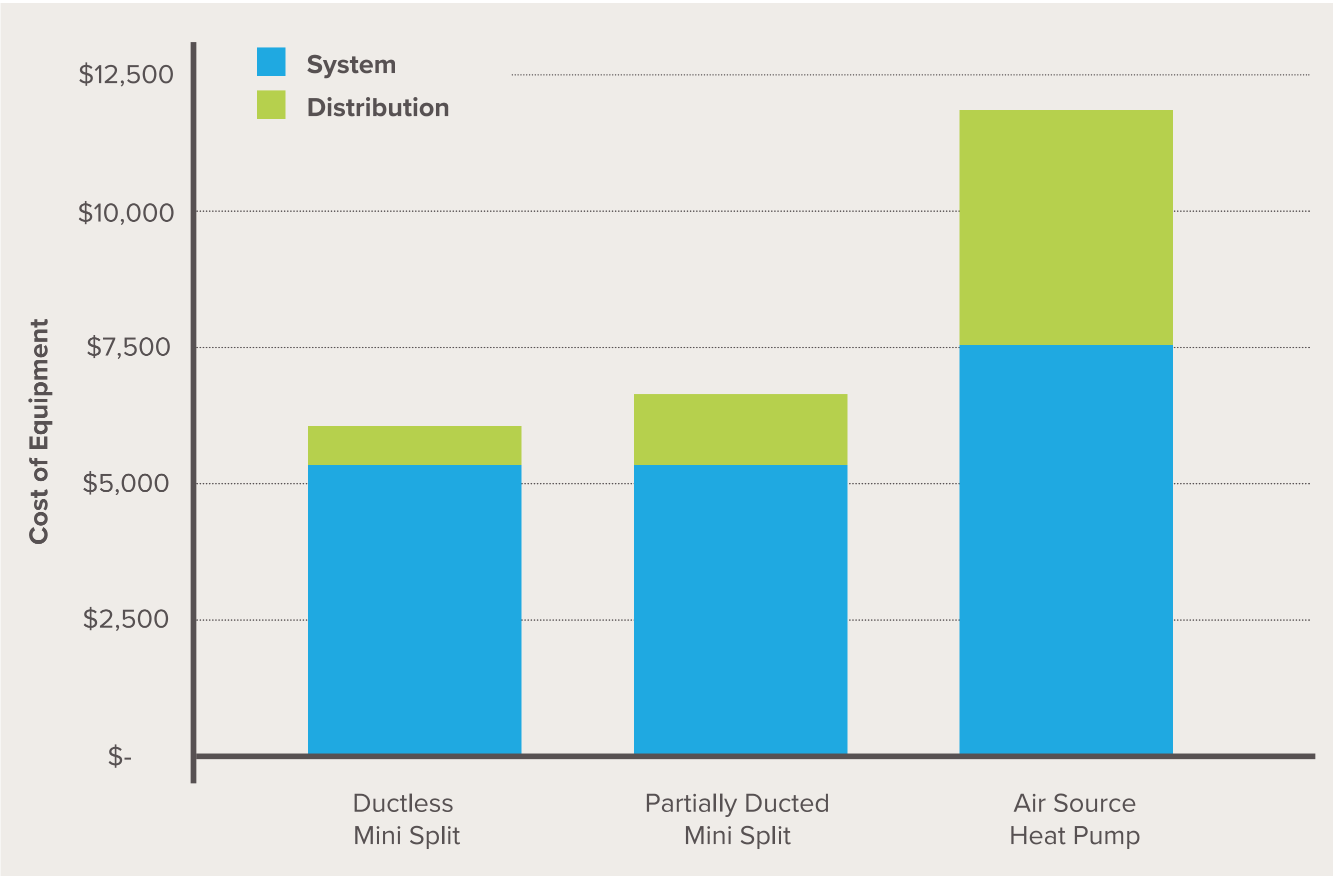
- **Ductless Mini Splits:** Mini split systems are capable of outperforming the efficiency of best-in-class central air conditioners (ACs) by over 30%.[27] Ductless mini splits can represent the lowest-cost system option in milder climates and smaller homes where whole-house comfort can be provided with only two heads and high-transfer grilles between rooms. Using additional heads can provide occupants with a level of personalized comfort control that isn't possible with centralized systems. Builders and policymakers must work with experienced installers or manufacturers to understand the limitations of ductless systems in their local context.

- **Partially-Ducted Mini Splits:** Builders can incorporate ductwork into mini split systems to promote whole-house comfort without the need for additional heads. They can use exposed ductwork, or tray or drop ceilings, to ensure that perimeter spaces are adequately ventilated while avoiding the energy losses introduced by situating ductwork in unconditioned attics. Targeting home layouts and mini split siting to minimize necessary distribution equipment can reduce duct costs by over 50% compared with traditional central system ductwork at a similar cost to ductless systems (see Figure 8 for a cost comparison).

- **ASHPs:** Centralized ASHP systems are typically more robust than mini split systems and do not present the same home design constraints (e.g., a need for open floor plans and careful siting of HVAC equipment). Centralized ASHPs are also capable of incorporating high-capture filtration systems,[28] a potentially significant benefit in urban environments. Progress in this industry is yielding a variety of offerings capable of competing with the cost of mini split systems.

Figure 8 provides a sampling of costs for the three heat pump HVAC systems specified for a ZER home in Baltimore. It is important to note that these costs are estimated for a single-family home layout and that cost-optimal solutions may vary for different home designs and climates.

FIGURE 8: COST OF MODELED HEAT PUMP HVAC OPTIONS FOR BALTIMORE[29]



Current-generation mini split ACs use an inverter to drastically increase efficiency by allowing the unit to ramp up or slow down to match heating or cooling loads, yielding unique commissioning and maintenance requirements that local contractor pools may not be adequately trained to handle. Policymakers can directly address this potential bottleneck by promoting training and education programs.

Ductless mini split units may not be the ideal HVAC solution for all situations. Radiant floor systems bring a measurable comfort advantage that may be appropriate in luxury applications. In mild climates, home builders may be able to avoid heating or cooling systems entirely. Like all the recommendations in the report, builders should perform their own research and consider local factors before specifying heat pump HVAC systems.

Easy Wins in Lighting, Appliances, and Water Fixtures

ENERGY STAR–certified appliances (namely refrigerators, dishwashers, and clothes washers), ENERGY STAR–certified LED lighting,[30] and EPA WaterSense–certified water fixtures were cost-optimal measures for all four locations modeled. These efficiency measures combined were able to reduce electric loads enough to downsize the necessary solar PV system by 1.5 kW–1.9 kW (a $3,000–$4,100 cost savings) at an average incremental cost of only $260.

It is important to acknowledge that some home builders and developers may be skeptical of the minimal incremental cost reported for these measures. LED lighting in particular was known as a low-value efficiency measure just a decade ago. However, costs have dropped by over 75% since 2010 and are now nearing cost parity with conventional options, while LED bulb efficiency has more than doubled over the same timeframe.[31] It may be necessary to educate builders about the rapidly changing market to ensure support for these solutions.

Heat Pump Water Heaters

Heat pump water heaters (HPWHs) use the same process as heat pump HVAC systems to provide domestic hot water (DHW) at an efficiency two to three times greater than conventional electric DHW heaters.[32] HPWH systems also cool and dehumidify the space they're in, making them ideal for hot and humid climates.[33] However, experts remain concerned about HPWHs' ability to perform in colder climates. Although the system modeled in this analysis successfully provided hot water year-round (even in Chicago), home builders and policymakers should work to verify that locally available options can provide comfort before specifying HPWH units. Specifying products that align with the Northwest Energy Efficiency Alliance Tier 3 HPWH specification may help ensure robust performance in colder climates.[34]

Beyond cold-climate performance concerns and a substantial added cost, HPWH systems also need more space than conventional systems, add complexity in commissioning and maintenance, and suffer from a reputation for being noisy. Similar to heat pump HVAC systems, there is potential for policymakers to begin addressing this issue by hosting or subsidizing training programs for this technology. If performance issues are a concern, builders could consider tankless water heaters or solar water heating.

Electrification in new developments:
For new housing developments, specifying HPWHs in conjunction with electric heating and cooking systems carries the added benefit of negating the need to install new natural gas pipelines, yielding developers additional cost-saving potential.

Envelope

The builders interviewed for this report used a wide array of framing systems to achieve their ZE designs, including structurally insulated panels (SIPs), insulated concrete forms (ICFs), and double-stud construction. Some builders used triple-pane windows. And much has been made of strategies to minimize air leakage, with builders reporting targets as low as 0.12 air changes per hour (over 50 times below IECC 2009 code).[35] However, our analysis found that even in new construction, many of the most aggressive envelope measures were not part of a cost-optimized design. Table 2 provides a summary of the envelope recommendations detailed in Appendix A.

TABLE 2: RECOMMENDATIONS FOR COST-OPTIMIZED ENVELOPE COMPONENTS

Envelope Component	Cost-Optimized Recommendations
Windows	Use high-performance windows. Specifications vary widely by climate, with an incremental cost range of $360 (climate zone 2) to $2,840 (climate zone 5).
Wall Insulation	Add R5 continuous insulation layer to wall sheathing in climate zones 3 and 4 at an added cost of $2,000–$2,100.
Roof Insulation	Use the minimum required by the DOE ZERH program (i.e., 2012/2015 IECC code levels) as a rule of thumb at an added cost of $300–$1,200.
Slab Insulation	Remain code compliant in all climates.

Although builders can typically construct ZE homes with envelopes that perform only marginally above code based on nominal specifications (such as wall R-value), ZER homes also integrate strategic enhancements (such as thermal breaks, air barrier continuity, and insulation installation quality checks) to ensure that envelopes adequately control moisture and perform to their potential.

Envelopes are far more sensitive to regional climatic conditions (including temperature, humidity, and sunlight availability) than other high-performance building components, and builders must work to ensure that they take these details into consideration when specifying envelope components. Builders should not simply use the recommendations outlined in this report, especially in climate zones outside the scope of our analysis (IECC climate zones 1, 6, 7, and 8), where envelope investments may be more prudent. Working with an energy auditor, or collaborating with other builders in the DOE ZERH program, can lead to smarter design.

For builders, there may be long-term advantages to over-engineering a super-efficient home's envelope design. Thicker walls and windows can reduce noise penetration, potentially increase a home's longevity, and improve indoor comfort in colder climates. Both SIPs and ICF wall systems bring the added benefit of increased seismic and wind resistance. Although these building methods can add thousands of dollars to the hard cost of home construction, they may result in significant cost offsets over time, including quicker construction, fewer tools, less waste, greater dimensional accuracy requiring less work, and inherently fewer defects.

Solar-Ready Roofing

Builders can employ several strategies to minimize the cost of a future PV installation in situations where immediate installation isn't preferred:[36]

- Use roof pitches of 10-30 degrees to allow for flush-mounted installation
- Use roofing that does not require roof penetrations to mount PV systems (e.g., metal stand and seam roofs)
- Minimize roof complexity: avoid wings, ells, and dormers; use gable end roof framing[37]
- Where possible, orient to maximize southern exposure
- Ensure landscaping and neighboring structures do not block solar exposure
- Minimize rooftop equipment, vents, and other obstructions
- Install mounting hardware and safety harness connection points upon roof construction

These measures have no immediate impact on a home's energy performance and may require city or state incentives to support adoption.

