Chapter 6
Envelope Misconceptions and Implications

Diminishing returns means that even the most beneficial principle will become harmful if carried far enough - Thomas Sowell
Knowledge is the only instrument of production that is not subject to diminishing returns - John Maurice Clark

Opening Questions:

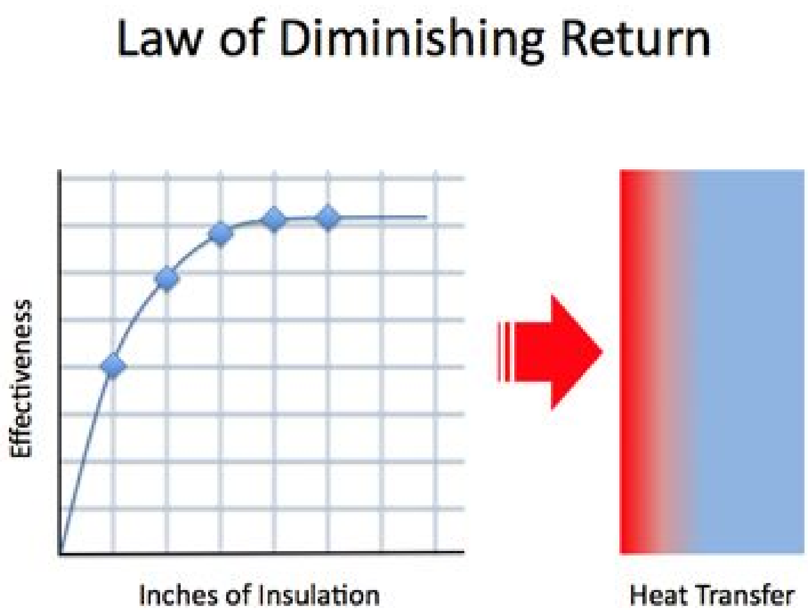
How can I understand the law and principle of diminishing returns?
What are the primary diminishing returns issues in building envelopes?
What misconceptions persist about wall/insulation thickness and upgrades?
What misconceptions persist about utility penetrations in the thermal envelope?
What misconceptions persist about mismatched elements in the thermal envelope?
What misconceptions persist about building envelope tightness and indoor air quality?
What misconceptions persist about passive solar, in light of weak links and net benefits?
What are the implications of a full understanding of diminishing returns of building envelopes?

Data and Analysis:

Even though *knowledge is the only instrument of production that is not subject to diminishing returns* (opening quote), the human mind too often ignores the concept in assumptions about scale. This deficiency leads to poor choices in many life circumstances, and it leads to notably egregious outcomes in the design and construction of buildings. Understanding the two related concepts of marginal analysis and opportunity costs would help grasp and effectively utilize the law of diminishing returns, but these are also too often ignored or misunderstood. It is impossible to evaluate diminishing returns without utilizing marginal analysis to calculate per-unit costs and benefits, at the margin, while scaling up. When applied to the building envelope, people embrace the logic that more is better; a heavier structure is stronger, and more insulation will reduce heat loss and energy use. Unfortunately, we too often fail to compare diminishing benefits against the cost of additional units, even when they approach negligible benefit. Without marginal analysis, homeowners and designers keep bulking-up the building envelope until budge runs out, making no reasoned calculation of whether each additional unit to the envelope was worth adding.

If the concern is for long-term structural integrity, it would be very difficult to quantify with precision the additional benefit for each step up in structural heft. Fortunately, we do not need to consider those complexities, because building codes in the U.S. have evolved over time with practice, cases, and research to now mandate a minimum inspected standard that achieves indefinite life. As we outlined in Chapter 5, and supported with objective research and data, the code-compliant house is expected to serve an indefinite life, if constructed with quality and maintained effectively. Whether homeowners are concerned about outliving their homes, passing a valuable asset to their heirs, or assuring good stewardship in the use of all the materials and energy that went into constructing the home, they may rest assured that the code-compliant house structure in the U.S. meets or exceeds those objectives. An important exception is for homes that are located in areas of high risk to natural disasters, such as hurricane, tornado, or earthquake. In those regions, local building codes may still be evolving with what seems like new weather patterns and more fierce and frequent storms. For most Americans, however, the typical standard construction of 2x4 wood stud walls is adequate for long-term structural integrity, and adding further structure will be more costly (in dollars and embodied energy) than beneficial (in longevity); it will also quickly escalate costs that are unlikely to be appraised at constructed cost and included in financing. Given the realities of consumer demand, an upgraded structure is more likely to result in a real (inflation-adjusted) financial loss at resale, or a lower return on investment compared with a standard structure. In other words, there are decreasing returns to scale, and building codes mandate a minimum structure along the scaling-up arc that already exceeds a cost-benefit optimum.

If the concern about the building envelope is reducing heat loss and energy use, the following paired graphics are instructive on the diminishing returns of insulation. The chart on the left is the effectiveness profile of insulation in resisting heat transfer, or heat loss, ranging from zero to seven inches. The image on the right takes the data from the performance profile and shows more intuitively how insulation resists heat transfer/loss across the full thickness of material. The right-side image could be considered a cross-section of insulation in a wall cavity during heating season, with the warmth of interior air from the left being lost or transferred through the insulation to cooler outside temperatures to the right.



People intuitively know that having insulation in the thermal envelope is important, and a good thing; unfortunately, many jump to the conclusion that more is always better. The opening quote of this chapter by Thomas Sowell implies this human nature: *“diminishing returns means that even the most beneficial principle will become harmful if carried far enough.”* While it should be acknowledged here that adding insulation will continue to reduce heat transfer and loss nearly infinitely, marginal analysis is needed to determine the point along the scaling-up arc where the cost of adding more insulation begins to exceed the benefit derived from it. As with the analysis of structural heft, building codes in the U.S. today already require minimum levels of insulation in wall and ceiling cavities (mandated in R-values) that exceed the cost-benefit optimum. Homeowners inflict harm on themselves by adding more insulation than required, and they harm the very environment that many aim to protect with that choice. Personal harm comes from extra costs that do not yield commensurate financial benefits, resulting in negative returns on investment, both in operations and on resale. Environmental harm comes from greater use of resources and energy in construction, which includes more raw materials, factory processing, transportation to site, and installation labor, without offsetting benefits of sufficiently reduced operational energy through the life of the home. More insulation also means more materials to landfill or recycle at end of life. In other words, there are decreasing returns to scale, and building codes in the U.S. mandate minimum levels of insulation along the scaling-up arc that already exceed a cost-benefit optimum. Windows, doors, and other weak links in the envelope present a different story and response; this is taken up in the discussion on mismatched elements later in this chapter.

The second issue that makes the concept of diminishing returns challenging to grasp and utilize with rationality is *opportunity costs*, defined as the next best alternative forgone. Most people understand this concept intuitively and utilize it effectively--if subconsciously--for small purchases with short durable use. If I really want a burger and fries and soda, but I only want to spend $2, I know that I can’t have all three, so I prioritize and choose one. The opportunity cost of choosing a burger is the benefit I would have derived from the fries and soda I didn’t choose. For larger purchases, and especially those that have long durable use, the human mind struggles to organize and understand this concept of opportunity costs. Building a house and investing in solar PV both fit that description; both are big purchases with expected long lives. A failure to consider opportunity costs on purchases this big often leads to suboptimal choices for the individual, and outcomes for society, and we discuss these later in this chapter. But where it connects to diminishing returns and marginal analysis is more subtle. We already established that increasing both structure and insulation have diminishing returns. The first unit returns the most benefit; this is sometimes referred to as the biggest *bang for the buck*. But as each additional unit is added, even when marginal benefits exceed marginal costs, the *bang for the buck* ratio declines. Assuming that there are many other competing interests for available dollars or budget, diminishing returns should be changing opportunity cost calculations even when returns are still positive, yet evidence of choices in the residential building industry suggest they are not. This becomes even more perplexing when we look at the poor economic returns for nearly all building envelope upgrades beyond code compliance.

The Department of Energy reports that the average U.S. household spends $1,945 annually on energy, from all uses (DOE, 2018a), and that 48% on average is used for conditioning indoor air (DOE, 2018b). Consequently, the average American household spends approximately $934 annually for heating, air conditioning and ventilation (HVAC). If building envelope upgrades are selected primarily to reduce heat loss, and reduce energy bills, those savings would come from reduced need for--and operation of--HVAC equipment. If it were possible to positively match each building envelope upgrade to the reduced energy use commensurate with that upgrade, it would be a simple process to calculate the financial return on investment (ROI) and determine whether that upgrade should be added for economic reasons. However, since direct matching of these elements is impossible because of the wide variability of factors, another way to consider ROI is to build hypothetical scenarios. The following chart displays that data for four levels of upgrade-savings possibilities. This analysis uses the energy data for the average American household and works in reverse to identify the largest expenditure for an upgrade to break even with commensurate energy/cost savings over 30 years.

30-year analysis, considered for upgrades in the thermal envelope	
Annual dollar savings (and % of HVAC cost) from reduced energy use and bills expected from an upgrade to the thermal envelope	Maximum cost (investment) in the thermal envelope to achieve the respective annual savings and simply break even in 30 years
$47 (5% of avg. HVAC cost)	$1,050
$93 (10% of avg. HVAC cost)	$2,100
$234 (25% of avg. HVAC cost)	$5,200
$467 (50% of avg. HVAC cost)	$10,500

Financial Model Assumptions (no inclusion of environmental cost of energy production):
1. Average annual American household cost of energy for HVAC operations ($934)
2. Cost of funds: 4.5%, proxy rate for 30-year mortgage (higher COFs, lower max. cost)
3. Rate of energy inflation 3.0%: conservative annual escalator, given historical trends
4. 30-year period for break-even ROI: common mortgage length and long-term analysis
5. Payback calculator hosted at: https://www.sustainableclimatesolutions.org/housing

What this analysis demonstrates, for the first scenario, is that if a particular envelope upgrade successfully achieved 5% reduction in energy need and cost from reduced HVAC use ($47), the maximum initial investment, for that upgrade to simply break even over 30 years, is $1,050. That is a very small allowance against the cost of almost any envelope upgrade. The other end of this scale is even more enlightening. Even if it were possible to reduce HVAC use and costs by 50%, which we will show is an unlikely achievement in any case, the *maximum* initial investment in upgrades to attain that reduction, and simply break even over 30 years, is $10,500. In short, $10,500 in upgrades will never come close to reducing HVAC energy use and cost by 50%; it is a miniscule amount compared to the cost of upgraded wall systems, insulation, windows, and doors. Stated differently, $10,500 will not purchase much in thermal envelope upgrades, and it certainly will not buy enough to cut HVAC costs in half. This analysis is based on the average American household, but we find that it scales quite well in either direction from the mean, both in envelope size and in the energy behaviors of occupants. While we do not have data for cases that would represent extreme outliers, such as for mansions or tiny homes, the physical limits and current economics of the analysis suggest similar conclusions even at those extremes.

