Chapter 5
Building Envelope Systems

Don't judge a book by its cover - Common English Idiom
A chain is only as strong as its weakest link - Ancient Proverb

Opening Questions:

What are the different building envelope options?
What are the tradeoffs between envelope systems?
What is the role of insulation, and what options exist?
What is thermal bridging, and how can it be addressed?
What is the role of air infiltration and how can it be reduced?
Can a house be too airtight and how might that be addressed?
What are the opportunity costs of selecting envelope upgrades?
Which envelope systems are better/worse for for the environment?
How do windows and doors impact the performance of the envelope?
How does the building envelope contribute to moisture and mold issues?
How does onsite generation of renewable energy alter envelope decisions?
How do building envelope elements influence the appraisal and resale value?
How does craftsmanship of the envelope influence durability and sustainability?
What steps in the design and build process help control for quality craftsmanship?

Data and Analysis:

As the metaphorical term implies, the building *envelope* refers to the outer shell of the building; it comprises the roof, walls (including windows and doors), and foundation (including ground floor), and it serves two primary functions. The building envelope provides both structural integrity and protection against outside elements; it is a key component of sustainable housing, and it involves the bulk of work and cost in new construction. Homeowners naturally want their significant investment to perform well on many metrics, including longevity, durability, comfort, effective control and retention of energy use within the home, and overall value. The number of different materials and systems available in the building envelope, and the combinations of elements, is enormous; this makes choices difficult, especially determining where to stop upgrading and how to package elements and systems together. When is enough enough? What systems and approaches offer the best financial return on investment? How do the various elements of the building envelope interact? What are the most responsible environmental choices? While the sheer number of options and combinations is nearly infinite, our analysis of many specific and integrated systems led to a few broad principles that can more simply and understandably guide choices.

To first ground this issue in current social and economic realities, there are an interesting set of incentives in the building, buying, appraisal, and financing processes that strongly impact building envelope decisions. The real economic (market) value of a home is only as much as a potential buyer is willing to pay for it, and since most homes are purchased on credit (with a mortgage), this requires appraisals that drive loan amounts and terms, and sales prices. Most of the key features of a building envelope are hidden from view after construction is complete, and most homebuyers do not value many upgrades at their installed cost, or for their ability to potentially reduce energy bills. The home shopping and buying process is the epitome of *judging a book by its cover*; what gets noticed and factored into market prices are the things seen on the surface, both outside and inside the home. Conversely, the materials inside the walls, and the integrated systems of the building envelope, are mostly out of view, out of mind, and left largely out of conversations and decisions about offers and sales. In addition to location, neighborhood, and local school district, which often factor significantly into home values, the strongest drivers of market prices are things seen on the surface such as curb appeal, space, number of bedrooms and bathrooms, kitchen cabinets and countertops, and flooring surfaces, among others. As evidence of the primacy of these factors, an expertise and healthy industry has emerged as a specific service to spruce up homes for resale, with all modifications done for outward presentation and improved sales price. Most homebuyers do indeed judge homes by their covers, which become a more significant determinant of market price than the robustness and energy efficacy of the building envelope.

Developers and builders live with this reality, which creates an incentive to build spec houses[1] with a minimal-cost envelope, choosing instead to upgrade on finishes that help sell the home at a higher price and profit. To do otherwise in a competitive environment would be to price their products out of the market, and their business out of existence. The green building industry, however, continues to push for more robust building envelopes to reduce heat loss and energy use; thicker and better insulated walls, roofs, windows, and doors, and selections and systems to reduce air infiltration. The goal is an airtight and heavily insulated envelope. These upgrades, however, which add tremendous expense to construction, are not fully valued in market price or in home financing, and with good reason given current market conditions and incentives. Lenders must ensure sufficient repossession value in case of loan default, and their liability is directly tied to market value, which is determined by homebuyers attracted to surface features and finishes. Buyers of existing homes do not fully value most building envelope upgrades; in fact, they are hardly valued, relative to more significant factors of location, size, and appearances. The result of this market reality is that houses with robust building envelopes are built primarily as custom homes for wealthy owners who qualify for larger loan amounts, and who can deposit more than the typical 20% down payment (while avoiding more costly pre-mortgage insurance--PMI). These wealthy homeowners are also better equipped to absorb value losses on resale, which is more likely to incur with such homes.

[1] Roughly three out of every four new homes built in the U.S. are speculative (Siniavskaja, 2016).

These trends set up an uncomfortable juxtaposition. It is still assumed that being environmentally responsible means building a house with a premium envelope. But the high cost of that premium makes this option accessible only to the wealthy and, even for them, it can be a poor financial investment due to financing and resale markets. Those who cannot qualify for a larger mortgage that would be needed to finance a premium envelope, or who cannot afford down payments in excess of 20% because appraisals do not fully value envelope upgrades, or who simply cannot allocate a higher percentage of a limited and squeezed income, have no choice but to seek more affordable housing, and that usually means a more basic thermal envelope. With these realities, it is no surprise that so few houses in the U.S. are built with premium building envelopes--the presumed *sustainable* home--and conventional wisdom suggests that most homebuyers, then, do not build or buy sustainable homes. However, due to declining costs of solar PV, and the advantages now of onsite renewable energy generation, we reject this juxtaposition as a false choice. This is where our three part typology is relevant, and how onsite renewable energy generation is linked with building envelope decisions.