04

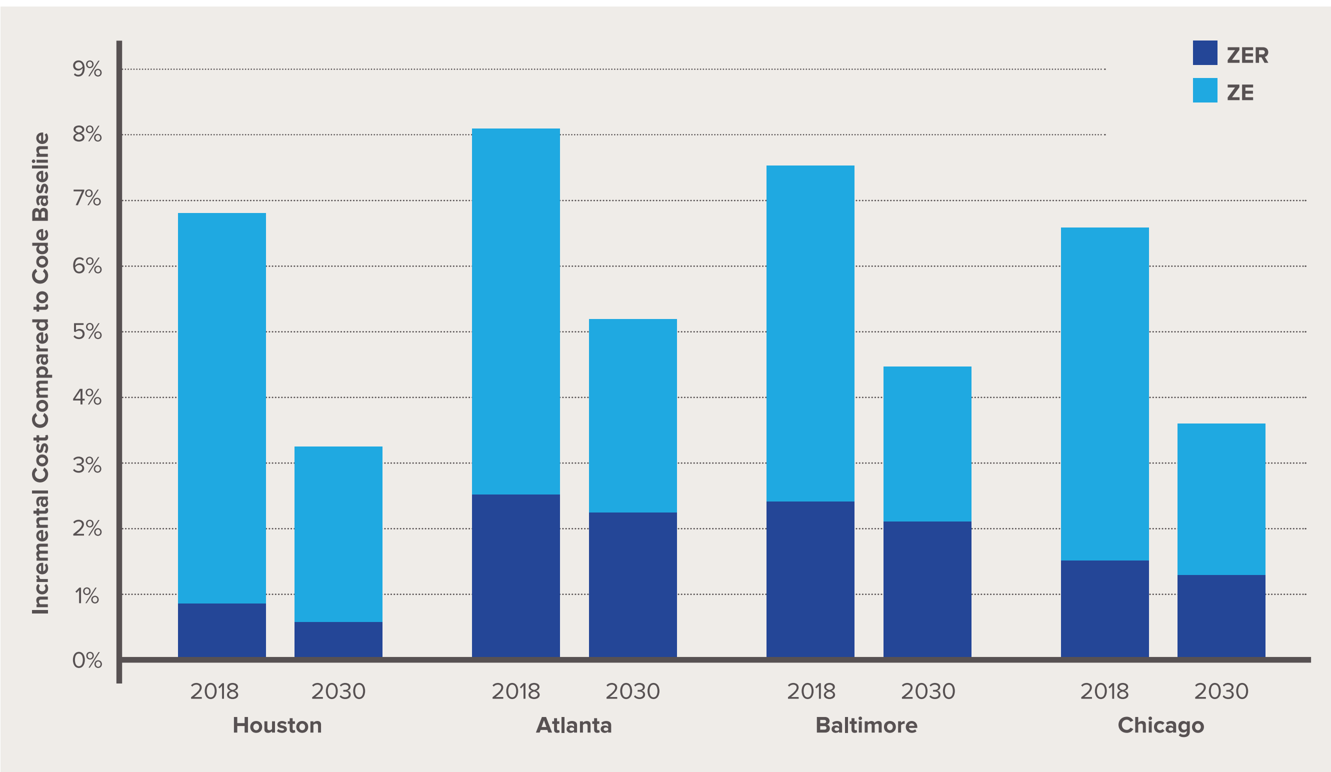
FUTURE COST PROJECTIONS

FUTURE COST PROJECTIONS

Although the results of this report show that constructing ZE homes can be economical for most homeowners in most locations today, it's important to understand how costs are expected to change in the future. Industry progress and demand for super-efficient building components are expected to drive cost savings over the next decade.

The cost factors detailed in this section significantly impact the cost for ZE homes, yielded from declining solar costs and reduced PV system size requirements (due to equipment efficient gains). These factors should bring ZE homes in the four locations modeled within a 3.1%–5.5% incremental cost by 2030, compared with a 6.7%–8.1% incremental cost today. The opportunity for cost savings in ZER homes is less significant, with incremental costs projected to drop roughly 20% by 2030 (see Figure 9).

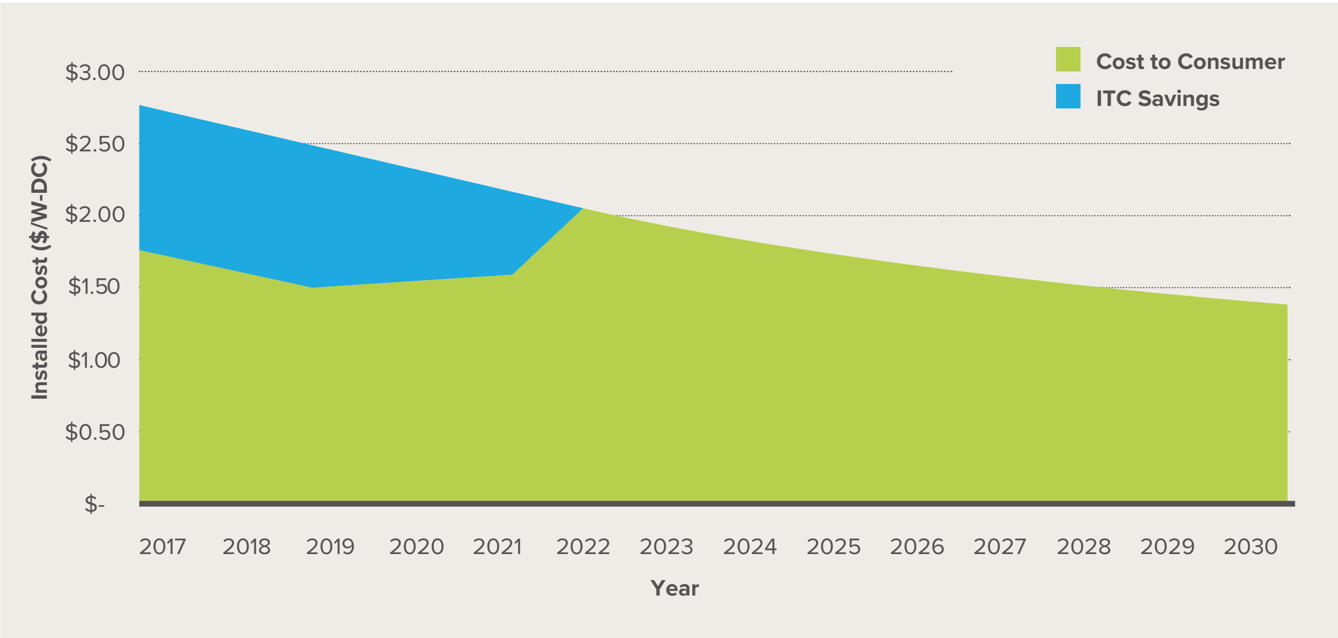
FIGURE 9: INCREMENTAL COSTS FOR ZER AND ZE HOMES, TODAY VS. 2030



Solar PV Installed Costs

Solar PV represents both the most significant incremental cost in reaching ZE today—and the most significant opportunity for future cost savings. However, the phasing out of the ITC could make these systems more expensive for a short time period, as Figure 10 shows.

FIGURE 10: SOLAR PV COST TO CONSUMERS WITH CURRENT ITC PHASEOUT TIMELINE[38]



However, despite a period of volatility with little accumulated savings through 2025, costs are expected to continue declining beyond 2030. NREL projects that $1.10/W rooftop solar may be available to homeowners by the end of 2030; third-party financing mechanisms allowing the capture of MACRS tax incentives could enable sub-$1.00/W PV systems in the same timeframe.

It's important to note that a majority of the cost savings potential for solar PV stems not from projected material cost savings but from soft-cost reductions, which can be accelerated through incentivizing policies.[39]

More Efficient Equipment to Reduce Solar Requirements

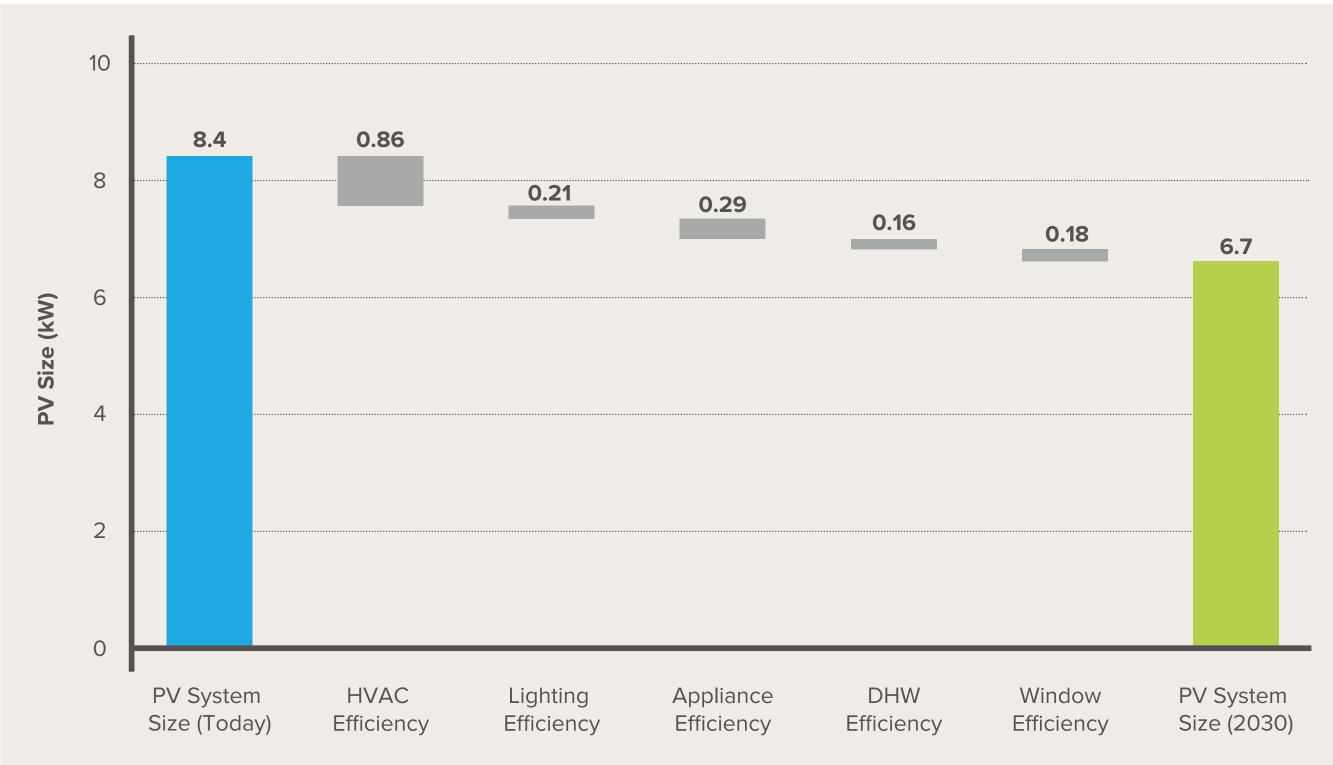
The past decade has yielded impressive progress in the efficiency of many of the building components incorporated in a cost-optimized design. Many of these trends are expected to continue through at least 2030, as summarized in Table 3.

TABLE 3: RECENT PROGRESS AND FUTURE PROJECTIONS IN RESIDENTIAL EQUIPMENT EFFICIENCY

Technology	Recent Progress	Future Projections
Heat Pump HVAC	Heat pump HVAC systems were once relegated to warmer climates but are now capable of operating below -10°F.[40] Efficiency has also drastically improved, with Carrier recently releasing a 42 SEER unit.	Global efforts are underway to commercialize a mini split AC technology that consumes 80% less electricity than the current average, or at least 50% better than current best-in-class offerings.[41]
LED Lighting	Average bulb efficacy has increased from below 50 lm/W in 2010 to roughly 130 lm/W in 2018.[42]	Bulb efficacy is expected to reach 200 lm/W by 2030, a 35% efficiency gain.[43]
ENERGY STAR Appliances	US and California appliance standards continue to drive efficiency gains, with refrigerators increasing efficiency over 40% since 2000.[44]	An additional 20% efficiency gain by 2030 has been assumed in Figure 11.
HPWH	Efficiency factors of 2–2.5 were once typical,[45] but now efficiency factor 3.0–3.5 models are common.[46]	An additional 20% efficiency gain by 2030 has been assumed in Figure 11. Forthcoming innovations may also resolve performance concerns in cold climates.
Windows	The use of thin glass in television screens has reduced material costs by over 80%, making triple-pane windows cost-effective in the coldest climates.[47]	Lawrence Berkeley National Laboratory is working with manufacturers to bring R5 to R7 windows to market at or near cost parity with existing double-pane options.[48]

This expected progress in unit efficiency will significantly reduce the internal load of a ZER home, minimizing the size of the solar PV installation necessary to achieve ZE. Expected cost savings ranged from $1,600 to $2,500 across the four locations modeled in this report.[49]