Environmentalists may chafe at these findings, at least in part because they fail to account for the environmental externalities of energy production from fossil fuel sources. Doing so for all possible scenarios would add nearly infinite variability, but the final verdict remains the same. As an example, the environmental externality of electricity produced in the SERC Virginia/Carolina region would add $0.0378/kWh to the cost of grid-distributed energy, at $80[1] per metric ton of CO2e. This is based on the actual fuel mix for the region[2], which is close to the national portfolio, and converting nitrogen oxides and carbon dioxide emissions to CO2-equivalent (CO2e). Internalizing the externality would add a 37.8% cost premium to regional grid rates, which we can add to HVAC costs for a comparative analysis.

30-year analysis, considered for upgrades in the thermal envelope, but now with 37.8% cost premium to account for CO2e	
Annual dollar savings (and % of HVAC cost) from reduced energy use and bills expected from an upgrade to the thermal envelope	Maximum cost (investment) in the thermal envelope to achieve the respective annual savings and simply break even in 30 years
$64 (5% of avg. HVAC cost)	$1,450
$129 (10% of avg. HVAC cost)	$2,900
$322 (25% of avg. HVAC cost)	$7,200
$644 (50% of avg. HVAC cost)	$14,500

Financial Model Assumptions:
1. Environmental externality included (37.8%); represents $80 per metric ton for CO2e
2. Average annual American household cost of energy for HVAC, with CO2e ($1,287)
3. Cost of funds: 4.5%, proxy rate for 30-year mortgage (higher COFs, lower max. cost)
4. Rate of energy inflation: 3.0%, conservative annual escalator, given historical trends
5. 30-year period for break-even analysis, common mortgage length and long-term anal.
6. Payback calculator hosted at: https://www.sustainableclimatesolutions.org/housing

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[1] $80 per metric ton is a mid-range rate for accounting for the environmental cost of CO2e emissions.

[2] Regional and national fuel mix data from EPA Power Profiler: https://www.epa.gov/energy/power-profiler

A couple of broad conclusions can quickly be drawn from this comparative analysis. First, even at these higher allowances for thermal envelope upgrades, the dollar amounts still pale in comparison to most upgrade materials and systems. More detail is offered in the Case Study section of this chapter, but for a sense of magnitude, envelope upgrades to the case house cost in excess of $100,000 and didn't come anywhere close to offsetting half of the HVAC energy needs and cost. Second, and for wholistic perspective, environmentalists should also be concerned about the increased embodied energy sunk into upgrades to the thermal envelope; the case analysis at the end of this chapter will discuss that more thoroughly. And finally, it has already been established that solar PV is the better choice for household energy; a strong financial investment even if we do not consider its enormous environmental benefits, and the embodied energy of a PV system pales in comparison to any envelope upgrade that has meaningful impact on reducing energy need and cost.

The charts above provide analysis for just four specific scenarios of reduced HVAC need and cost, with the highest reduction rate of 50%. Readers may be wondering, like we did, how different thermal envelopes actually perform in reducing household energy needs. The industry literature is crowded with theoretical claims of energy savings from specific materials, methods, and wall systems, but we were able to find very little evidence-based impact from whole-house lived experience. Part of this may be due to the complexity and integration of many component parts of both the thermal envelope and HVAC systems. For example, there are many different types of structures, windows, and doors, and houses have a wide range of permutations in the proportional coverage of each of those elements. Weather variations and broad choices of HVAC system-type and efficiency rating add further permutations, and that is all before there is any account for number of inhabitants and their unique energy behaviors. Perhaps because of these challenges at the whole-house level, manufacturers and policy interests have focused on lab-based research of component parts. While we did not question those research findings, we found it an impossible task to piece it all together with any level of confidence or magnitude.

Performance of Thermal Envelopes

Because our research team included seasoned industry professionals with years of experience in residential design and building, we realized that we could build a sizeable database of existing homes of various building envelope system and HVAC type. If we could also obtain energy use data and a measure of conditioned space to proxy HVAC energy needs/use, the analysis would provide a rough sense of impact by system, and help answer the question of magnitude of impact. There were many factors that we could not control for, a challenge indicative of this task, but at least with all the households in relative close proximity, this analysis would control for weather variation and energy rates (all uses). Knowing that we also could not statistically isolate individual systems and impacts with precision, we expected that the blunt measures we would obtain would still provide a sense of magnitude of impact of building envelope upgrades.

As the raw data accumulated, most individual cases fell into three wall system types, 2x4 wood stud (code base), 2x6 wood stud (common mid-range option), and insulated concrete forms (ICF; premium system). Since ICF is often considered the most robust and premium building envelope type, these three classifications would provide information on the purported best system (ICF), the most basic application of building code (2x4), and a mid-range system between (2x6). The results of our analysis were shocking. Not only did the purported best thermal envelope fail to deliver energy savings, households in ICF structures averaged more energy use per square foot of living space than either of the two lesser structures.

Annual household energy use & cost by building envelope wall system	
Wall System	Household Energy Cost (annual, average)
2x4 wood stud (code-minimum)	68 cents per square foot living space
2x6 wood stud (common upgrade)	53 cents per square foot living space
Insulated Concrete Form (premium)	70 cents per square foot living space

Notes:
1. Data includes averages across wall system classification of more than 40 cases
2. The differences in energy costs are not statistically significant (small sample size)
3. Some data screening to account for anomalies such as well pump and EV charging
4. Volume of conditioned space rather than square foot would provide a more direct link between HVAC energy use and building envelope type; however, volume data were difficult to obtain in retrospect, and for the smaller sample for which we had volume measures, it did not appreciably alter overall placement or magnitude outcomes.

We need to be clear that our analysis is not a precise and direct measure of the impact of thermal envelope system on HVAC energy needs and use. However, across averages of over 40 cases, one would expect less overall energy use in premium envelope structures due to reduced HVAC need and operations; that is why environmentally-conscious homeowners accept an enormous cost premium in construction. In the region of our study and case home, where there is little known threat of catastrophic structural damage from natural disasters, why would homeowners pay such a high premium in construction cost or purchase price if not for an expected reduction in energy use and cost, or reduced environmental impact? All of the ICF homeowners in our sample selected the more expensive wall system because they thought it was the more responsible environmental choice. Lab-based research and component-specific benefits of upgraded wall systems paint a convincing story in the industry, even as advocates struggle to claim overall magnitude of impact, and almost no one is utilizing marginal analysis, opportunity costs, diminishing returns, and cost of funds to an overall value assessment.

The complexity of integrated systems and plethora of permutations is noted above as one reason for a lack of whole-house, whole-systems impact analysis of building envelopes types.

Another reason is the human element. Two same-sized families living in identical side-by-side homes will not demand the same amount of energy. Individual and collective interests and behaviors can mean that two families could have vastly different energy demands. Skeptics could argue that homeowners of the ICF structures in our sample must be more wealthy to be able to afford the much more expensive construction or purchase price, and maybe that explains a more voracious use of energy in the home. On the other hand, each of the families in our sample that chose to build or buy an ICF home did so for supposed environmental responsibility, and one could argue that would show up in thrift for energy in all areas of life. This lack of a perfect control group mechanism blurs and confuses envelope system impact assessments; fortunately, our case project would present a revealing comparison both on impact and on cost comparison.

Reducing environmental impact was the preeminent priority in design of the case home and selection of building materials and systems; every element was considered through that filter. Careful and long-term study of the literature in the building industry, best practices, and research led our team to a premium thermal envelope, and insulated concrete form (ICF) walls specifically. The homeowner had been living in a new house with many similar characteristics, except that the thermal envelope was code-minimum. The square footage and conditioned volume were nearly the same, both had partially submerged (walk-out) basements, and they are located in the same neighborhood, which controlled for weather. Perhaps most notably, the inhabitants would move from the code-minimum house to the premium thermal envelope house with the same people and energy patterns and behaviors. In addition to the premium envelope, which would be expected to reduce operational energy, the new case home was equipped with a geothermal heat pump and more energy-efficient appliances. The code-minimum, home utilized a basic 13 SEER air-to-air heat pump and standard appliances. Our research team expected reduced energy use in the new home, but we were left with the question of overall magnitude.

The case home would have a limited period where the human conditions would be the same as in the code-compliant house. Fortunately, the six month timeframe would span across cooling, swing, and heating seasons, and we compared month-to-month to control for temperature and other weather variability. By the time monthly energy data began arriving for the new home, our research had already introduced a measure of skepticism on the energy efficacy of a premium thermal envelope. Still, we were surprised to discover that the case home had used nearly 10% *more* energy than the code-minimum home through the first six months of operation[3]. We cross-checked energy use with average monthly temperatures across the two successive years to ensure that weather variation was not so extreme as to skew operational demand. The side-by-side data is provided below:

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[3] Move occured in mid-May. Since half of May and all of June included extraordinary energy use associated with moving and settling in, data comparison started in July to reflect normal living patterns and behaviors.

Season		Code-minimum home, Jul-Jan, 16/17		Premium-ICF home, Jul-Jan, 17/18	
Mo.	HVAC	Avg. mo. temp. (F)	KWh/Mo.	KWh/Mo.	Avg. mo. temp (F)
Jul	cool	74	766	815	75
Aug	cool	75	756	770	70
Sep	cool	69	590	558	64
Oct	mix	57	408	529	58
Nov	heat	45	508	580	42
Dec	heat	36	742	868	33
Jan	heat	38	761	863	30
Totals	6-Mo.	Darker blue = higher use	4,531	4,872	9.98% ***more*** energy

Notes:

1. Electricity is the only energy source in both homes
2. Thermostats set to same readings for both cooling and heating seasons
3. People and use patterns intentionally kept the same through comparison period
4. Average monthly temperatures: mean of means, from *Weather Underground* URL

This two-home comparison provided one of the best available cases of control group (same people and patterns) testing, and this study was independent of the broader dataset of regional homes categorized by thermal envelope type. The results and findings of both studies were conclusive; that premium thermal envelope homes (at least those represented by ICF wall systems) do not in reality result in lower operational energy demand and use. How could this be? The following chart highlights select features of the two homes that should have impact on overall operational energy use.