FIGURE 11: PROJECTED PV SYSTEM DOWNSIZING FROM FUTURE EFFICIENCY GAINS FOR CHICAGO



Other Component Cost Savings

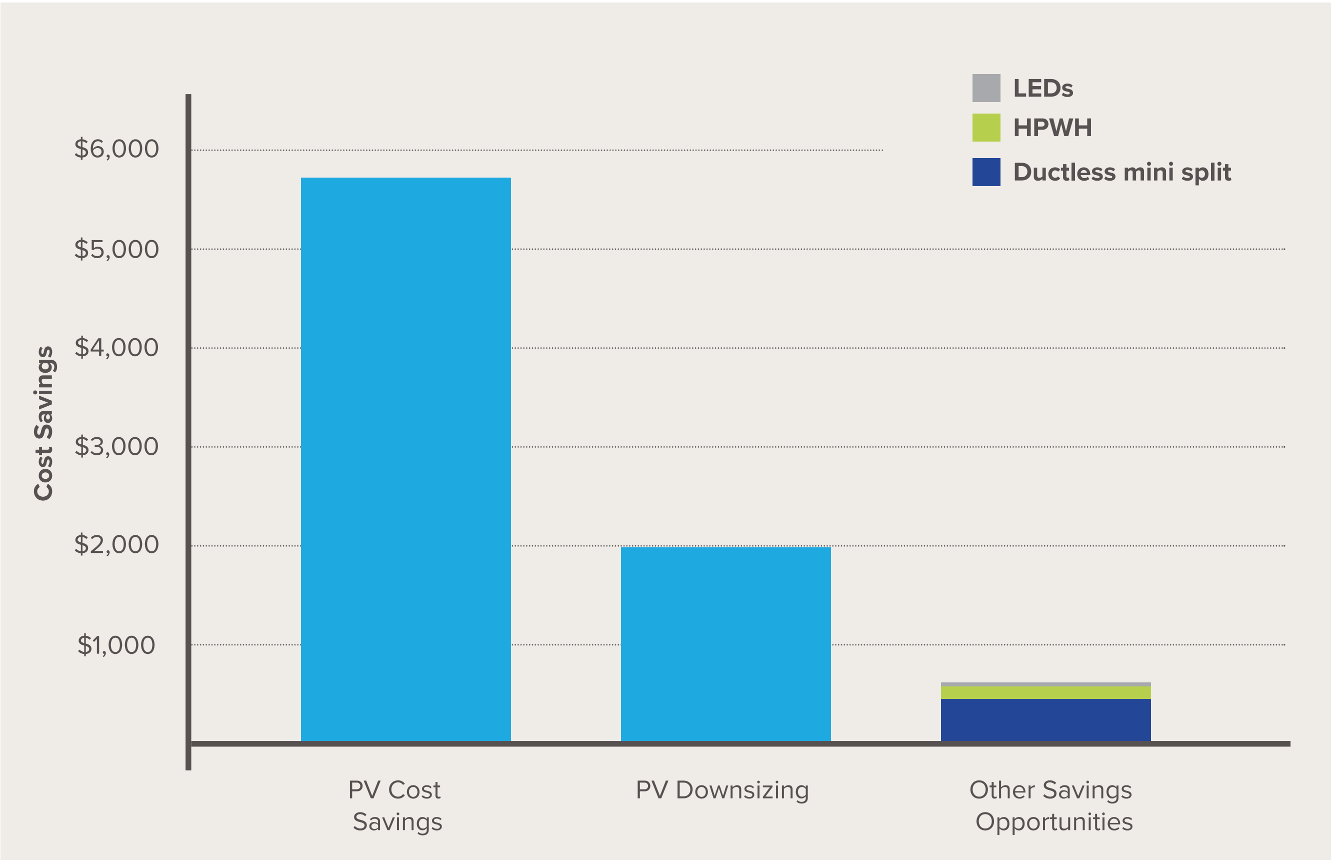
Additional cost savings may occur as other super-efficient building components—particularly HPWHs and HVAC systems—enter the mainstream following consumer demand, builder leadership, and government policies. However, these savings are expected to be minimal in comparison with the solar PV savings available through declining costs and efficiency improvements (as shown in Figure 12).

"With California implementing zero requirements, manufacturers are going to have a much bigger market for their high-efficiency products. I expect that to bring costs down, even for us in Colorado."

GENE MYERS,

Owner and CEO at Thrive Home Builders

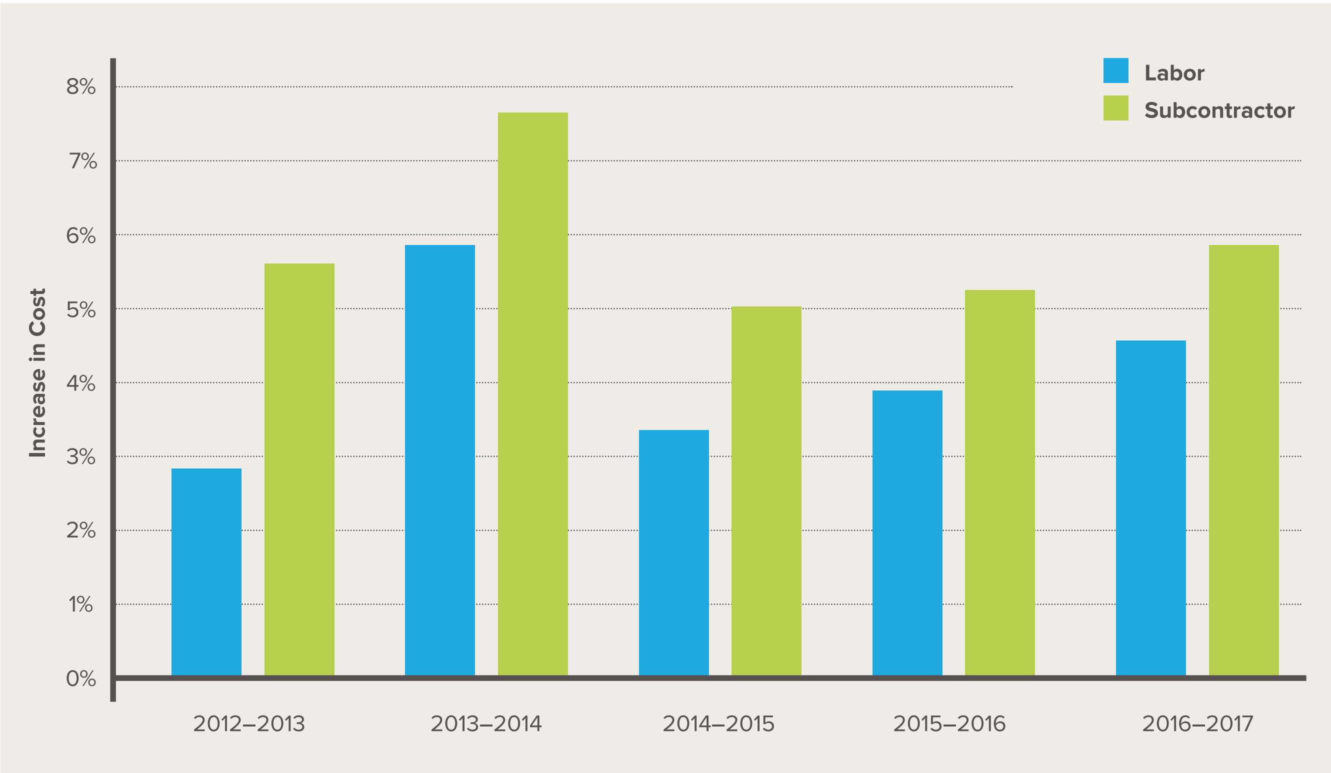
FIGURE 12: COST SAVINGS OPPORTUNITIES BY 2030, AVERAGE ACROSS FOUR LOCATIONS[50]



Labor Costs Yield Uncertainty

The cost of labor is a significant concern for conventional and super-efficient home builders alike. The cost for construction labor has steadily risen since the recession, with the trend recently rising above a 4% per annum increase as shown in Figure 13. Notably, the cost for subcontractor labor has outpaced the cost of labor overall, signifying a shortage of carpenters, electricians, HVAC technicians, and other skilled construction labor.

FIGURE 13: ANNUAL INCREASE IN HOME BUILDING COSTS, 2012–2017[51]



What this means for the incremental cost of ZE homes is unclear. Most of the home builders interviewed for this report noted that their ZE homes required more labor expenditures than code-compliant construction, a sensible conclusion given the technical complexity and lack of subcontractor familiarity with many modern building components. Modern mini split AC units, HPWHs, and air sealing barriers require more effort to properly install and commission than legacy products. However, these labor cost increases are counteracted by the fact that the cost-optimized designs covered in this report avoided advanced framing systems and heating/cooling ductwork (components that many interviewed builders still use in their designs). Whether costs are offset entirely will depend largely on local factors and will require further study.

It is important to note here that the shortage of skilled labor is an ongoing crisis for the residential construction industry—one that policymakers have the potential to influence. Providing or sponsoring training programs focused on high-performance building components represents an essential step for ensuring that the supply of ZE homes is capable of meeting demand—and for turning an industry-wide crisis into an opportunity to proliferate efficient home building practices.

"The labor market aging out is a massive issue for all home builders. This industry simply doesn't have enough resources to meet demand. But the other side of that coin is that as new labor comes on, you can teach them new tricks."

C.R. Herro,
Vice President of Energy Efficiency and Sustainability at Meritage Homes

Note Potential for Evolving Design:
Advancements in nascent building technologies may fundamentally change the cost-optimized design of a ZE home in the near future. This is particularly true of SIPs and energy recovery ventilators. Although these technologies were not identified as cost-optimal design components in our analysis, they bring measurable benefits, can be sensible solutions in the right situation, and may yet have a significant impact on the home building industry. Both builders and policymakers should stay apprised of these technologies and consider incentivizing them.

05

RECOMMENDATIONS FOR BUILDERS

RECOMMENDATIONS FOR BUILDERS

The following sections summarize the implications of this report for home builders and developers looking to provide ZE or ZER offerings.

Use This Report to Inform Future Construction

Both prospective and established ZE home builders can use the cost-optimized efficiency measures identified in this report as a starting point for informing or updating their home designs. Note that DOE provides additional ZERH climate-optimized efficiency packages as part of its Building America Solution Center.[52] Home builders should iterate on these recommendations to ensure that the recommendations adequately consider their local context, including existing contractor relationships and pricing, climate considerations, code requirements, and available incentives.[53]

A truly cost-optimized design is dependent on an integrated design that considers the various systems that comprise home energy use in parallel. The Building America program is helping builders navigate these issues with focused research and development on integrated solutions, and it may be a valuable supplement to the resources provided in the DOE ZERH program.[54] Builders should also work with energy modeling professionals to analyze integrated solutions that account for local climate, costs, incentives, and site constraints.

Collaborate in the DOE ZERH Program

The fact that home builders specializing in green homes report a cost premium less than half that stated by conventional home builders shows just how significantly experience itself can influence costs.[55] However, for those conventional home builders looking to break into a new market segment, the promise of reduced costs after their first, tenth, or hundredth green home is not particularly soothing.

The DOE ZERH program works to address this hurdle by offering dozens of case studies,[56] encouraging collaboration between green home builders, providing training webinars on advanced building topics, and providing prescriptive guidance on the design and construction of ZER homes.

The ZER certification process also provides builders with a method of quality control by requiring that buildings undergo a HERS rating (including blower door tests and energy modeling) and use checklists for thermal and air barriers, quality HVAC installation, comprehensive indoor air quality measures, and solar-ready construction (in locations with a significant solar resource). These steps can help home builders (especially those new to super-efficient construction) ensure quality, regardless of whether they complete the other requirements for ZER certification. Although this report focuses on ZER certification, builders can pursue other certifications that also provide design guidance and credibility to a ZE home, including LEED, National Green Building Standard, and ENERGY STAR for homes.

Find the Right Subcontractors

The costs identified in this report assume that projects are bid competitively by subcontractors. Builders and developers rooted in conventional building practices may find that their preferred subcontractors have limited experience in the super-efficient technologies and building techniques incorporated in this report (e.g., commissioning the inverters on ductless mini splits) and that they thus quote prices substantially higher than those listed here to minimize their risk and uncertainty.

The costs listed in this report are derived from trusted resources based on real-world cost data (see Appendix A for details). Home builders should be able to achieve similar costs in their locations. Home builders should look for subcontractors that are amenable to taking on new technologies and techniques without introducing extreme contingency costs to learn new skills—more likely if a high-volume builder is asking. Where meeting resistance to change, home builders should look to establish and build new relationships.

Hone Your Salesmanship

There is some disagreement in the real estate community regarding the difficulty in selling green homes, with 34% reporting a sales advantage and 29% reporting a disadvantage.[57] Regardless of the current state of affairs, it's clear that there is room to improve.

Many of the first movers in this industry can share painful stories about the overly technical presentations they first used to try to sell a ZE or ZER home. These builders have learned through experience that a successful sales pitch does not focus on technical aspects. In fact, many home builders report that even highlighting the superior total cost of ownership for a super-efficient home doesn't provide the emotional pull necessary for a prospective buyer. Green home builders are quickly learning that establishing this emotional connection is essential to their success.

"We don't talk about just 'energy performance' with our homebuyers. We focus instead on how that performance impacts the pain points they encounter every day: comfort, quiet, air quality, health, and price predictability."
Parlin Meyer,
Director at BrightBuilt Home

"The last thing a customer wants is for you to tell them how the engine works under the hood."
Tom Wade,
Owner at Palo Duro Homes, Inc.

Home builders can learn more about successful marketing strategies and phrases for super-efficient homes using the Building America Building Science Translator[58] and the Building America Solution Center Sales Tool.[59]

Engage with Local Policymakers

This report includes recommendations for policymakers interested in promoting ZE or ZER new construction. Builders should share those recommendations with government officials in the cities or states where they operate to help accelerate this industry. Better, they should work with those government officials to share their perspective as a local home builder to ensure that enacted policies represent an optimal approach to accelerating adoption.

06

RECOMMENDATIONS FOR POLICYMAKERS

RECOMMENDATIONS FOR POLICYMAKERS

Policymakers have an important role in improving grid reliability, meeting community energy needs, supporting affordability, improving the housing stock, and addressing climate change. Driving ZE home construction can be an essential action in addressing all of these issues. The following sections summarize the implications of this report for policymakers interested in driving the construction of ZE and ZER single-family homes in their city, county, or state.

Clarify Goals to Inform Actions

It is essential to set clear, ambitious, and measurable goals to guide policies and actions. The content of this report can be used in concert with other available resources to inform the discussions and analysis necessary to define the goals that policies will drive toward.

RMI will be providing additional tools for policymakers to accelerate ZE construction in 2019.[60]

Use This Report to Inform and Support Policy

The cost-optimized home constructions highlighted in this report can be used to guide incentives and quantify the economic impact that these measures will have on real estate developers and home buyers. The previous pages highlight several high-value opportunities, including:

1. Prescriptive incentives, especially for heat pump HVAC systems, HPWHs, and high-performance windows (climate dependent)
2. Subsidized costs for building certifications (e.g., the DOE ZERH program); the cost of ZER certification can make up over one-quarter of the cost for a ZER home,[61] though the cost is significantly less for production homes
3. Incentives for solar-ready roofing
4. State standardization of permitting, inspection, and interconnection procedures to reduce soft costs for installing solar PV
5. State legislation enabling community solar, PPAs, or property-assessed clean energy (PACE) financing

Policy can also be used to enable a number of other benefits to incentivize first movers, including expedited permitting, density or height bonuses, and setback exceptions. Although most builders interviewed didn't consider these bonuses essential drivers of adoption, they can be provided at little to no cost to governing bodies and communities.

It's also worth highlighting the benefit of energy disclosure programs in promoting the value of high-performance homes. Particularly innovative disclosure programs are in place in Portland, Oregon; Austin, Texas; and Berkeley, California.[62] Although these policies aren't focused on new construction, they are important pieces in ensuring that the energy performance of all homes is considered and properly valued by consumers.

Support Labor Training Programs

This report highlights that an essential aspect driving adoption of ZE and ZER homes is supporting a larger and more skilled construction workforce. Labor shortages are driving up costs as the industry struggles to secure skilled specialty subcontractors. Policymakers can address this issue by supporting, promoting, or partnering with local trade schools.

Super-efficient home builders are particularly affected by skilled labor shortages due to the specialty requirements for advanced building techniques and products. Policymakers can work to address this issue by establishing or supporting training programs, especially in the following topic areas:

- Installing, commissioning, and servicing heat pump ACs with inverters
- Installing and servicing HPWHs
- Air sealing techniques and products

- Certification program compliance
- Solar-ready roofing
- Window specification

It is worth incentivizing home builders to collaborate with the DOE ZERH program, which provides both a performance and prescriptive path for ZER homes that has been vetted with hundreds of buildings on thousands of homes across the country. Moreover, the program actively encourages collaboration between builders to share experiences and proliferate lessons learned.

"The Zero Energy Ready Homes program has been a huge benefit to this industry. It helps builders to see that this isn't just possible, it is easy, and repeatable."
Ted Clifton,
founder and CEO at Clifton View Homes

Support Training for Other Influencing Parties

Home builders are not the only stakeholder group that will need to enhance skill sets to support a push toward ZE or ZER new construction. The real estate appraisal industry is critical to ensuring that efficiency and renewable energy investments are properly and transparently considered as part of the home valuation process. The Appraisal Institute, the nation's largest professional association of real estate appraisers, offers a professional development program on the valuation of sustainable buildings (among other resources), and its registry of green residential appraisers continues to grow.[63]

Real estate agents can also benefit from training to learn how to best market the largely hidden value of high-performance features to prospective home buyers. In addition, as with skilled labor in the construction industry, training and capacity building for residential solar installers—particularly in less-developed solar markets in parts of the country outside of California—can also be important as demand for ZE and ZER new construction scales nationally.

07

CONCLUSION

CONCLUSION

As this report highlights, ZE and ZER homes can be built without a significant cost burden, and current costs are already meeting consumer thresholds—and continuing to decline. With ZE and ZER incremental costs as low as they are, builders and policymakers should seriously consider providing and supporting ZE offerings. Policymakers can also use findings from this report to begin a conversation around how they can increase market penetration of ZE and ZER homes in their states, regions, and cities.

Based on the analysis in this report and extensive case studies in the DOE "Tour of Zero" project database, ZER homes routinely save tens of thousands of dollars on utility bills for consumers over the lifetime of a 30-year mortgage.[64] Where solar financing is available, solar panels can bring these homes to ZE at little or no added cost (and greater long-term value). Because first cost is no longer a significant barrier, state and city policymakers should consider how to support building ZE homes from the start and avoid developments that will suffer from obsolescence and require expensive retrofits in the future. In addition, city policymakers should think about barriers beyond the first cost that builders and consumers may be facing and provide resources such as trainings, incentives, and benefits for first movers to drive the industry forward. In the end, ZE and ZER homes are good business for communities, as the value of these homes adds up to additional housing value and tax revenue over their lifetimes.

08

COLD CLIMATES ADDENDUM

COLD CLIMATES ADDENDUM

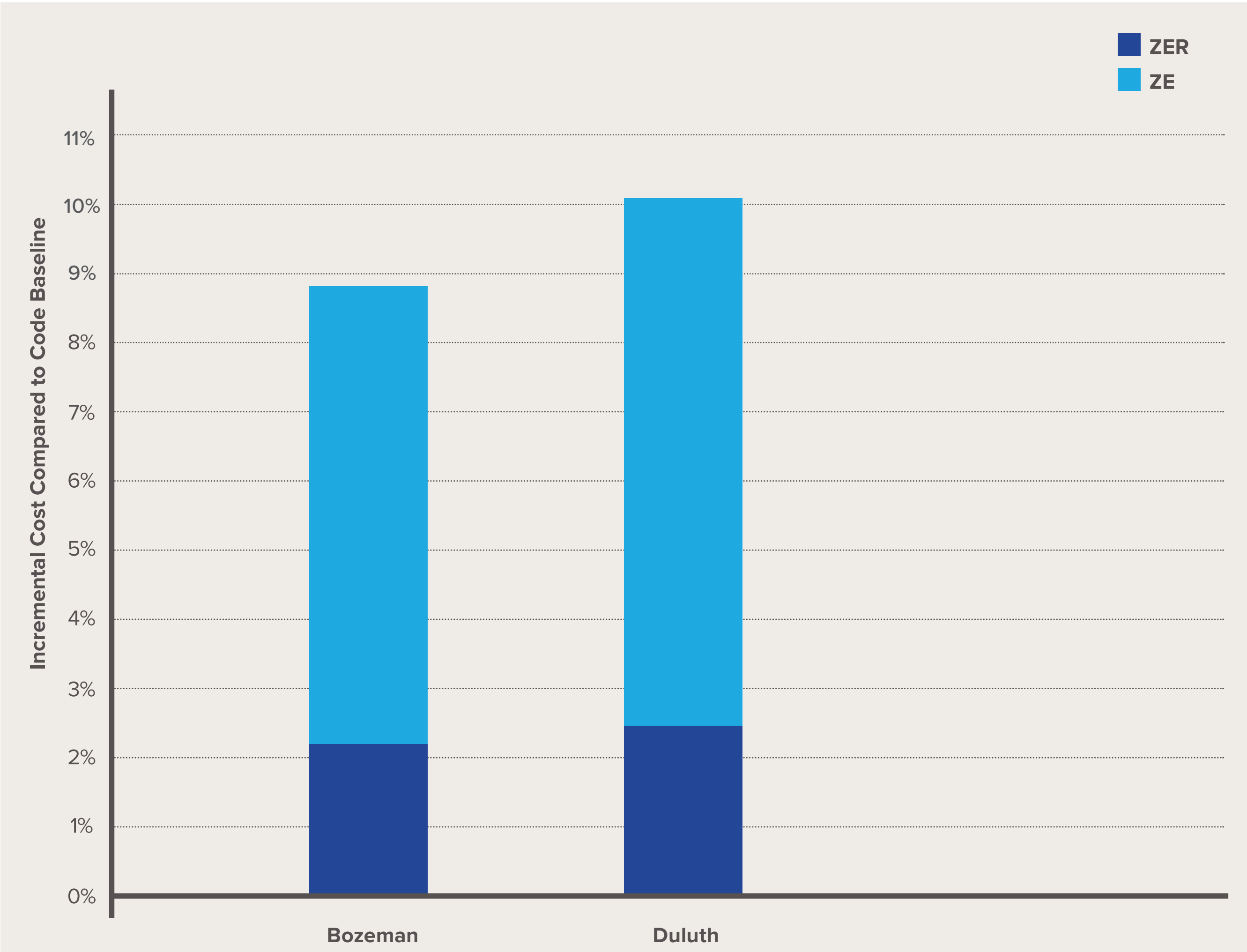
Cold climates face challenges in ZE and ZER design that aren't as present in more moderate climates, including performance concerns and higher energy consumption. This cold climate addendum is intended to add to the original report and offer additional guidance for ZE and ZER homes built in climate zones 6 and 7. The key results provided in the main body of this report for climate zones 2–5 have been replicated below for climate zones 6 and 7.

Local climates range widely even within a specific climate zone, and climatic conditions in these coldest climates can have a significant influence on optimized home construction practices. Builders and policymakers in cold climates should consider employing their own energy models to ensure that the recommendations given here can provide adequate indoor comfort in local conditions.

TABLE 4: KEY RESULTS

	CZ6	CZ7
Modeled City	Bozeman, MT	Duluth, MN
Utility Energy Rate ($/kWh)	0.101	Tiered ($0.07/kWh–$0.14/kWh)
Baseline Energy Use Intensity (kBtu/sf/yr)	57.0	80.0
Proposed Energy Use Intensity (kBtu/sf/yr)	18.0	20.0
Solar PV Size (kW)	8.6	10.9
Baseline Cost ($)	$247,435	$273,553
Incremental Cost for ZER Homes ($)	$5,358	$6,722
Incremental Cost for ZER Homes (%)	2.2%	2.5%
Incremental Cost for ZE Homes ($)	$28,750	$36,508
Incremental Cost for ZE Homes (%)	11.6%	13.3%
Incremental Cost for ZE Homes with ITC ($)	$21,733	$27,572
Incremental Cost for ZE Homes with ITC (%)	8.8%	10.1%

FIGURE 14: INCREMENTAL COSTS FOR ZE AND ZER HOMES



Surprisingly, both ZE and ZER homes in these cold climates meet similar cost thresholds to the four cities covered in the main body of this report, achieving the resale, willingness to pay, and mortgage threshold for ZER homes and the mortgage threshold for ZE homes.