Comparison of the two 2,500 square foot homes with same inhabitants and energy patterns	
Code-minimum home relevant features	**Premium envelope home relevant features**
2x4 wood stud walls, fiberglass batt insulation in wall and ceiling cavities, in-wall utility boxes	ICF walls (8”-12”), 14” spray-foam ceiling insulation, no utility boxes in exterior walls
Heat pump HVAC (basic, 13 SEER, air-to-air)	Geothermal heat pump (with desuperheater)
No designed passive heat; one south window	Extensive passive design on south elevation
Appliances basic; no ultra-efficient models	Appliances all high-efficiency models

No mechanical ventilation system (no ERV)	ERV installed, running 24/7 for first 4 months

While the list of features in the chart above is not meant to be all-inclusive, the first four are known to be significant factors that in isolation should translate to lower energy use in the case home. The fifth feature, mechanical ventilation with an ERV, would clearly tip operational energy use in the opposing direction, but we did not encounter in the research much energy analysis on that element and its trade-offs. Further, we expected the energy impact of an ERV to be more than offset by the combination of the other factors. Among the data we collected on regional homes and energy use, we noted that all of the ICF homes in the sample employ mechanical ventilation except one; that one ICF (non-ERV) exception was among the best performing on operational energy use, but there were also wood-framed homes in a similar performance range. Could the use of an ERV wipe out operational energy savings from a premium thermal envelope? We will return to this question in the energy analysis chapter, but first we need greater understanding of the impact of weak links and mismatched elements in the building envelope.

Weak Links

Residential building codes in the U.S. require minimum insulation of the thermal envelope by threshold R-value ratings in structural sections of each of the envelope elements. However, there are many aesthetic and functional features that compromise those minimum standards. Obvious examples are holes that are intentionally opened in wall sections for windows and doors that have R-values far lower than code requires for the structural wall they reside in. There are also many less-obvious compromises to the whole-house R-value; here is a sample list of some of the worst offenders, along with an assessment of impact:

The less-obvious compromises to thermal envelopes	
Compromising issue	Explanation and/or impact
Insulation installation	Poor installation leaves gaps and cracks in the insulation cavity
Insulation settling	Gravity may weigh cavity insulation down, leaving uninsulated gaps
Electric wiring	Displacement is insignificant, but it complicates insulation installation
Electrical boxes	Significantly displace and compromise insulation, especially in walls
Plumbing pipes	Drain and water pipes both displace and compromise insulation
Plumbing vent(s)	Large and un-dampered hole in the important ceiling insulation plane
Bath exhaust fans	Not only hole in thermal envelope, they also exhaust conditioned air

Range hood fan	Not only hole in thermal envelope, they also exhaust conditioned air
Clothes dryer exhaust	Not only hole in thermal envelope, they also exhaust conditioned air
Access doors	To unconditioned attic and storerooms, they are usually weak spots
Thermal bridging	Not only transfer heat through structure, but also displaces insulation
Mechanical ventilation	Not only two holes in thermal envelope, they exhaust conditioned air

Even a structure without windows, doors, vents, and utilities would not achieve code-required R-values for the entire building envelope because the structural members not only displace insulation, but their thermal bridging properties work at opposing purposes by transferring heat through the structure. And since people do not want to live in homes without windows and doors, and electricity and plumbing, we need to accept still further compromise of whole-house heat loss through those weakest elements. As weak(er) links increase in size and number, they become responsible for a larger proportion of the overall heat loss from the thermal envelope and progressively diminish the proportional value of insulation in structural elements.

An extreme example helps illustrate this lesson. Consider two houses side-by-side in winter heating season, having identical designs, but one with a premium thermal envelope and the other with a standard code-compliant structure. Now consider that a hole the size of a dinner plate is cut into each front door and left open for the free flow of air; this would be an extremely weak link. We quickly realize that nearly all the heat produced inside these two homes would escape out the front door breach, and if both houses had the same heat source, their energy use and cost for HVAC operations will be nearly identical. In other words, the very expensive premium thermal envelope house will not return savings in operational energy from reduced heat loss. Now consider that a small hole in the front door may not actually be extreme in comparison to all of the non-obvious list of compromises noted above. The holes that we do not often think about could be several 3-4 inch diameter pipes through the envelope for dryer, plumbing vent, range hood, and several bath fans. It could also include two 6-inch pipes for the fresh and exhaust sides of an ERV. Most of these will have dampers or gravity louvers, but none are airtight, most will allow an outside wind to pass through, all of these pipes displace insulation from the thermal envelope, and many are metal with high thermal bridging properties. And this list of “holes” does not even include compromised insulation from utility incursions in exterior planes, or poorly installed insulation, or thermal bridging through structural members, or windows and doors with vastly lower insulating value than walls or ceilings.

It should be clear by now that thermal envelopes have many weak points and mismatched components in resistance to heat loss, and the strongest element by far is the insulation across structural sections. Now consider the diminishing returns on insulation thickness explained earlier in this chapter, and the performance profiles arcs that show most of the value in heat loss resistance is already achieved by code-minimum requirements. Wall systems are most often upgraded to reduce heat loss, even though there is negligible value gained from that isolated element, and nothing gained if weak links are not strengthened from independent processes. Furthermore, the opportunity costs of very expensive wall system upgrades are often the weak(er) links that do not get addressed. Priority effort and home building budgets should go toward improving the weakest links; here are a few strategies for addressing the same elements noted above.

Strategies to improve weak links in the thermal envelope	
Compromising issue	Strategies for minimizing impact
Insulation installation	Employ independent quality control inspector to evaluate & remedy
Insulation settling	Employ independent quality control inspector to ensure spec’d install
Electric wiring	Employ independent quality control inspector to evaluate & remedy
Electric boxes	Surface-mount where box required; otherwise, place in interior walls
Plumbing pipes	Design plumbing so no piping needs to be located in exterior walls
Plumbing vent(s)	Combine into one before penetrating thermal envelope; use min. size
Bath exhaust fans	Integrate with mechanical ventilation so exchange is more efficient
Range hood fan	Use closed-loop, filtered, type to avoid thermal envelope penetration
Clothes dryer exhaust	Consider system to damper (and/or stuff) thru-pipe when not in use
Access doors	Minimize use and, where needed, careful attention to insulation/seals
Thermal bridging	Use material with less bridging & add exterior continuous insulation
Mechanical ventilation	Add timer or sensor to use as sparingly as possible for healthy air

Even if all of these strategies are employed, these weak links remain significantly weaker in resistance to heat loss than wall system structures across insulated sections. Given these physical realities, and the insulation performance profile at code requirements, it is not surprising that upgraded wall systems do not significantly reduce operational energy; this is consistent with the findings of the regional database of homes and also with the case home comparison. The simple conclusion is that upgrading wall systems beyond code minimum, without strengthening the weakest links, is like throwing away money and using more resources than necessary. With priority first given to the worst offenders, which are also the least-obvious, the next step is to consider the more obvious weak links of windows and doors.

Mismatched Elements

Because code-minimum construction in the U.S. requires more insulating value in walls and other structural planes than is possible with even the best windows and doors, the closest match of whole wall components is code-minimum structure and premium windows and doors. Other combinations progressively widen the gap between the relative strength of structural elements and the relative weakness of windows and doors, with wider gaps further compromising the desired benefits of structural elements in the thermal envelope. This bears repeating. Investing in more robust structural elements (as in thicker and better-insulated walls) returns less benefit to offset the higher cost, as the gap widens between the insulating value of the wall structure and the windows and doors mounted within. Very wide gaps will eliminate most or all of the benefits of the thicker wall; this leaves a homeowner having spent significant treasure and embodied energy in a robust structure, but not able to receive its intended benefits. Here is a matrix that addresses nine broad combinations of matched and mismatched elements:

Element Combos	Standard[4] Windows and Doors	Mid-range Windows and Doors	Premium Windows and Doors
Code Min. Structure	Unmatched envelope elements, but least expensive, and suitable for SOAR homes when coupled with solar PV	Unmatched elements, moderate-high window expense; suitable for SORTA homes to reduce energy use to PV limits	Matched elements, but very high window costs; suitable for SORTA and SNAIL homes to reduce operational energy use
Mid-range Structure	Unmatched envelope elements, moderately diminished benefits of more robust structure; not recommended	Unmatched & significant expense in both elements; suitable only if codes require bolstered structure (hurricane, tornado, etc.)	Nearly-matched, but heavy expense on both elements; suitable only if codes require bolstered structure (hurricane/torn.)
Premium Structure	Unmatched envelope elements, high level of diminished benefits of expensive structure; not recommended	Unmatched envelope elements, diminished benefits and value of expensive structure; not recommended	Unmatched and very high expense on both elements; suitable only if codes require bolstered structure (hurricane/torn.)

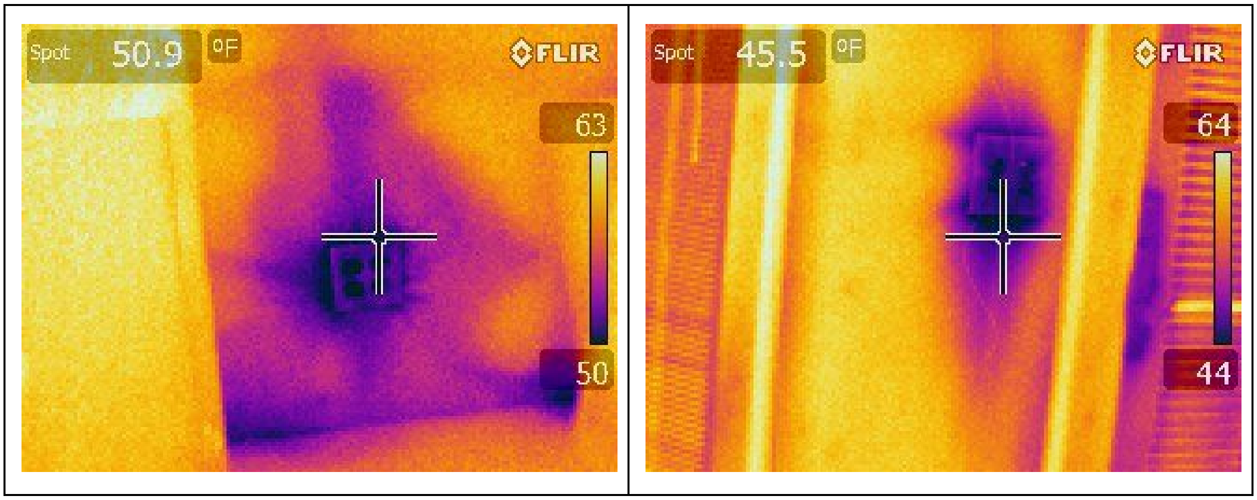
We have returned to our three-part classification of homes in relation to their suitability or availability for onsite clean energy generation. The cells shaded in red highlight scenarios with highly mismatched elements; these should be avoided unless the structure is required by code

[4] Standard refers to simplest and least costly units that are build for long-term functionality and durability; this should not be assumed to be the least expensive options on the market.

(as in hurricane or tornado areas), and the budget does not allow upgraded windows and doors. There is only one combination with these elements closely matched (yellow shaded), which could be recommend for SORTA and SNAIL homes with goals of reducing operational energy because onsite clean energy generation is either limited or not available. Even though the green-shaded scenario has mismatched elements, that represents the best combination of cost, value, resource-use, and environmental responsibility, when onsite clean energy generation can meet 100% of household energy demand, as in a SOAR home.

The green and yellow cells also provide a fantastic example of opportunity costs informing choices in homebuilding. Selecting premium windows and doors for a typical average-sized home can cost $20,000 or more, and the benefits in lower HVAC costs will never break even on the investment (when including cost of funds; see previous chapter). Meanwhile, installing enough solar PV to generate total net annual household energy needs will cost less than $20,000 initially (net after ITC; see Chapter 3), and that investment will do far better than break even (see chapter 3), while directly eliminating a significant climate footprint. Furthermore, if any spending on premium windows and doors uses budget that would otherwise go toward onsite solar PV, the outcome will be worse for the homeowner and society. The homeowner would be selecting the choice that provides the worst return on the original investment that is also least likely to be valued in appraisal and financing. That choice would also be worse for the planet, with greater use of resources for much less environmental benefit, and an opportunity will have been lost to eliminate household climate emissions (and possibly also from transportation).

Mid-range structures require a bit more nuance. There are a number of options between a base code-minimum structure and a premium envelope, but the most common mid-range choice is the upgrade of wood stud walls from 2x4 to 2x6. This adds more structural material (timber), more insulation, and more finish materials, as in window and door extensions. The classification averages in our regional database indicated promising efficacy in reducing overall energy use from an upgrade to 2x6 wall structure, but without more research we would like to temper any enthusiasm for that wall type. First, this structural envelope included the fewest cases in the database, and too few for us to draw broader conclusions. The second reason has to do with utility incursions in exterior walls. Electrical boxes are particularly egregious, and the common practice across most of the U.S. is to recess these into walls were required by code (for outlets and switches), regardless of wall thickness. In code-compliant 2x4 wood stud walls, such boxes displace more than half of the cavity insulation, creating weak points in an otherwise unbroken plane. Additionally, the practical challenge of installing insulation around these boxes almost always results in imprecise fill or notching, leading to air infiltration. One member of our team has performed energy audits on hundreds of homes, where he commonly finds breaches around and through recessed electrical boxes; see images below.



Recessing electrical boxes in exterior walls invites significant compromise through and around those features, and it adds weak links that widen the mismatch of elements and further reduces the proportional value of the strongest elements of the thermal envelope. The 2x4 wood stud wall is adequate for structural integrity and longevity[5]. That base wall is also thick enough to provide optimal levels of insulation[6] in stud cavities, but not if holes are created every 10-12 feet for electrical boxes. In the previous chapter we appeal for design work that minimizes utilities in exterior planes, and attractive surface-mount fittings where codes require placement along the thermal envelope (see examples in previous chapter). If the homeowner or builder is not willing to make these accommodations, than we recommend upgrading to 2x6 stud walls simply to reduce the impact of these weak links.

Opportunity Costs

An upgrade to thicker walls requires sacrifice or cost in one of two ways. Either living space is reduced with the same exterior footprint, or the footprint is enlarged to retain the same living space. This can be significant in both dollar cost and environmental impact. The case home has three levels with linear wall footage of 144, 144, and 92 respectively. Since it was built with thick ICF walls, the total 380 linear feet amount to 250 additional square feet, just for the additional wall thickness, compared to basic code minimum[7]. At the constructed square-foot cost of $160 for the case home, the extra square footage alone might represent $40,000 for what amounts to unusable living space. What makes this even more troubling are the findings of our study that suggest premium envelopes do not appear to render operational energy benefits; in fact, our data show ICF homes using more energy, both for the two-house comparison and in the larger regional dataset.

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[5] If built with integrity and maintained effectively (see Chapter 5).
[6] If installed correctly to avoid gaps and settling (see Chapter 5).
[7] Two of the case project walls are below grade, which require greater thickness for code and structure. In addition, multistory buildings require greater structure (usually wall thickness) on lower levels to support superstructure above.

This case provides another excellent example of opportunity costs in building systems that also helps place these choices in perspective. Using the example of the case home, we will consider that the opportunity cost of enlarging the footprint to accommodate thicker ICF walls as installation of solar PV and switching to EV transportation fueled (charged) by the onsite clean energy generation.

Comparative impact of wall thickness on dollar cost and environmental impact; based on case home example of spending $40,000 for 250 more square feet (taken up in thicker wall), vs. opportunity costs of that choice in onsite clean energy generation and EV transportation.		
Priorities & sequence	**Premium envelope (ICF)**	**Code envelope with PV and EV**
$40,000 budget max.	$40,000 for 250+ square feet	$12,600 (net) for 7.2KW solar PV
HVAC energy demand	Same; see control house case	Same; see control house case
Embodied energy	Much more than PV system	Much less than premium envelope
Household emissions	No change; possibly higher	Eliminated due to clean energy
Next purchase priority	None; no balance remaining	$27,400; trade car for new EV
Transport energy use	No change; F.Fuel, as before	Electric from clean onsite PV
Transport emissions	No change; F.Fuel, as before	Eliminated due to clean energy
HH+Transp. emissions	No change; still unsustainable	Approx. 50% reduction in CO2e
Financial ROI	Neg. returns; no break even	Positive and attractive ROI

As if this comparison is not convincing enough, consider that the $40,000 in extra costs associated with an enlarged footprint does not even account for the cost premium of the more expensive upgraded wall system, which can run into six figures for moderate-large homes! Once again, even if the premium envelope showed success in reducing operational energy demand (which our findings do not support), these additional premiums are far more in initial investment than any rate of benefit could return for financial break even. Stated another way, premiums paid for thicker envelope sections will be many times more than the cost of an onsite solar PV installation that will not only fully offset household operational and transportation energy, but also render an attractive financial return on investment. And the latter will have sequestered much less embodied energy!

Mechanical Ventilation (need for)

Earlier in this chapter we noted that all of the ICF cases in our regional dataset--except one--had an ERV installed and in use. Another claim by premium envelope advocates is that they are so airtight that mechanical ventilation must be added to maintain healthy indoor air quality. In the recent past indoor air quality concerns have been largely in the areas of carbon monoxide, volatile organic compounds (VOCs), and molds. Carbon monoxide poisoning can be fatal in high concentrations, but risks have declined significantly in modern homes with fewer open flames and code-required CO sensors/alarms. VOCs off-gas from building materials and adhesives, can accumulate to high concentrations in enclosed spaces, and may create health risk to inhabitants. However, VOC off-gassing levels diminish significantly with time, and an initial flush regimen for newly-constructed homes will minimize the threat; VOCs occur in nature and are ubiquitous in low concentrations that do not threaten human health. Further, manufacturers have also found ways reduce VOCs in building materials. Most contractors now purchase and install no/low VOC products; we recommend addressing this in design and building specifications. Mold also occurs in nature and is always present; low concentrations do not threaten human health, but homes without sufficient ventilation and humidity control can permit mold colonies to thrive and threaten human health. ERVs provide ventilation, but indiscriminate use can make indoor humidity levels worse. If envelope systems are designed and constructed properly, they will dry effectively in multiple directions, and HVAC use in tightly enclosed spaces can effectively control humidity.

Carbon dioxide (CO2) is a relatively new concern for indoor air quality and human health. CO2 receives a lot of attention in climate science, where general atmospheric concentrations are now typically above 400 parts per million (ppm). CO2 at those levels is not known to be harmful for human respiration, though climatologists document many current harms and significant future threats from a warming planet occurring primarily from rising atmospheric CO2. Indoor concentrations of CO2 have long been used as a proxy for the aesthetic quality of indoor air (ASHRAE 2013), but only recently has it emerged as a direct pollutant and threat to human cognition (Satish, et al. 2012). A recent controlled study led by a Harvard environmental health researcher (Allen, et al. 2015) found that from a base CO2 rate of 550 ppm, “cognitive function scores were 15% lower for the moderate CO2 day (~945 ppm) and 50% lower on the day with CO2 concentrations around 1400 ppm.” These statistically significant findings add an entirely new variable to indoor air quality and health and, based on our small sample of readings, it appears that most homes in the U.S. have an indoor CO2 problem if they are not ventilated in some way (ERV or open windows).