FIGURE 15: SUMMARY OF ZER HOME COST THRESHOLD ACHIEVEMENT IN COLD CLIMATES

	Bozeman (CZ6)		Duluth (CZ7)	
ZER Incremental Cost	$5,358		$6,722	
Mortgage Threshold (30 years)	✓	$13,877	✓	$19,953
Resale Threshold (12 years)	✓	$7,047	✓	$10,133
Customer Willingness to Pay Threshold (4%)	✓	$9,897	✓	$10,942
First Cost Threshold (0%)	✗	$0	✗	$0

FIGURE 16: SUMMARY OF ZE HOME COST THRESHOLD ACHIEVEMENT IN COLD CLIMATES

	Bozeman (CZ6)		Duluth (CZ7)	
ZE Incremental Cost	$21,733		$27,572	
Mortgage Threshold (30 years)	✓	$36,358	✓	$46,590
Resale Threshold (12 years)	✗	$18,465	✗	$23,661
Customer Willingness to Pay Threshold (4%)	✗	$9,897	✗	$10,942
First Cost Threshold (0%)	✗	$0	✗	$0

Electrification Should Be Implemented Thoughtfully

One significant change in assumptions has taken place in performing this cost analysis for colder climates: the baseline HVAC system is assumed to be natural gas. This assumption is guided by existing industry trends: electric heating systems remain relatively uncommon in climate zones 6 and 7, representing 8% of existing homes and 12% of new construction,[65] because they can result in significantly higher annual utility costs in heating-dominated climates. See Table 5 for a summary of the costs and energy savings noted between these design alternatives. Selected baseline assumptions are highlighted.

Table 5 illustrates that while an all-electric baseline home assumption in climate zones 6 and 7 would have resulted in lower first costs (as it was for climate zones 2–5), the same assumption would have dramatically increased the estimated life-cycle value of ZER and ZE homes. Builders and policymakers in these climates should carefully consider the assumptions made in this report regarding electrified systems and adjust according to their priorities and local context.

TABLE 5: MODELED COSTS AND ENERGY SAVINGS FOR ELECTRIC AND NATURAL GAS BASELINES

		Chicago	Bozeman	Duluth
Electric Baseline	Incremental Cost of Building to ZER	**$5,369**	$4,499	$5,029
	Annual Energy Bill Savings	**$1,052**	$985	$2,934
	Payback (years)	**5.1**	4.6	1.7
Natural Gas Baseline	Incremental Cost of Building to ZER	$3,652	**$5,358**	**$6,722**
	Annual Energy Bill Savings	$921	**$708**	**$1,018**
	Payback (years)	4.0	**7.6**	**6.6**
Moving from an Electric Baseline to Natural Gas	Change in Incremental Cost for Building ZER	-$1,717	-$859	-$1,693
	Change in Payback (years)	-1.1	+3	+4.9

Note: Bold numbers indicate the baseline used for each location.

Policymakers should keep in mind that in heating-dominated climates, the electrification of heating systems will be an important (perhaps even requisite) strategy for achieving any stated climate or carbon goals due to the inability to offset GHGs from natural gas or heating fuels. This reality may support a rationale for following an all-electric baseline assumption. Furthermore, comparing the cost-benefit of building electrification with other carbon mitigation strategies may support a case for aggressively incentivizing electric heating systems to offset any increased energy cost to consumers.

Cost-Optimal Building Practices

Many of the key results from warmer climate zones still hold true: all-LED lighting, ENERGY STAR appliances, and EPA WaterSense hot water fixtures are still among the most cost-effective energy measures. More surprisingly, heat pumps are still an important technology for both space and water heating. However, the extreme cold of climate zones 6 and 7 yields some unique recommendations for ZE and ZER homes in these locations.

Maximize South-Facing Solar

Optimized energy models in climate zones 6 and 7 both maximized available south-facing rooftop area for solar PV; climate zone 7 required additional north-facing panels in order to achieve zero-energy performance. While these north-facing PV panels remained a more cost-effective measure than alternative investments in envelope insulation, they are substantially less cost-effective than their south-facing counterparts.

Homebuilders can beat the costs stated in this report for ZE and ZER homes in climate zone 7 by ensuring their home designs maximize the capacity for south-facing solar PV panels. With sufficient capacity, the production of the 10.9 kW system specified in our analysis (8.5 kW south facing and 2.4 kW north facing) could be replaced with a 10.0 kW south-facing system, reducing the first cost for a ZE home in Duluth by roughly $2,500. Added south-facing capacity could be achieved with a home design maximizing south-facing roof space, an unshaded ground-mounted system, a community solar program, or other off-site options.

Capacity for south-facing solar PV is thus a limiting factor for ZE and ZER home designs in both climate zones, and should be considered by homebuilders in the early stages of design.

Heat Pump HVAC Systems Need Help

Despite the extreme winter temperatures in these colder climates, optimized BEopt models still utilized ductless mini splits as the primary HVAC system. These heat pump units were supported by electrical resistance heating systems, which provided 4% of annual heating demand in climate zone 6 and 10% of annual heating demand in climate zone 7. These electric resistance systems can be included in an integrated ASHP system or can take the form of separate electric resistance baseboard units.

The availability of heat pump systems capable of performing in subzero temperatures is a relatively recent development. Some homebuilders, code officials, and prospective users may be skeptical of these systems' potential due to past experience; some areas may not have an established market for the purchase and installation of these systems. The Cold Climate Housing Research Center provides research that can be used by policymakers, builders, and other stakeholders to advocate for and guide the deployment of heat pump systems.[66] The Northeast Energy Efficiency Partnership offers best practice guides for both the design, installation, and operation of cold-climate heat pump systems that builders can use to ensure intended performance.[67]

Heat Pump Water Heater Considerations

Heat pump water heaters (HPWHs) are typically not capable of performing in extreme winter temperatures unless they are sited indoors. HPWHs cool the air around them and thus present an energy penalty to space heating systems when sited indoors. This may present an issue for developers and homeowners in climate zones 6 and 7 who are unwilling to relinquish conditioned square footage to mechanical systems. The NEEA Advanced Water Heater Specification should be utilized to ensure adequate long-term performance.[68]

Balance Envelope Measures with Indoor Air Quality

BEopt models specified more efficient envelope systems in climate zones 6 and 7; see Appendix A for details. The impact on the incremental costs noted in Figure 14 and Table 4 was mitigated by the more aggressive baseline building energy codes in these colder climates.

BEopt energy models initially recommended a significantly tighter envelope in climate zone 6. However, increasing the airtightness of envelope wall systems beyond code requirements reduces passive ventilation and has the potential to introduce indoor air quality (IAQ) issues not considered by energy modeling software. Mitigation can be achieved with two different strategies:

1. **Allow for a leakier envelope:** Code-compliant envelopes (3 ACH with standard exhaust systems) typically allow enough active and passive ventilation to address IAQ concerns. Heating systems will need to be sized slightly larger to accommodate for the higher air exchange. This was the most cost-effective option identified by energy models.

2. **Install an energy recovery ventilator:** An energy recovery ventilator (ERV) allows for increased ventilation without a significant thermal energy penalty by harnessing the heat from exhaust air and using it to warm intake air. ERVs were only identified as a cost-optimal measure in climate zone 7; they often aren't cost-effective in milder climates because the thermal energy saved is offset by increased fan power. This active ventilation strategy allows for increased control but increases the complexity of the building system and depends on proper occupant behavior for operation.

There is no "one size fits all" solution to envelope systems in ZE and ZER homes, and this is especially true in colder climates, where it is important to consider the added comfort and resilience benefits of a better insulated home. The need for higher levels of insulation and airtightness in these climates supports a case for considering complex envelope systems, including double-stud walls, structurally insulated panels, and insulated concrete forms. These solutions may prove more economical in certain locations given local labor rates, installer expertise, and/or site characteristics. However, the results of our BEopt energy models support the idea that more extreme insulation levels are not necessary for cost-optimized solutions for ZE and ZER home design (other benefits aside), even in the coldest climates where they are most cost-effective.

Conclusion

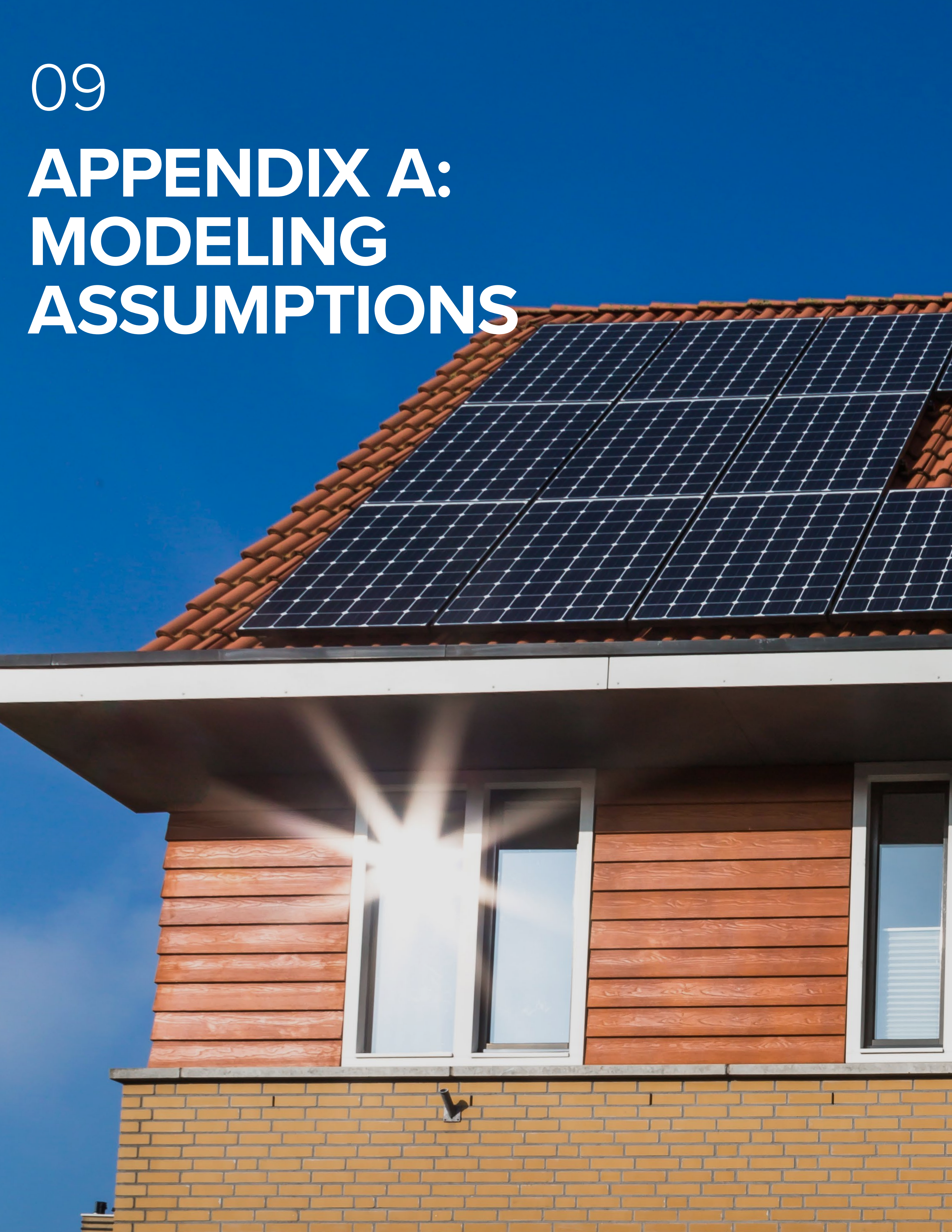
The recommendations in the body of this report hold true for colder climates: builders should continue to consider design alternatives, take advantage of available resources, and control quality in construction; policymakers should continue to prime the market by designing incentive programs for high-impact building components and offering workforce development programs. The results covered in this addendum also support an increased focus on two important issues:

1. **Electrification:** Policymakers in cold climates should realize that deep efficiency paired with electrification is oftentimes more cost-effective than electrification using code baseline equipment. Therefore, they should consider an increased focus on incentive programs that are less prescriptive and more integrated.
2. **Solar:** Builders in cold climates can minimize incremental costs by harnessing all available options for solar PV, including both on-site resources (e.g., south-facing roof area or ground-mounted installations) and off-site options (e.g., community solar programs). Policymakers should work to support off-site procurement with enabling legislation and incentive programs.

The results of the energy and economic analysis for this report show that ZE and ZER homes can be cost-effective even in some of the United States' coldest climates. This conclusion is supported by a growing body of evidence, including case studies and research projects sited as far north as the Arctic Circle.[69] Stakeholders should prepare now for these super-efficient homes to enter the mainstream.