Even homes that employ mechanical ventilation are likely to see unhealthy concentrations of CO2 from extended human (and possibly pet) respiration in enclosed rooms, unless effective and sufficient distribution of fresh air is designed into the system. Bedrooms, especially, are susceptible to this problem, because people spend many hours sleeping, in relatively small spaces, and typically behind closed doors. ERV manufacturers specify that fresh air input from the ERV must be dumped into the return side of a central air ducted system. ERV specs warn against connection on the supply side because the much stronger HVAC blower fan would compete against the weaker ERV fan; this could damage the ERV fan, and possibly even push HVAC-conditioned air back through the ERV and out of the building. Most residential central air systems rely on just one or a few central returns; often one on each floor of a multi-story building. These central returns are also placed in the largest open areas; it is very rare to find effective returns directly out of bedrooms. When fresh air from the ERV is dumped into return side ductwork, it will flow to the path of least resistance, which is out the central return air grille(s). HVAC units place an air filter where the return air enters the blower fan, and the filter offers resistance to ERV-freshened air to flow through the air handler and out the supply vents. When the ERV runs at the same time as the HVAC system, the fresh air will be distributed to all spaces with supply vents; however, the conditions for both to operate in tandem are infrequent. Since bedrooms rarely have direct returns, and since ERV operation together with the HVAC is only by chance and infrequent, the rooms most in need of continuous fresh air (bedrooms) get very little, and none if the HVAC does not operate.

The case project offers a practical example to highlight this problem. The home has three levels and, as typically designed, the HVAC contractor placed one large return in the open space of each floor. The ERV fresh air input was ducted to the return air plenum just ahead of the filter, as required by ERV specs. Predictably, this pushed the fresh air out the three central return air grilles when the HVAC system was not operating. This problem was positively determined, with no fresh air flowing through supply vents, and all of it flowing out of the central return grilles; that fed the large common areas with fresh air, but not individual rooms. Bedrooms with doors closed overnight, encounter CO_2 levels close to 2,000 ppm with two sleeping occupants, and nearly 1,600 for one, even with the ERV running continuously (24/7). If the HVAC runs during the night as required periodically to maintain thermostat setting, some of the fresh air is supplied to the bedrooms, but in dilute concentrations, and the infrequency of operation still allows CO_2 to concentrate to unhealthy levels in occupied enclosed bedrooms. After documenting this phenomenon, which we have since learned is common in nearly every ERV installation, we wired the HVAC blower fan to operate whenever the ERV runs. This unconventional *fix* solved the problem by drawing the ERV-freshened air through the filter and out the supply vents, more evenly distributing fresh air into all rooms. It solved the distribution problem, but at the cost of additional energy demand, which we will discuss further in the next chapter on energy.

Readers may at this point be wondering about CO_2 concentrations in their own homes, and especially in bedrooms. Fortunately carbon dioxide monitoring equipment has recently become affordable to homeowners; small CO_2 meters can be purchased for about $100 as of this writing. This is allowing homeowners for the first time to measure and track indoor CO_2 levels, and we have discovered that every home we've been able to test in our region exhibits concentrations high enough to cause cognitive impairment. The severity obviously depends on size of space, number of humans (and pets) respirating, and whether (and frequency) windows and doors are used. ERVs have historically been recommended only for premium envelope homes that were thought to be so tight as to require mechanical ventilation. Ironically, we have found unhealthy levels of CO_2 in all house types, even in very old buildings, and we contend that even code-minimum structures can be tight of air infiltration with careful design, quality craftsmanship, and a recommended blower-door test during construction (see chapter 5). In other words, every home in the U.S. should consider this indoor CO_2 problem and design systems to address it. Houses without forced-air central HVAC systems are at particular risk because they have no distribution network for fresh air delivery.

We expect fresh air design will eventually work into residential building codes as the prevalence and health implications of indoor carbon dioxide become more widely understood. In any case, indoor air highly-laden with CO_2 should be replaced, as needed, with outdoor air; this could occur through leaky windows and doors, intentionally opening/cracking windows, or by mechanical ventilation. Any of these scenarios represents weak links in the thermal envelope, which further diminish the proportional value of the most robust thermal elements and further erodes rationale for investments in wall systems beyond code requirements.

Passive Solar

One of the misconceptions that persists today about passive solar is how much solar heat gain has become compromised with better insulated windows. Years ago, passive solar offered net benefits at a time when the best available windows were plain single-pane glazing. Those units had very poor insulating properties, but since people prefer living in homes with windows, and there were no better options available, at least a few were added in strategic locations. Placing these windows on the south elevation to receive the winter sun offered desirable benefits in passive solar heat gain, and the costs were accepted as necessary for simply having windows. However, as designs and technologies evolved over time with coatings, multi-paned glazing, and vacuum or gas-filled gaps, windows improved dramatically in insulating value, but they also filtered out more of the sun's incident solar radiation. How has this tradeoff affected passive solar? Let's apply these principles--in concept--to the matching elements chart from above, but now only with the recommended code-minimum structure:

Code-Compliant Structure matched against three levels of Windows and Doors		
Standard[8] Windows and Doors	Mid-range Windows and Doors	Premium Windows and Doors
Unmatched envelope elements, but least expensive overall; suitable for SOAR homes when coupled with solar PV	Unmatched envelope elements (but closer), moderate-high window expense; suitable for SORTA homes to reduce energy use to solar PV limits	Matched envelope elements, but very heavy window costs; suitable for SORTA and SNAIL homes to reduce operational energy use
Good passive solar potential due to highest-available solar heat gain coefficients (SHGC); reasonable trade-offs in decisions to add south-facing windows	Mild passive solar potential due to mid-range SHGC; still aim for most windows on south side, and likely not worth extra investment for thermal heat sinks (masonry capture)	Weak passive potential due to lowest-available SHGC; placement of windows not as critical, and not worth extra investments for thermal heat sinks (masonry capture)

[8] Standard refers to simplest and least costly units that are build for long-term functionality and durability; this should not be assumed to be the least expensive options on the market.

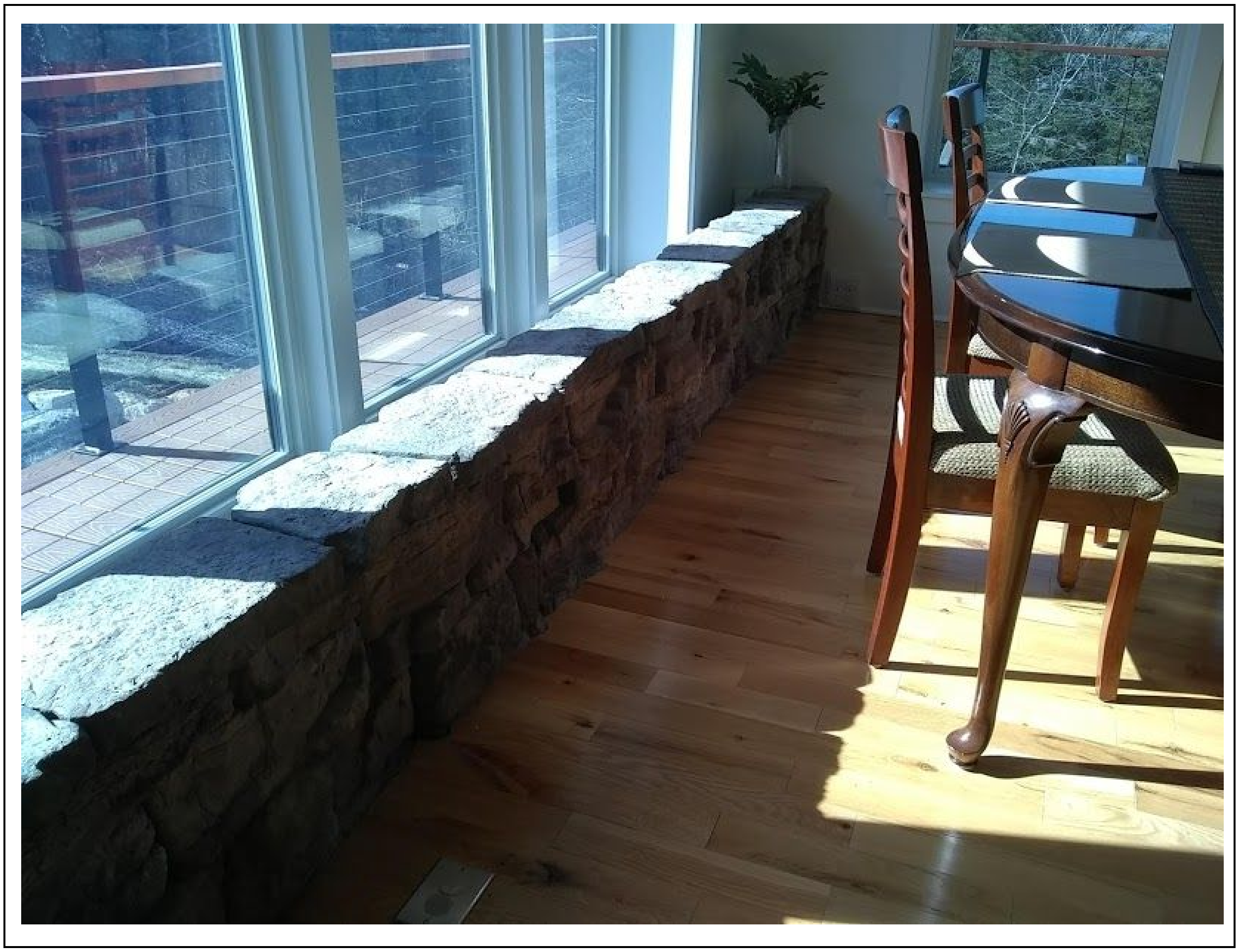
As with the overall impact and value proposition from earlier in this chapter, the code-compliant structure matched with standard windows and doors offers the best available package for passive solar. Some may, in the interest of increased passive gains, suggest lower U-factor windows only on the south side in order to improve SHGC coefficients. However, the mismatched elements logic does not support that choice on the insulation side, as that would proportionally weaken the value and investment in all stronger elements, including premium expense on all non-south-facing windows, but especially on any wall system upgrades.

In addition to southern glass and thermal sinks, passive solar designs often call for a robust thermal envelope to retain the heat accepted from the sun. A common misconception about overall performance is the significant compromise of passive solar heat gain when windows are placed in thick walls. Another reason for a code-compliant structure with passive solar design is that thinner walls allow more direct sunlight to cast onto indoor surfaces and possibly thermal sinks. The window extensions across thick walls, such as with double-stud or ICF structures, are not likely--or advised to be--made from thermal mass material and instead they block more of the sun's direct rays during all period of the day except the few moments when they are perpendicular to the glass.

Another misconception about passive solar is the value of precision in orienting southern collection and control zones. Even though active PV systems are not significantly compromised within ten degrees of true south, passive solar systems are. This is the result of designed shading, which cannot compensate for imprecise orientation. A skew just a few degrees west of south provides too much/lengthy shade of the sun during its eastern arc throughout the winter, and too much/lengthy heat gain from the western sun in swing seasons. We do not recommend passive solar design unless southern exposure can be oriented to true south, or within just one or two degrees. Once again, the case project presents a relevant example.

Case Study:

The case home was constructed on a hillside with the fall line oriented ESE-WNW. Squaring the building to the fall line (and property lines) would have oriented the south face approximately 15 degrees west of perfect south. In excavation and setting the foundation, we were able to turn the house slightly to achieve a southern orientation of 188 degrees, just 8 degrees west of due south. This precise azimuth was surprisingly optimal for PV solar production, due to local weather conditions, but there was minimal fall-off within 10 degrees, meaning that 180 degree orientation would have meant little sacrifice in active solar production. Unfortunately, our team did not give enough attention to passive solar at the constructed orientation at 188 degrees. The full passive design included masonry trombe walls (thermal sinks; see image below) just inside large south-facing windows on two levels. This is common packaging for passive heat gain; design for the sun's incident solar radiation to pass through the glass during heating seasons to warm a thermal mass, which captures the energy during the day and radiates the heat through the night.



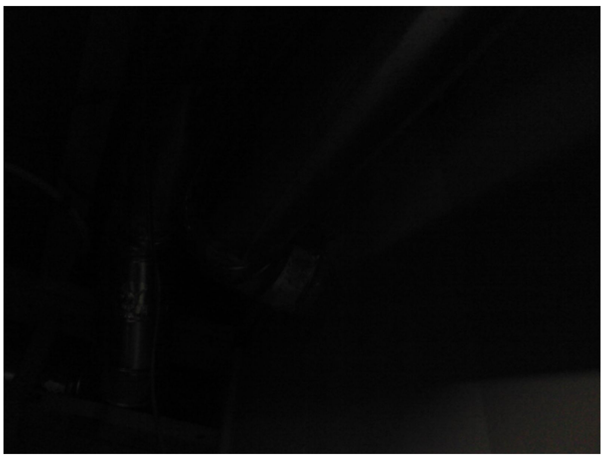
The technique for passive solar in homes with both heating and cooling seasons is to design eaves to shade southern windows from direct sunlight during cooling and swing seasons. The eaves on the case house were designed and sized for its precise latitude, which is critical for sun angles, but it assumed perfect south orientation, and that feature was not adjusted when the final footprint was set at 188 degrees. With the house just 8 degrees west of due south, the actual result is some sacrifice of desired solar heat gain during morning hours of heating months, and too much afternoon solar heat gain during swing seasons. To be more precise, the afternoon sun begins casting onto trombe walls in mid August, when there are still 6-8 weeks of cooling conditions. In the spring, the southern windows are not fully shaded until mid April, several weeks beyond the optimal swing. There are increasingly undesirable trade-offs for passive design with each degree of orientation away from perfect south. Illustrating with the case home, lengthening southern eaves to extend afternoon shading of southern glass during swing seasons would further diminish passive solar gain during morning hours when desired.

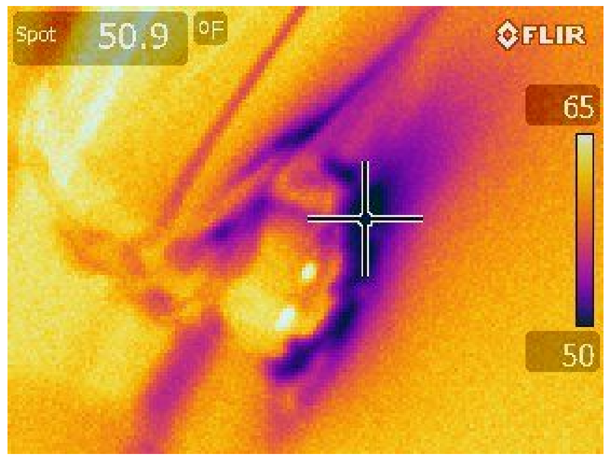
The logical conclusion is that unless the house can be oriented with a southern face within 1-2 degrees of perfect south, it is not worth any additional design or expense to include passive solar elements. It is still better for homes with heating seasons to have windows on the south side than on other flanks, but unless the home can be oriented to true south, other features of passive solar are likely to incur negative returns. Furthermore, triple-paned windows on the case house, selected for best insulating value, meant compromising solar heat gain through southern glazing. This reduced passive solar effectiveness, and return on investment for the additional cost of the trombe walls.

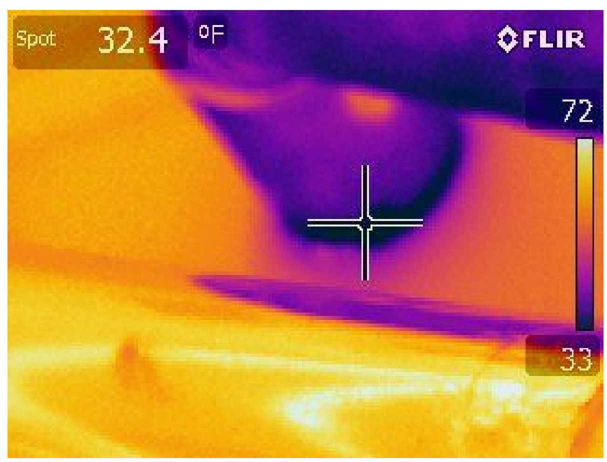
The case home also provides some graphic and numeric examples of the problem of weak links and mismatched elements in the thermal envelope. Thermal imaging highlights these concerns with color and temperature readings. The images captured below link a photograph (left side) with its paired thermal image (right side). The crosshairs on the thermal image indicate the spot temperature (in degrees fahrenheit, upper left), and the scale on the right shows the range of temperatures in the image frame. All these images were taken with 32°F outdoor air temperature, and 67°F indoor thermostat setting.

These first images show the outbound side of the ERV, with the upper inlet pipe and lower exhaust. In the first two pairs, the ERV has not been operating, but the compromise around the collars is evident in the cold readings of 56.5°F and 50.9°F, respectively, even while some surfaces in this utility room are as high as 71°F. Sealing out air infiltration around penetrations through the thermal envelope is exceedingly difficult, especially across mixed materials and when any have high thermal bridging properties, as metal does. While the images do not capture the entire sacrifice of the uninsulated “hole” through the thermal envelope (ICF in this case), the colder temperatures on the surface of the pipe indicate ambient outdoor air finding its way through the thermal envelope; this is a constant incursion. The third pairing shows these same two pipes, but with the ERV in operation. Predictably, the coldest temperatures around the pipe collar, where outdoor air first enters the home, drops to 32.4°F. Furthermore, look at the cold temperatures (by color) on the entire section of metal pipe between the entry through the thermal envelope and the inlet side of the ERV; this is effectively a cooling coil through interior conditioned space. The warmer exhaust-side pipe indicates the heat that is lost out of the building for the benefit of mechanically ventilating for fresh air.

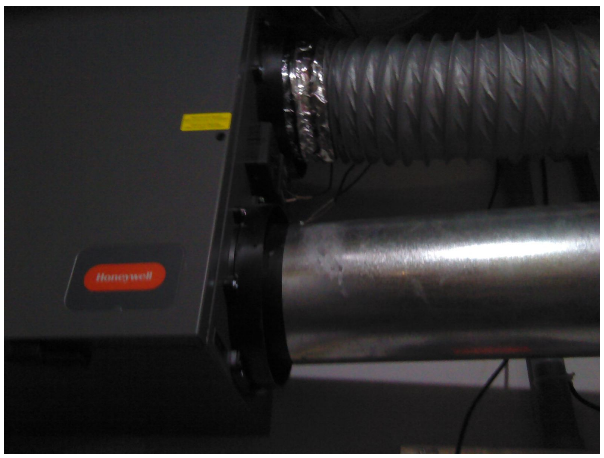
These few images depict several of the compromising weak links that diminish the value of stronger elements of the thermal envelope (e.g., wall and ceiling structure and insulation). Two six-inch holes have been punched through the wall, thereby eliminating insulation across 57 square inches (almost half a square foot), with no damper at or outside the thermal envelope. The connection collars are leaking air, even with careful attention and robust sealers. The highly-conductive metal material through the wall wicks (transfers) cold air into the home and indoor conditioned air to the outside, and the open six-inch pipe allows ambient outdoor air into the thermal envelope at all times, even when the ERV is not in operation. And when the ERV operates, the inlet pipe fills with cold air, which then radiates through the highly-conductive metal pipe wall like a cooling coil.

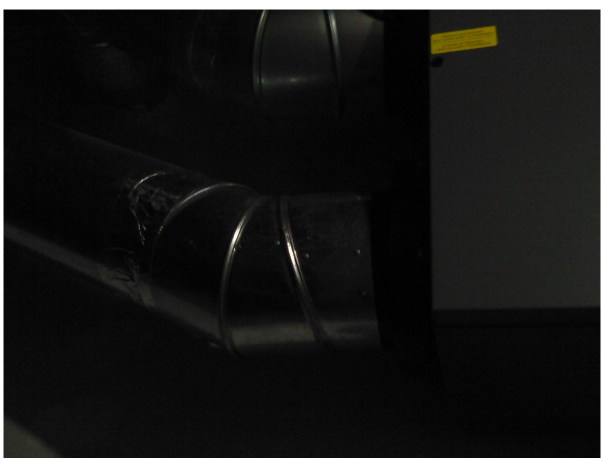


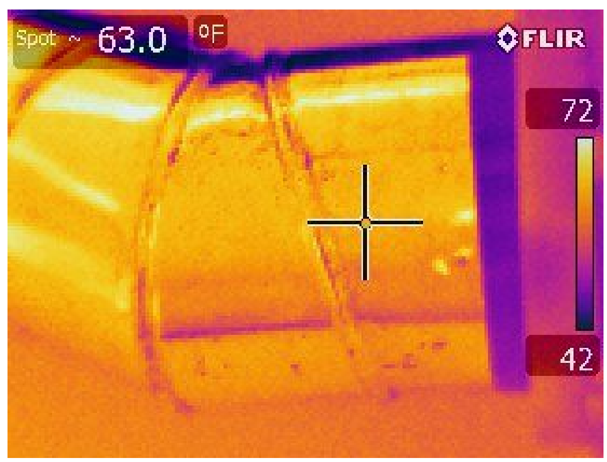




The second set of images illustrate heat loss, and recovery, from the ERV. The first pair show the inbound side of the ERV, with the top pipe carrying exhaust air from three bathrooms, and the lower pipe bringing in fresh outdoor air, but after the recovery process inside the ERV. The thermal image indicates a pipe temperature[9] of 62.6°F for outdoor air entering the house after the heat exchanger of the ERV. In the exact conditions at the time of these photos, 32°F outdoor air has been warmed to 62.2°F through the ERV by the exhausted 69°F indoor air. This demonstrates the energy recovery feature of an ERV, though it also illustrates the heat loss in an exchange process less than 90% efficiency. Similarly, the second pairing shows the exhaust pipe on the outbound side of the ERV at 63°F; the ERV has recovered some of the heat from the 67°F exhausted indoor air to warm the 32°F outdoor air as it passes through the heat exchanger.