09

APPENDIX A: MODELING ASSUMPTIONS

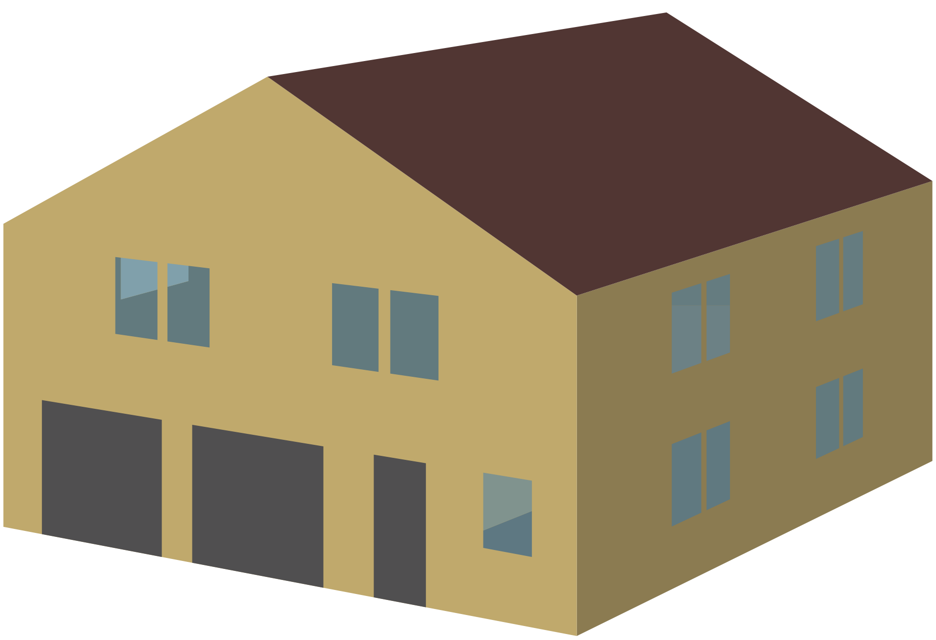


APPENDIX A: MODELING ASSUMPTIONS

Key Assumptions:

- For consistency, each house was identical across climate zones, with exception to code required climate zone differences (roof insulation, wall insulation, window properties). An image of the BEopt energy model is shown in Figure A1.
- For simplicity, this analysis used an all-electric baseline when justifiable. Although ASHPs are not very common in the existing residential market, they are the most typical HVAC system for new construction homes in climate zones 2–4.[70] In climate zone 5, natural gas is still most common for heating, so both a natural gas and electric baseline were modeled for consistency and accuracy.
- IECC 2009 code was used as the baseline code because that is the most common baseline code.[71] In addition, choosing a less aggressive code was more conservative in considering incremental cost.
- This analysis assumed a fuel escalation rate of 2% and a discount rate of 5%.
- The locations determined to represent climate zones were based on the Pacific Northwest National Library (PNNL) detailed code analysis.[72]
- Cost included certain requirements of the ZERH program including HERS rater because this quality check is crucial for high performance.

FIGURE A1: A VISUALIZATION OF THE BEOPT BUILDING ENERGY MODEL USED IN THIS REPORT



Summary of Baseline and Proposed Models:

Tables A1–A6 summarize the baseline and proposed cost-optimized building models in the four analyzed locations. A location-specific incremental cost is noted for all recommended energy upgrades.

TABLE A1: SUMMARY OF HOUSTON (CZ2) ANALYSIS

<table>
<tr><th></th><th>Baseline</th><th>Proposed</th><th>Incremental Cost</th><th>Baseline Source</th></tr>
<tr><td>Geometry</td><td colspan="2">Two-story, 2,200-square-foot home with 400-square-foot garage, three bedrooms, two bathrooms</td><td>$0</td><td>ZERH for size, RSMeans for geometry</td></tr>
<tr><td>Wall</td><td colspan="2">Wood frame, R13 stud insulation</td><td>$0</td><td rowspan="6">IECC 2009 code for baseline, ZERH minimum requirements for proposed</td></tr>
<tr><td>Window</td><td>15% window-to-wall ratio U-0.65, SHGC-0.3</td><td>15% window-to-wall ratio, U-0.4, SHGC-0.25</td><td>$362</td></tr>
<tr><td>Unfinished Attic</td><td>R30 fiberglass, vented</td><td>R38 fiberglass, vented</td><td>$287</td></tr>
<tr><td>Slab</td><td colspan="2">Uninsulated</td><td>$0</td></tr>
<tr><td>Air Leakage</td><td>7 ACH50</td><td>2 ACH50</td><td>$469</td></tr>
<tr><td>Mechanical Ventilation</td><td>Exhaust</td><td>Exhaust</td><td>$0</td></tr>
<tr><td>Space Conditioning System</td><td>ASHP, SEER 14, 8 HSPF, 3.75 ton</td><td>Two mini splits, SEER 25.3, 13.4 HSPF, 1.25 ton</td><td>$1,589</td><td rowspan="2">ASHP is the most typical HVAC system for new construction homes in this climate zone</td></tr>
<tr><td>Distribution</td><td>Ducts in unconditioned space</td><td>Five high-flow grilles (no ducts)</td><td>($2,656)</td></tr>
<tr><td>DHW Heater</td><td>Electric</td><td>Heat pump water heater, 3.5 EF</td><td>$727</td><td>Used electric as baselines to avoid fuel switching from baselines to proposed; 42% of homes use electric</td></tr>
<tr><td>Misc. Plug Loads</td><td colspan="2">2,261 kWh/yr</td><td>$0</td><td>Used BEopt assumption</td></tr>
<tr><td>Hot Water Fixture Types</td><td>Standard flows</td><td>Low-flow fixtures</td><td>$42</td><td rowspan="4">IECC 2009 code</td></tr>
<tr><td>Appliances</td><td>Conventional appliances</td><td>ENERGY STAR refrigerator, clothes washer, and dishwasher</td><td>$158</td></tr>
<tr><td>Lighting</td><td>50% CFL, 50% incandescent</td><td>100% LED</td><td>$15</td></tr>
<tr><td>Thermostat Type</td><td>Standard</td><td>Smart thermostat</td><td>$173</td></tr>
<tr><td>DOE ZERH Certification</td><td>N/A</td><td>Cost included, except EPA Indoor airPLUS</td><td>$900</td><td>Taken from ZERH cost analysis</td></tr>
<tr><td>Solar PV (With ITC)</td><td>N/A</td><td>6.5 kW</td><td>$13,423</td><td>N/A</td></tr>
</table>

TABLE A2: SUMMARY OF ATLANTA (CZ3) ANALYSIS

	Baseline	Proposed	Incremental Cost	Baseline Source
Geometry	Two-story, 2,200-square-foot home with 400-square-foot garage, three bedrooms, two bathrooms		$0	ZERH for size, RSMeans for geometry
Wall	Wood frame, R13 stud insulation	Wood frame, R13 stud insulation with R5 continuous insulation	$2,007	IECC 2009 code for baseline, ZERH minimum requirements for proposed
Window	15% window-to-wall ratio U-0.5, SHGC-0.3	15% window-to-wall ratio, U-0.3, SHGC-0.25	$2,977	
Unfinished Attic	R30 fiberglass, vented	R38 fiberglass, vented	$304	
Slab	Uninsulated		$0	
Air Leakage	7 ACH50	3 ACH50	$336	
Mechanical Ventilation	Exhaust	Exhaust	$0	
Space Conditioning System	ASHP, SEER 14, 8 HSPF, 3.75 ton	Two mini splits, SEER 25.3, 13.4 HSPF, 1.25 ton	$1,388	ASHP is the most typical HVAC system for new construction homes in this climate zone
Distribution	Ducts in unconditioned space	Five high-flow grilles (no ducts)	($2,816)	
DHW Heater	Electric	Heat pump water heater, 3.5 EF	$771	Used electric as baselines to avoid fuel switching from baselines to proposed; 42% of homes use electric
Misc. Plug Loads	2,261 kWh/yr			Used BEopt assumption
Hot Water Fixture Types	Standard flows	Low-flow fixtures	$44	IECC 2009 code
Appliances	Conventional appliances	ENERGY STAR refrigerator, clothes washer, and dishwasher	$167	
Lighting	50% CFL, 50% incandescent	100% LED	$15	
Thermostat Type	Standard	Standard	$0	
DOE ZERH Certification	N/A	Cost included, except EPA Indoor airPLUS	$900	Taken from ZERH cost analysis
Solar PV (With ITC)	N/A	6.5 kW	$13,454	N/A

TABLE A3: SUMMARY OF BALTIMORE (CZ4) ANALYSIS

	Baseline	Proposed	Incremental Cost	Baseline Source
Geometry	Two-story, 2,200-square-foot home with 400-square-foot garage, three bedrooms, two bathrooms		$0	ZERH for size, RSMeans for geometry
Wall	Wood frame, R13 stud insulation	Wood frame, R13 stud insulation with R5 continuous insulation	$2,099	IECC 2009 code for baseline, ZERH minimum requirements for proposed
Window	15% window-to-wall ratio U-0.35, SHGC-0.44	15% window-to-wall ratio, U-0.29, SHGC-0.56	$2,331	
Unfinished Attic	R38 fiberglass, vented	R49 fiberglass	$903	
Slab	2 feet R10 exterior insulation		$0	
Air Leakage	7 ACH50	2 ACH50	$520	
Mechanical Ventilation	Exhaust	Exhaust	$0	
Space Conditioning System	ASHP, SEER 14, 8 HSPF, 3.75 ton	Two mini splits, SEER 25.3, 13.4 HSPF, 1.25 ton	$949	ASHP is the most typical HVAC system for new construction homes in this climate zone
Distribution	Ducts in unconditioned space	Five high-flow grilles (no ducts)	($2,944)	
DHW Heater	Electric	Heat pump water heater, 3.5 EF	$806	Used electric as baselines to avoid fuel switching from baselines to proposed; 42% of homes use electric
Misc. Plug Loads	2,261 kWh/yr		$0	Used BEopt assumption
Hot Water Fixture Types	Standard flows	Low-flow fixtures	$46	IECC 2009 code
Appliances	Conventional appliances	ENERGY STAR refrigerator, clothes washer, and dishwasher	$176	
Lighting	50% CFL, 50% incandescent	100% LED	$16	
Thermostat Type	Standard	Smart thermostat	$191	
DOE ZERH Certification	N/A	Cost included, except EPA Indoor airPLUS	$900	Taken from ZERH cost analysis
Solar PV (With ITC)	N/A	6.8 kW	$13,090	N/A

TABLE A4: SUMMARY OF CHICAGO (CZ5) ANALYSIS

	Baseline	Proposed	Incremental Cost	Baseline Source
Geometry	Two-story, 2,200-square-foot home with 400-square-foot garage, three bedrooms, two bathrooms		$0	ZERH for size, RSMeans for geometry
Wall	Wood frame, R13 stud insulation with R5 continuous insulation		$0	IECC 2009 code for baseline, ZERH minimum requirements for proposed
Window	15% window-to-wall ratio U-0.35, SHGC-0.44	15% window-to-wall ratio, U-0.29, SHGC-0.56	$2,843	
Unfinished Attic	R38 fiberglass, vented	R49 fiberglass, vented	$1,236	
Slab	Uninsulated		$0	
Air Leakage	7 ACH50	3 ACH50	$482	
Mechanical Ventilation	Exhaust	Exhaust	$0	
Space Conditioning System	Gas furnace, SEER 13 split AC, 3 ton **OR**	Two mini splits, SEER 25.3, 13.4 HSPF, 1.25 ton	$531	Gas furnace with split AC is most common in this climate zone; for consistency across climate zones, we modeled two baselines
	ASHP, SEER 14, 8 HSPF, 3.25 ton		$2,246	
Distribution	Ducts in unconditioned space	Five high-flow grilles (no ducts)	($4,032)	
DHW Heater	Electric	Heat pump water heater, 3.5 EF	$1,104	Used electric as baselines to avoid fuel switching from baselines to proposed; 42% of homes use electric
Misc. Plug Loads	2,261 kWh/yr		$0	Used BEopt assumption
Hot Water Fixture Types	Standard flows	Low-flow fixtures	$63	IECC 2009 code
Appliances	Conventional appliances	ENERGY STAR refrigerator, clothes washer, and dishwasher	$240	
Lighting	50% CFL, 50% incandescent	100% LED	$22	
Thermostat Type	Standard	Smart thermostat	$262	
DOE ZERH Certification	N/A	Cost included, except EPA Indoor airPLUS	$900	Taken from ZERH cost analysis
Solar PV (With ITC)	N/A	8.4 kW	$17,758	N/A

TABLE A5: SUMMARY OF BOZEMAN (CZ6) ANALYSIS

	Baseline	Proposed	Incremental Cost	Baseline Source
Geometry	Two-story, 2,200-square-foot home with 400-square-foot garage, three bedrooms, two bathrooms		$0	ZERH for size, RSMeans for geometry
Wall	Wood frame, R13 stud insulation with R5 continuous insulation	Wood frame, R13 stud insulation with R10 continuous insulation	$1,088	IECC 2009 code for baseline, ZERH minimum requirements for proposed
Window	15% window-to-wall ratio U-0.35, SHGC-0.44	15% window-to-wall ratio, U-0.3, SHGC-0.4	$ 2,071	
Unfinished Attic	R49 fiberglass		$0	
Slab	4 feet R10 exterior insulation		$0	
Air Leakage	7 ACH50	3 ACH50	$344	
Mechanical Ventilation	Exhaust	Exhaust	$0	
Space Conditioning System	Gas furnace, SEER 13 split AC	Mini splits, SEER 25.3, 13.4 HSPF, electric resistance baseboards	$2,254	Gas furnace with split AC is most common in this climate zone
Distribution	Ducts in unconditioned space	Mini split minimal ducting	($2,507)	
DHW Heater	Electric	Heat pump hot water heater, 3.5 EF	$788	Used electric as baselines to avoid fuel switching from baselines to proposed; 42% of homes use electric
Misc. Plug Loads	2,261 kWh/yr		$0	Used BEopt assumption
Hot Water Fixture Types	Standard flows	Low-flow fixtures	$45	IECC 2009 code
Appliances	Conventional appliances	ENERGY STAR refrigerator, clothes washer, and dishwasher	$172	
Lighting	50% CFL, 50% incandescent	100% LED	$16	
Thermostat Type	Standard	Smart thermostat	$187	
DOE ZERH Certification	N/A	Cost included, except EPA Indoor airPLUS	$900	Taken from ZERH cost analysis
Solar PV (With ITC)	N/A	8.6 kW	$16,374	N/A

TABLE A6: SUMMARY OF DULUTH (CZ7) ANALYSIS

	Baseline	Proposed	Incremental Cost	Baseline Source
Geometry	Two-story, 2,200-square-foot home with 400-square-foot garage, three bedrooms, two bathrooms		$0	ZERH for size, RSMeans for geometry
Wall	Wood frame, R13 stud insulation with R5 continuous insulation	Wood frame, R13 stud insulation with R10 continuous insulation	$1,202	IECC 2009 code for baseline, ZERH minimum requirements for proposed
Window	15% window-to-wall ratio U-0.35, SHGC-0.44	15% window-to-wall ratio, U-0.29, SHGC-0.56	$2,566	
Unfinished Attic	R49 fiberglass		$0	
Slab	4 feet R10 exterior insulation		$0	
Air Leakage	7 ACH50	0.6 ACH50	$1,102	
Mechanical Ventilation	Exhaust	ERV 70%	$919	
Space Conditioning System	Gas furnace, SEER 13 split AC	Mini splits, SEER 25.3, 13.4 HSPF, electric resistance baseboards	$1,467	Gas furnace with split AC is most common in this climate zone
Ducts	Ducts in unconditioned space	Mini split minimal ducting	($2,772)	
DHW Heater	Electric	Heat pump hot water heater, 3.5 EF	$872	Used electric as baselines to avoid fuel switching from baselines to proposed; 42% of homes use electric
Misc. Plug Loads	2,261 kWh/yr		$0	Used BEopt assumption
Hot Water Fixture Types	Standard flows	Low-flow fixtures	$50	IECC 2009 code
Appliances	Conventional appliances	ENERGY STAR refrigerator, clothes washer, and dishwasher	$190	
Lighting	50% CFL, 50% incandescent	100% LED	$17	
Thermostat Type	Standard	Smart thermostat	$207	
DOE ZERH Certification	N/A	Cost included, except EPA Indoor airPLUS	$900	Taken from ZERH cost analysis
Solar PV (With ITC)	N/A	10.9 kW	$20,850	N/A

Table A7 and the following resource descriptions provide a summary of the sources and methods used to define the cost of each energy measure considered in this report.

TABLE A7: SUMMARY OF COST SOURCE USED FOR EACH ENERGY EFFICIENCY MEASURE

Energy Efficiency Measure	Cost Source
Wall Stud Insulation	Baseline cost came from RSMeans: Residential Costs 37th Annual Edition
Wall Sheathing	Averaged RSMeans: Residential Costs 37th Annual Edition and National Residential Efficiency Measure Database
Window Properties	Averaged RSMeans: Residential Costs 37th Annual Edition and National Residential Efficiency Measure Database
Unfinished Attic Insulation	National Residential Efficiency Measure Database
Slab Insulation	Averaged RSMeans: Residential Costs 37th Annual Edition and National Residential Efficiency Measure Database
Air Sealing	Averaged RSMeans: Residential Costs 37th Annual Edition and National Residential Efficiency Measure Database
Mechanical Ventilation System	National Residential Efficiency Measure Database
Space Conditioning System	National Residential Efficiency Measure Database
Ducts	National Residential Efficiency Measure Database
DHW Heater	National Residential Efficiency Measure Database; efficiency factor updated based on models on the market
Hot Water Fixture Types	Based on market research and interviews with builders
Appliances	National Residential Efficiency Measure Database for labor cost and market research for equipment cost
Lighting	Based on market research and interviews with builders
Thermostat Type	Based on market research and interviews with builders
High Transfer Grills	RSMeans: Residential Costs 37th Annual Edition
DOE’s ZERH Certification	Based on DOE’s cost estimate

Cost Sources:

- **National Residential Efficiency Measures Database**: NREMD is the backbone of measure cost estimates provided within the BEopt modeling software. It relies on a plethora of available cost studies and statistical analyses. This was the most commonly used cost resource in this analysis.

- **RSMeans:** RSMeans provides cost models and unit cost data for a variety of residential (and commercial) building types and is a well-known and trusted cost resource in the construction community. We used RSMeans' 2018 Residential Cost Data predominantly for estimating the cost of envelope and appliance measures.

- **National Institute of Standards and Technology:** NIST's 2016 report *Net-Zero Energy Residential Building Component Cost Estimates and Comparisons* uses seven data sources to estimate the incremental cost of a ZE test facility in Maryland. We used the report to inform the cost of envelope, HVAC, and water heater measures.

- **Electric Power Research Institute:** EPRI has recently published a number of reports analyzing the cost and performance of ZE homes in partnership with Meritage Homes Corporation. We used their 2016 report *Establishing Feasibility of Residential Zero Net Energy Community Development - Learnings from California's First ZNE Neighborhood* for estimating the costs of ductless mini split units.

- **American Society of Heating, Refrigerating, and Air-Conditioning Engineers:** ASHRAE's 2009 report *Economic Database in Support of ASHRAE 90.2* provides cost information specific to both single-family and multifamily constructions. Although this data is now a decade old, we used it as a rough validation measure for costs defined by other sources.

- **Expert Contractors:** We consulted with eight residential builders with ZE and ZER home building experience to validate modeled cost estimates: Anthony Aebei of Greenhill Contracting, Bill Decker of Decker Homes, Geoff Ferrell of Mandalay Homes, C.R. Herro of Meritage Homes Corporation, Parlin Meyer of BrightBuilt Home, Gene Myers of Thrive Home Builders, Ted Clifton of Clifton View Homes, and Tom Wade of Palo Duro Homes, Inc.

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APPENDIX B: HOW TO SCALE ZE COST RESULTS

APPENDIX B: HOW TO SCALE ZE COST RESULTS

General Approach: RMI modeled ZE homes in four climates (see Table B1). To scale the results to other cities, we identified a list of factors that influence cost and created a method to update the results for other cities. This approach provides a very rough approximation that can give city policymakers a sense for where costs currently stand in their cities.

TABLE B1: NATIONAL AVERAGE COSTS BY IECC CLIMATE ZONE COMPARED AGAINST IECC 2009

Climate Zone	Incremental Efficiency Cost	PV Cost	Energy Savings for ZE	Energy Savings for ZER
CZ2	$2,488	$14,887	$1,842	$757
CZ3	$6,925	$14,180	$1,968	$852
CZ4	$6,514	$16,049	$2,210	$1,049
CZ5	$4,260	$20,726	$2,459	$1,116

Factors that influence cost:

- Climate zone
- Utility rate
- Labor and material cost
- Baseline code
- Incentives
- Solar resource
- Solar cost

Climate Zone:
We modeled homes using IECC climate zones 2, 3, 4, and 5 because they account for 90.6% of single-family homes in the United States.[73] We did not model cities in climate zones 1, 6, 7, and 8; extrapolating costs from this report to these extreme climates is not recommended.

Utility Rate:
The DOE State and Local Energy Data can be used to find electric utility rates by city,[74] so policymakers will be able to look up what utility (or utilities) serve their cities to determine how their utility rates vary from the national average. The national average price of electricity was $0.1299 per kWh when this report was written.[75]

Labor and Material Cost:
RSMeans has labor and material cost factors compared with the national average for many cities.[76]

Baseline Code:
The baseline code will affect the incremental cost to build ZE as well as the estimated energy savings. This analysis used IECC 2009 as the baseline code (see Table B2), so cities with different baseline codes will need to adjust the results accordingly. Construction cost and energy bill estimates come from PNNL's cost-effectiveness analysis for IECC 2012 and IECC 2015.[77]

TABLE B2: INCREMENTAL CONSTRUCTION COST AND ANNUAL ENERGY BILL COST COMPARED WITH IECC 2009

	Climate Zone	2	3	4	5
IECC 2006	Construction Cost	($164)	($197)	($1,362)	($161)
	Energy Bill Cost	$186	$164	$143	$167
IECC 2009	Construction Cost	$0	$0	$0	$0
	Energy Bill Cost	$0	$0	$0	$0
IECC 2012	Construction Cost	$934	$4,899	$3,538	$2,717
	Energy Bill Cost	($213)	($248)	($346)	($348)
IECC 2015	Construction Cost	$934	$4,899	$3,538	$2,717
	Energy Bill Cost	($220)	($256)	($353)	($353)

Incentives:
This analysis does not include local incentives, but cities could use the Database of State Incentives for Renewables & Efficiency,[78] or work with their local utility to determine how incentives will affect up-front cost.