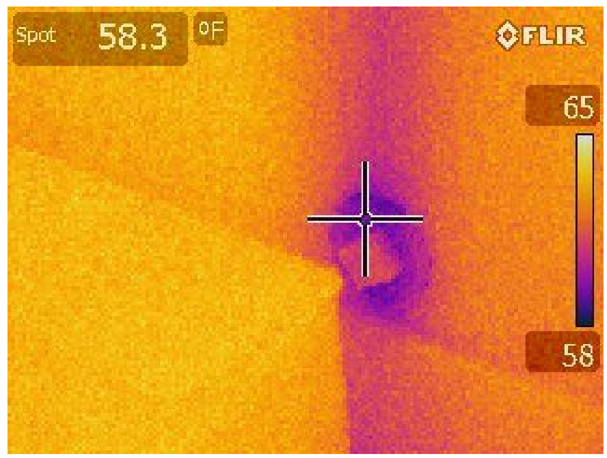




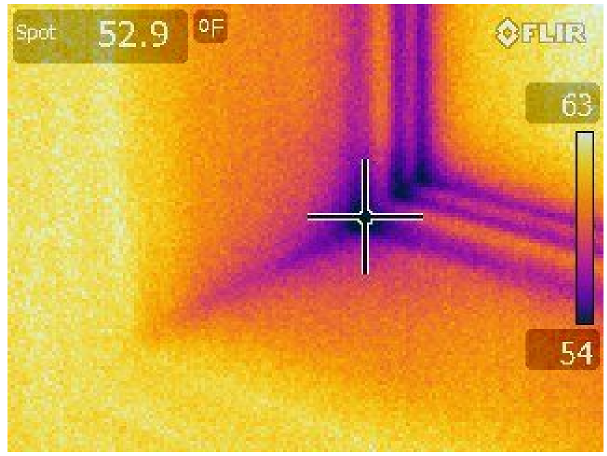
To place the value of an ERV into broader perspective, bringing fresh air into the home through a heat exchanger captures much of the energy being lost through exhaust, but clearly not all of it. In addition, using an ERV has other offsetting energy implications, including the energy needed to operate the ERV, HVAC energy to condition more air, and the energy lost through the introduction of many weak links, as detailed above. These trade-offs are explored in more detail in the next chapter.

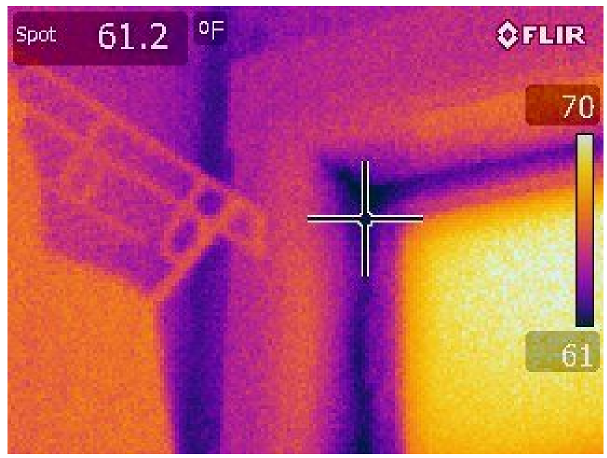
[9] With metal highly heat-conductive, the temperature on the surface of the pipe is a close proxy for the temperature of air flowing within the pipe.

This next image shows the vertical plumbing vent stack inside an interior wall. The vent stack, usually in two or three inch PVC pipe, extends through the ceiling and out the roof. When commodes are flushed, or other fixtures drained, outdoor air is pulled down the vent stack to allow rapid and suction-free drainage. Vent stacks are not dampered, so outdoor air has freedom to fill the pipe, resulting in a significant weak link. As with the penetrations needed for the ERV pipes (above), the vent stack passes through the ceiling section of the thermal envelope, leaving a “hole” in that critical element resisting heat loss in the winter. The clean-out in this image provides a closer reading on the temperature of the pipe (58.3°F), but the thermal image also reveals the compromise of the empty vent stack through any section of wall it passes through; it cools the entire stud cavity and radiates into indoor spaces, much like the cooling coil effect described in the ERV section above.

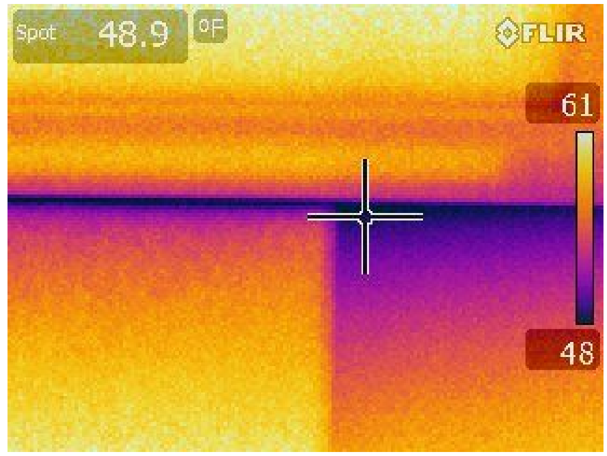


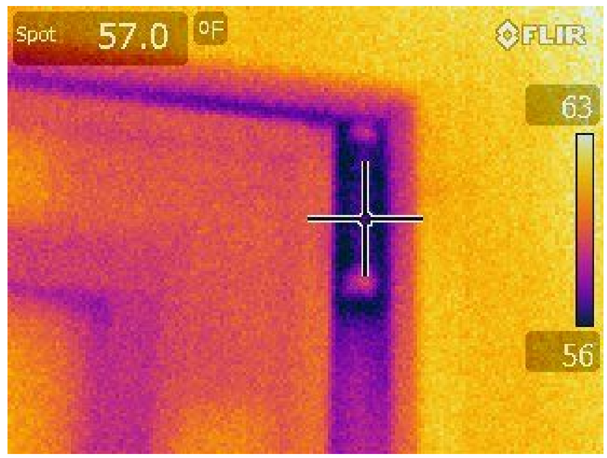
The next few images depict problems with weak points and mismatched elements designed into the thermal envelope. This first two images show the corner area of windows (one fixed and one operable) at 52.9°F and 61.2°F, respectively. Recall that the case home installed triple-pane, fiberglass-framed, and casement-style windows, which are all premium features from both a heat loss and price perspective. Even with meticulous care taken at window installation to seal window frames (with anterior tape) and insulate all window frame gaps (with interior spray foam), the weakest link shows up at the edges and corners. Fiberglass frames are less conductive (as a thermal bridge) than aluminum or steel, but more conductive than wood or vinyl (other common window frame materials). The thermal images clearly show the weakest links in the entire window assembly are the connecting points with walls, with significantly more heat loss bridged at the edges than through the glass. There is no solution, that we know of yet, to this connecting point compromise, which will be present regardless of window type; this is one of the inherent weak points in the thermal envelope that further diminish the value of stronger elements, and especially of premium upgrades.

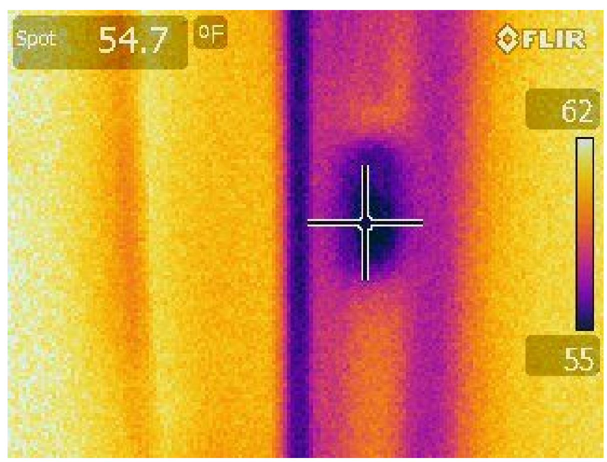




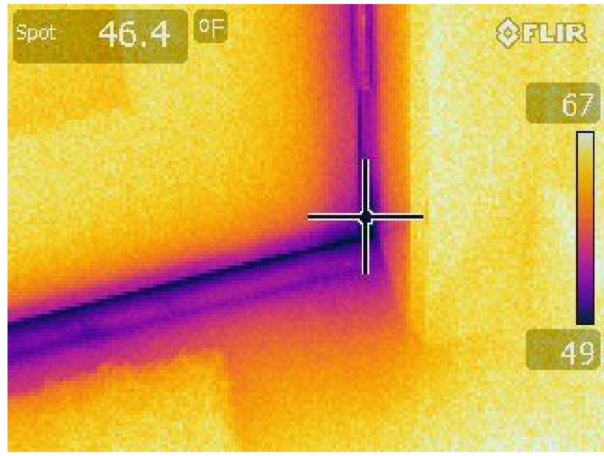
The next three pairings show weak points around doors, and in this case a triple-pane, fiberglass-framed, patio door. The first image shows temperature reading of 48.9°F along the lower edge of the door and threshold. If homeowners are going to enjoy operable doors, they will need to live with weak points where they attempt to seal against/within the thermal envelope. The next two images show thermal bridging through door hardware; in this case, a hinge at 57°F and a lock knob at 54.7°F. The case house was built to the highest-available quality standards, by a builder with careful attention to detail, and quality control oversight by the homeowner and architect. We believe that the weak points that show up in this sample are about as strong as they could be expected to achieve. The lesson to draw from these weak links is not how weak, or how many, weak points exist; rather, this helps explain why thermal envelope upgrades are almost always carried out in vain.