Solar Resource:
Solar PV electricity production is dependent on solar resources in the city, so cities with better solar resources won't need to install as much solar to achieve ZE. The average solar production of the 50 cities included in this scaling exercise was 1,481 kWh/kW, but it ranged widely from 1,103 kWh/kW to 1,790 kWh/kW. A city's solar resource can be determined using PVWatts, a free resource developed by NREL.[79]

Solar Cost:
Solar costs follow different material and location factors than energy efficiency measures. The national average solar PV cost for residential applications as of 2018 was $3.14/W. EnergySage is a good resource to determine how solar costs vary by state.[80]

Example Calculation:
This example uses New York City to demonstrate how someone can scale modeled results to a city not included in Figure B1. To apply these results to New York City, we used the following information:

- Climate Zone: 4
- Utility Rate: $0.1588/kWh
- Labor and Material Cost Multiplier: 1.4
- Residential Energy Code: IECC 2015
- Solar Resource: 1,325 kWh/kW
- Solar Cost: $3.36/W

The calculations use the following equations:

- **To calculate incremental cost of ZER:** [Incremental efficiency cost for the climate zone in Table B1] – [Additional construction cost for the climate zone and code in Table B2] * [Labor and material cost multiplier]
- **To calculate cost of solar PV:** [Solar PV cost taken from correct climate zone in Table B1] * [Ratio of solar resource compared with average] * [Ratio of solar cost compared with national average]
- **To calculate energy savings from ZE:** [Energy savings taken from climate zone in Table B1] – [Additional energy bill cost for the climate zone and code in Table B2] * [Ratio of utility cost compared with national average]
- **To calculate energy savings from ZER:** [Energy savings taken from climate zone in Table B1] – [Additional energy bill cost for the climate zone and code in Table B2] * [Ratio of utility cost compared with national average]

FIGURE B1: ZER RESULTS SCALED TO THE 50 MOST POPULOUS CITIES IN THE UNITED STATES (NOTE: MILWAUKEE, MINNEAPOLIS, AND MIAMI WERE AMONG THE TOP 50 MOST POPULOUS CITIES BUT WERE EXCLUDED BECAUSE THEY ARE OUTSIDE OF IECC CLIMATE ZONES 2–5)

City	ZER incremental Cost	Energy Savings for ZER	Mortgage Threshold?	Resale Threshold?	Consumer WTP Threshold?	First Cost Threshold
New York City, NY	$4,166	$850	✓	✓	✓	✗
Los Angeles, CA	$2,330	$701	✓	✓	✓	✗
Chicago, IL	$1,945	$746	✓	✓	✓	✗
Houston, TX	$1,290	$431	✓	✓	✓	✗
Phoenix, AZ	$1,769	$602	✓	✓	✓	✗
Philadelphia, PA	$7,621	$608	✓	✗	✓	✗
San Antonio, TX	$1,243	$444	✓	✓	✓	✗
San Diego, CA	$2,228	$393	✓	✓	✓	✗
Dallas, TX	$1,681	$513	✓	✓	✓	✗
San Jose, CA	$2,634	$607	✓	✓	✓	✗
Austin, TX	$1,228	$441	✓	✓	✓	✗
Jacksonville, FL	$1,243	$464	✓	✓	✓	✗
San Francisco, CA	$2,694	$909	✓	✓	✓	✗
Columbus, OH	$3,877	$1,094	✓	✓	✓	✗
Fort Worth, TX	$1,661	$513	✓	✓	✓	✗
Indianapolis, IN	$3,919	$889	✓	✓	✓	✗
Charlotte, NC	$6,509	$722	✓	✓	✓	✗
Washington, D.C.	$2,738	$699	✓	✓	✓	✗
Seattle, WA	$3,125	$505	✓	✓	✓	✗
Atlanta, GA	$6,094	$794	✓	✓	✓	✗
Denver, CO	$1,358	$674	✓	✓	✓	✗
Boston, MA	$1,837	$658	✓	✓	✓	✗
El Paso, TX	$1,600	$571	✓	✓	✓	✗
Detroit, MI	$1,574	$909	✓	✓	✓	✗
Nashville, TN	$5,406	$860	✓	✓	✓	✗
Memphis, TN	$5,817	$699	✓	✓	✓	✗
Portland, OR	$2,976	$573	✓	✓	✓	✗
Oklahoma City, OK	$1,641	$479	✓	✓	✓	✗
Las Vegas, NV	$2,066	$558	✓	✓	✓	✗
Louisville, KY	$5,667	$840	✓	✓	✓	✗
Baltimore, MD	$2,738	$749	✓	✓	✓	✗
Albuquerque, NM	$5,406	$998	✓	✓	✓	✗
Tucson, AZ	$1,321	$466	✓	✓	✓	✗
Fresno, CA	$2,390	$607	✓	✓	✓	✗
Sacramento, CA	$2,411	$639	✓	✓	✓	✗
Mesa, AZ	$2,140	$616	✓	✓	✓	✗
Kansas City, MO	$3,035	$711	✓	✓	✓	✗
Long Beach, CA	$2,269	$478	✓	✓	✓	✗
Omaha, NE	$3,834	$986	✓	✓	✓	✗
Raleigh, NC	$6,440	$707	✓	✓	✓	✗
Colorado Springs, CO	$3,578	$1,034	✓	✓	✓	✗
Virginia Beach, VA	$2,827	$566	✓	✓	✓	✗
Oakland, CA	$2,613	$607	✓	✓	✓	✗
Tulsa, OK	$1,661	$396	✓	✓	✓	✗
Arlington, TX	$1,702	$513	✓	✓	✓	✗
New Orleans, LA	$1,337	$418	✓	✓	✓	✗
Wichita, KS	$2,440	$703	✓	✓	✓	✗

FIGURE B2: ZE RESULTS SCALED TO THE 50 MOST POPULOUS CITIES IN THE UNITED STATES (NOTE: MILWAUKEE, MINNEAPOLIS, AND MIAMI WERE AMONG THE TOP 50 MOST POPULOUS CITIES BUT WERE EXCLUDED BECAUSE THEY ARE OUTSIDE OF IECC CLIMATE ZONES 2–5)

City	ZE incremental Cost	Energy Savings for ZE	Mortgage Threshold?	Resale Threshold?	Consumer WTP Threshold?	First Cost Threshold
New York City, NY	$19,534	$2,270	✓	✓	✗	✗
Los Angeles, CA	$18,661	$2,011	✓	✓	✗	✗
Chicago, IL	$19,702	$2,059	✓	✓	✗	✗
Houston, TX	$14,713	$1,365	✓	✗	✗	✗
Phoenix, AZ	$15,619	$1,728	✓	✓	✗	✗
Philadelphia, PA	$22,103	$1,281	✓	✗	✗	✗
San Antonio, TX	$15,298	$1,340	✓	✗	✗	✗
San Diego, CA	$17,733	$1,128	✓	✗	✗	✗
Dallas, TX	$15,195	$1,473	✓	✗	✗	✗
San Jose, CA	$18,581	$1,743	✓	✗	✗	✗
Austin, TX	$15,066	$1,331	✓	✗	✗	✗
Jacksonville, FL	$12,806	$1,390	✓	✓	✗	✗
San Francisco, CA	$17,953	$2,608	✓	✓	✗	✗
Columbus, OH	$20,095	$2,410	✓	✓	✗	✗
Fort Worth, TX	$15,291	$1,473	✓	✗	✗	✗
Indianapolis, IN	$19,903	$1,957	✓	✗	✗	✗
Charlotte, NC	$18,857	$1,668	✓	✗	✗	✗
Washington, D.C.	$17,121	$1,855	✓	✓	✗	✗
Seattle, WA	$13,815	$1,349	✓	✗	✗	✗
Atlanta, GA	$19,548	$1,833	✓	✗	✗	✗
Denver, CO	$24,248	$1,860	✓	✗	✗	✗
Boston, MA	$21,050	$1,816	✓	✗	✗	✗
El Paso, TX	$17,694	$1,639	✓	✗	✗	✗
Detroit, MI	$19,753	$2,508	✓	✓	✗	✗
Nashville, TN	$19,355	$1,812	✓	✗	✗	✗
Memphis, TN	$18,864	$1,613	✓	✗	✗	✗
Portland, OR	$15,551	$1,531	✓	✗	✗	✗
Oklahoma City, OK	$16,153	$1,374	✓	✗	✗	✗
Las Vegas, NV	$17,793	$1,589	✓	✗	✗	✗
Louisville, KY	$19,647	$1,771	✓	✗	✗	✗
Baltimore, MD	$15,828	$2,000	✓	✓	✗	✗
Albuquerque, NM	$26,654	$2,103	✓	✗	✗	✗
Tucson, AZ	$16,306	$1,396	✓	✗	✗	✗
Fresno, CA	$18,013	$1,743	✓	✗	✗	✗
Sacramento, CA	$17,915	$1,834	✓	✓	✗	✗
Mesa, AZ	$16,586	$1,499	✓	✗	✗	✗
Kansas City, MO	$19,806	$1,897	✓	✗	✗	✗
Long Beach, CA	$18,305	$1,372	✓	✗	✗	✗
Omaha, NE	$24,060	$2,171	✓	✗	✗	✗
Raleigh, NC	$18,805	$1,633	✓	✗	✗	✗
Colorado Springs, CO	$26,694	$2,277	✓	✗	✗	✗
Virginia Beach, VA	$16,773	$1,502	✓	✗	✗	✗
Oakland, CA	$17,911	$1,743	✓	✗	✗	✗
Tulsa, OK	$16,887	$1,136	✓	✗	✗	✗
Arlington, TX	$15,296	$1,473	✓	✗	✗	✗
New Orleans, LA	$16,859	$1,261	✓	✗	✗	✗
Wichita, KS	$19,162	$1,865	✓	✗	✗	✗

11

ENDNOTES

ENDNOTES

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[28] Defined here as filters achieving a minimum efficiency reporting value (MERV) rating of 13 or greater.

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[34] The specification can be found at https://neea.org/our-work/advanced-water-heater-specification

[35] Anthony Aebei interview by Michael Gartman and Alisa Petersen, February 13 2018.

[36] Detailed recommendations can be found in NREL's 2009 report *Solar Ready Buildings Planning Guide* (2009). The costs of these measures were not explicitly modeled in our analysis.

[37] These measures can reduce the cost of constructing a 2,200-square foot home by over $6,000, assuming change from hip roof framing and two avoided dormers (Source: Residential Costs, RSMeans, 2018). This value is not considered in this report.

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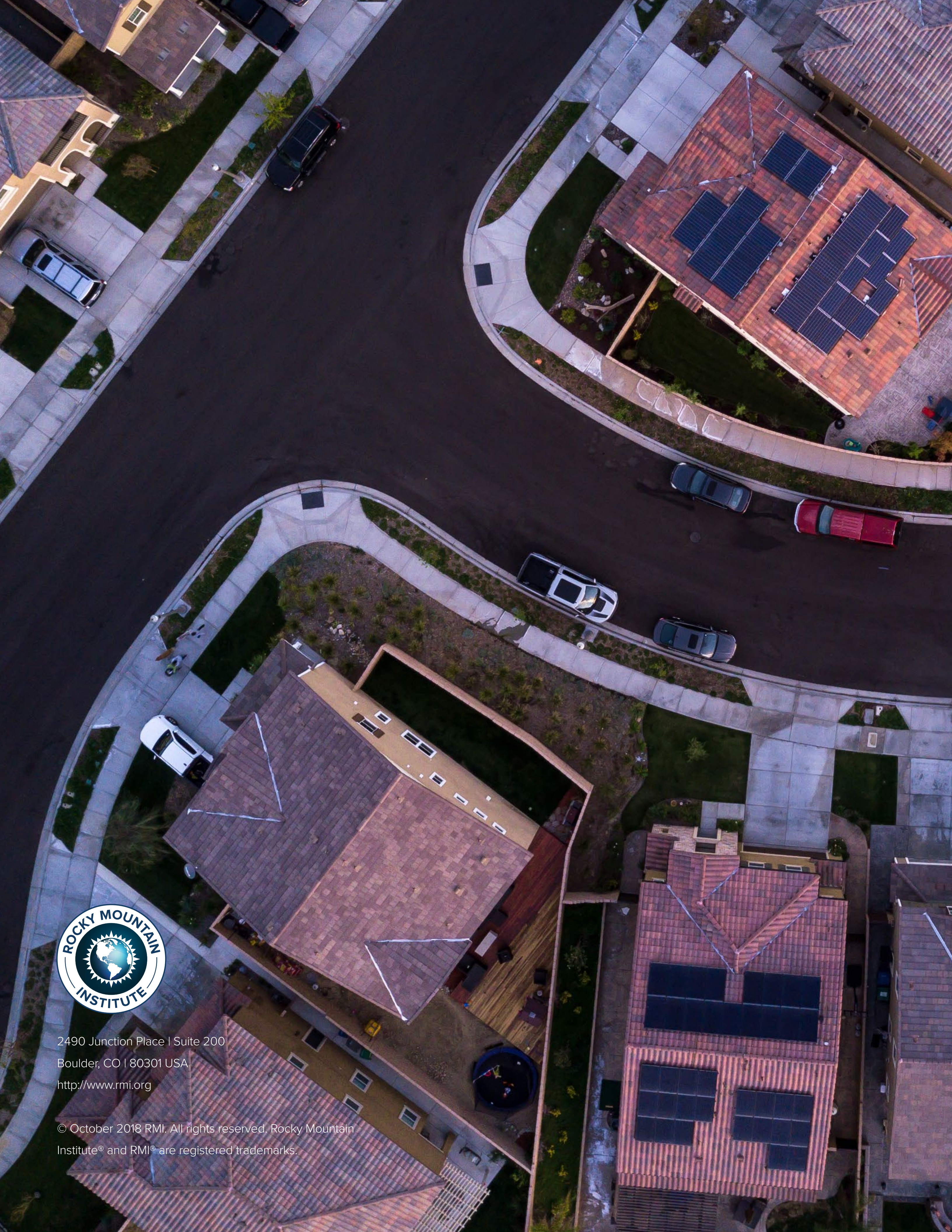

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