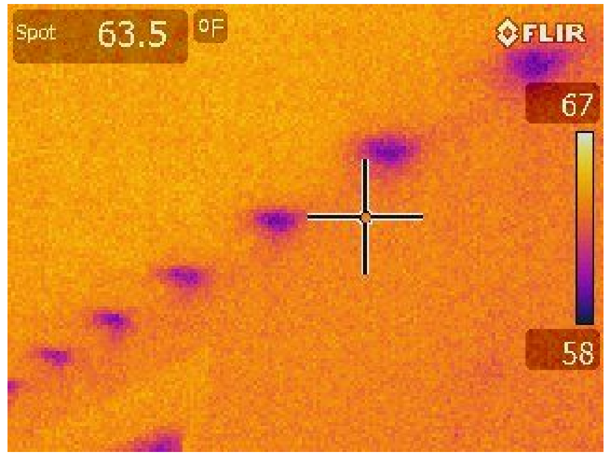


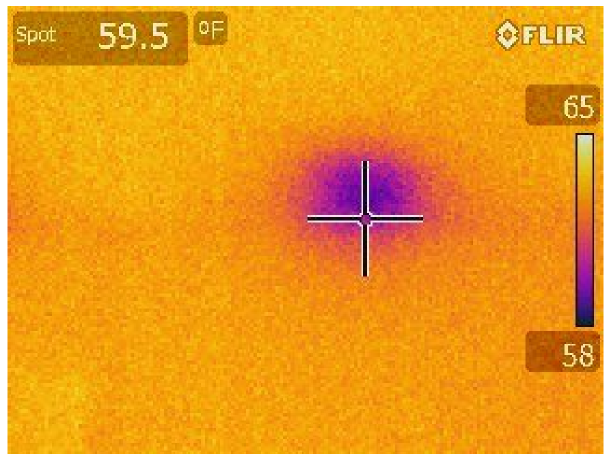


The next images show some of the weak points around a premium insulated door; this model was an upgrade at more than double the cost of a baseline standard exterior door. Doors are rated on the basis of their insulating value, and this image shows minimal heat loss through the door itself, while connecting points around the door indicate temperature readings at least as low as 46.4°F. Doors are weak links compared to wall sections, and the connecting points around doors are even weaker than the doors themselves.



An ICF wall across an uncompromised section is one of the best thermal insulators, and lab testing bears that out with some of the highest R-values in the industry. However, in each instance where walls need to connect with other structural components, such as floors, roofs, and decks, hangers are embedded into the concrete core, which is the only structural member of the ICF system. The hangers or anchors are steel, for the combined purposes of strength and longevity in interaction with concrete over time. Unfortunately, steel has high thermal bridging properties, which transfers heat to the concrete core, which is a very effective heat sink. The following images illustrate this flaw in the ICF system; the first thermal image shows cold spots on the drywall surface at every point where a floor joist hanger was embedded in the ICF wall in close proximity to deck joist hangers to the exterior. The second thermal image clocks the indoor temperature of one of those cold spots at 59.5°F. If the compromise is that severe even through the insulating properties of drywall, imagine how cold the concrete core might be, and that concrete is a very effective thermal sink, attracting and harboring the cold and distributing it broadly throughout the entire wall section. In other words, any hanger or anchor embedded in the ICF for exterior structural connections (deck, porch roof, garage roof, etc.) wicks the outdoor temperatures into the concrete core where it is readily captured and stored. Then any hangers or anchors embedded in the ICF for interior structural connections (floors, interior walls, roof trusses, etc.) transfer that energy to indoor conditioned space.





It is interesting that one of the big selling points of ICF wall systems is reduced thermal bridging; this can be documented in lab testing and is intuitively attractive to industry insiders. However, unless hanger and anchor systems can be devised from materials with low thermal bridging properties, the structural connection problem will continue to poke holes in the ICF story. We believe this is one of the reasons that ICF homes performed worse than expected in our regional analysis.

Given the argument in this chapter that weak and mismatched elements pose a strong threat to the value of the strongest sections of the thermal envelope, this final item from the case home may seem trite. The building team had already decided on triple-pane windows, on the basis of competitive pricing from a Canadian supplier at a time when the the USD-CAD exchange rate was attractive to U.S. buyers. The order was placed for all windows and two patio doors; those with glass sections. The window company did not sell solid doors, so we sourced those locally. The front door was designed as solid core, but with integrated sidelight and transom windows, which we could not order in triple-pane. This unfortunately added another weak and mismatched element, which further diminished the insulating value of the triple-paned windows.

Overall the case house was a hard lesson that we needed to learn by doing, measuring, testing, and living in the home. We followed the conventional wisdom in the industry, and we did not yet have the benefit of our own research and findings. The case house has an ICF wall system, which we now know to be significantly diminished in its purported insulating value due to the many weak links and mismatched elements. The added cost for this premium thermal envelope was well in excess of $100,000, yet it required more energy to operate than the code-minimum house that the homeowners moved from. Fortunately, solar PV was installed from the beginning, which cleanly produces enough energy for household and transportation needs, but this all could have been accomplished for much less cost, and reduced environmental impact.

Summary and Conclusions:

Marginal analysis is critical to find optimal thresholds in bolstering the thermal envelope, and that informs the diminishing returns to scale of insulation. Performance profiles for different insulation products and thicknesses demonstrate that building codes across the U.S. already require insulation values in excess of a cost-benefit optimum[10]. Our findings rebut the conventional wisdom that thicker walls and insulation is better; we show how it is worse from both a financial return perspective and ecological impact. Too little thought and research goes into the impact of utility penetrations through the thermal envelope, and how that further diminishes the intended value of the most robust thermal systems. Weak links and mismatched elements abound in American homes, which is not a critique of those compromises as much as it enlightens the folly of thermal envelope upgrades.

Our findings of energy use by wall type and living space was both surprising and disappointing at first. We expected to apply the tools of environmental economics to show attractive return on investment for thermal envelope upgrades when accounting for the ecological externality. That was impossible when whole-house, lived-experience cases seemed to show no benefit at all from premium upgrades. Though initially mystifying, a careful cataloging of weak links and mismatched elements provided the logic we now see in the data. Our team had fallen into the industry pattern of trying to analyze component parts in isolation, but our data suggested a broader, whole-systems review. Adding the tools of finance, and especially opportunity cost of funds and energy inflation, drove the nail still deeper into the coffin of thermal envelope upgrades.

As long as we live with utilities in the home, and operable windows and doors, the weak links will always overwhelm theoretical benefits of nearly all thermal envelope upgrades. Our findings point strongly toward an optimal thermal envelope simply built to code standards. While this was unexpected and disappointing at first, we soon realized that placing this knowledge in the context of whole-life sustainability makes this recommendation very good news indeed. It means that the most sustainable choice is also the most affordable. Homeowners building or

[10] Wall thickness is largely governed by structural and safety concerns that in the base application (2x4 wood stud walls) provides more than sufficient cavity space for optimal levels of insulation.

buying a code-minimum house are more likely to have it appraise and financed at actual cost, and they are more likely to see an acceptable return[11] on investment at resale. If homeowners resist expensive upgrades to the thermal envelope, they are more likely to add solar PV, which on reasonably good installations, accrues attractive financial returns. Eschewing expensive thermal envelope upgrades would preserve household resources for the transition to electric vehicles. These are the opportunity costs of thermal envelope upgrades foregone.

Many people believe that premium thermal envelope homes are tight enough to require mechanical ventilation. Our findings suggest that every thermal envelope type can be constructed and maintained tight enough to create debilitating concentrations of CO_2. Options for fresh air ventilation are addressed in the next chapter; however, here we can debunk the theory that the threat occurs only in certain construction systems and methods.

Our study on passive solar uncovers further misconceptions. Windows have improved dramatically over the past few decades in insulating value, and that is helpful to narrow the gap between mismatched elements in the thermal envelope. However, the sacrifice of stronger U-values is less solar heat gain through windows, and this alters the calculus for passive solar design. In cold climates, windows are always better placed in south-facing walls, but unless the home can be oriented to perfect south, extra effort, costs and provisions for a full passive solar package is likely to offer a poor cost-benefit return.

Understanding diminishing returns for building envelope upgrades beyond code-minimum will lead to the most sustainable outcome, with an attractive financial return on investment, that also would cut 50% of climate emissions in the U.S. Code-minimum houses, built with quality, are the least expensive among a wide variety of options. Adding solar PV to meet household and transportation energy actually provides an attractive and stable rate of return. The industry has homeowners thinking building envelope first and solar second; however, with building envelope upgrades off the table, solar should be planned as a priority from the beginning. Finally, with a least-costly building envelope, and a strong financial investment in solar PV, homeowners will have more resources to transition to emissions-free transportation, charging their electric vehicle with the clean energy of their home solar system.

Dos and Don'ts:

Dos related to envelope misconceptions and implications

1. Learn enough about diminishing returns to apply it intentionally in all areas of life.
2. Learn enough about opportunity costs to apply the concept intentionally in all areas of life.
3. Apply the tools of finance to understand return on investment for envelope upgrades.

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[11] Return on investment for real estate varies by region and other factors; nationally, home values have kept pace with inflation, on average, in the U.S. economy since WWII.

4. Orient structure to 180° (true south), if possible, for optimal solar heat gain and control.
5. Prefer window placement on south side, for cold-climate homes, as optimal for passive.
6. Build thermal envelope to local code compliance (varies by region), with quality control.
7. Employ verifiable craftsmanship to minimize weak links in the thermal envelope.
8. Give consideration to mismatched elements when selecting windows and doors.
9. Plan for a system of ventilation to keep CO2 within healthy levels in all rooms
10. Given a reorientation about the value of thermal envelope upgrades, plan for solar PV as a first priority in any new home construction project; design for it!
11. Place choices about home construction in the context of broader life issues and impact.

Don’ts related to envelope misconceptions and implications

1. Don’t assume that thermal envelope upgrades will reduce HVAC energy use.
2. Don’t spend money on thermal envelope upgrades beyond what is code-compliant.
3. Don’t design for passive solar unless true south orientation range between 178°-182°.
4. Don’t assume that any house would not exhibit unhealthy levels of CO2
5. Don’t run an ERV (or other mechanical ventilation, if installed) more than necessary.

Chapter notes:

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