Recall that we identify SOAR scenarios as homes that have the capacity to install solar PV in sufficient size to meet annual household energy demand; recall also that in most cases it is less expensive to install solar than not to install solar! SNAIL homes are the opposite case, where solar PV is not available, and SORTA homes are where solar PV is available, but limited in size or production. From an overall sustainability perspective, the ideal home generates all the energy it needs onsite, from clean and renewable sources; solar PV meets that objective and has become financially advantageous in most areas of the U.S. Another sustainability objective is to use fewer resources in construction, with materials that are less damaging to the earth in extraction, processing, and transportation to the building site; this is called embodied energy. The ratio between embodied and operational energy varies with many factors, but building scientists agree that operational energy over the full lifecycle of a house far exceeds embodied energy; Johnston and Gibson (2010, p. 6), in *Toward a Zero Energy Home*, estimate the ratio at 13 to 1. This suggests a theoretical priority for reducing operational energy when onsite renewable energy generation is not available, as in a SNAIL home, but as we discuss later in this chapter, theory and observed reality are often incongruent.

Where solar PV or other clean energy generation is not available on a residence, the only sustainable choice is to make building envelope decisions to reduce heat loss and operational energy, the same prescription as proffered by the green building industry. Even while recognizing that most envelope upgrades have higher embodied energy, the purported continuous operational energy saved over the life of the building would be expected to surpass the additional embodied energy and more damaging environmental impact of the more robust envelope. A far better outcome, however, is the SOAR home, where onsite solar PV generates all operational energy needed (annually); ironically, this points to a more basic and less costly building envelope--if built with quality and integrity--that is also less environmentally damaging from embodied energy. The SORTA home, where solar PV is available, but limited in production at levels below operational energy demand from a basic envelope, strategic upgrades to the envelope might be selected to bring operational energy needs down to available (limited) solar production. To recap, SOAR homes are optimal from a whole house, whole life, sustainability view, and fortunately they are also the least costly to build, most affordable to own, easiest to sell, and most likely to return the highest investment value on resale. SORTA homes are second best among these three options, and SNAIL homes are the most damaging to the environment in both embodied and operational energy, most costly to construct, least affordable, and most difficult to sell at prices that would recoup investment value.

The code-minimum house, in most cases, has the lowest embodied energy. The conventional wisdom in the building industry suggests that such homes also require the most operational energy, compared to homes with more robust thermal envelopes; we test that assumption later in this chapter. If we assume it's true for now, it raises an interesting trade-off question for SOAR homes of whether to add building envelope upgrades to reduce operational energy, or increase the size of the solar PV system to produce the energy needed to power a more basic envelope. Both solar PV and envelope upgrades add initial cost, both in dollar and embodied energy (environmental impact) terms, but both also provide a future stream of benefits; what are the tradeoffs? Our team analyzed a broad, though not all-inclusive, range of building envelope upgrades and solar system types and sizes to arrive at some general principles outlined in Table 5.x below. The data and analysis leading to these broad conclusions is provided in this chapter and the next two. This assumes a benchmark base (code-compliant building envelope) consistent with the International Residential Code that permitting offices in the U.S. use to develop their own local and context-relevant building codes.

Tradeoff analysis by investment and criteria	Building envelope upgrades beyond min.	Solar PV: initial and scaling up
Economic return from lower heat loss	Varies (mostly poor)*	N/A (some shading)
Economic return from energy generation	N/A (possible passive)	Strong (Chapter 3)
Economic return in market/resale value	Poor/limited (above)	Varies by region
Environmental impact of embodied energy	Relatively heavy*	Relatively light
Environmental impact on operational energy	Relatively small*	Full and complete
Embodied energy to operational energy ratio	Poor; some negative*	Fantastic (Chap. 3)
Economic return on environmental investment	Most low or negative*	High in most areas

Table 5.x; *Data and analysis for these conclusions provided in this and the next two chapters.

The comparison of building envelope upgrades (generally) vs. solar PV on both economic and environmental costs and benefits is not even close. Increasing the relative size of solar PV has far less embodied energy implications than most building envelope upgrades, and far superior return on investment from the stream of operational benefits. To put this into perspective, an entire solar PV system providing 100% of annual residential energy needs often has less material weight[2] than many of the individual upgrade systems to the building envelope, each of which *may* reduce energy use/loss by a mere fraction of the whole, if any at all. Of course the materials are different, and not all equal in environmental impact, but the reality of this scale and magnitude helps keep perspective when comparing these two systems, both of which attempt to either save or provide energy and reduce environmental harms.

This leads to an interesting question: are there *any* building envelope upgrades beyond code-minimum standards that offer reasonable and recommended financial and environmental tradeoffs? In other words, what upgrades are advisable because lower energy use and cost in operations offset higher embodied energy and costs in construction? Air infiltration, insulation, and thermal bridging are the three primary concerns of the building envelope from an operational energy perspective, and moisture and condensation/vapor control is an issue determined by the interrelated performance of all three. Insulation and air infiltration are commonly understood and descriptive by name. Thermal bridging may be new to some; in construction it refers to the heat transfer properties of materials[3]. As an example, steel is highly conductive and transfers heat through the material; a thermal bridge in wall construction would be metal studs in an exterior wall that conduct outside heat into the building in the summer, and cold into the building in the winter, regardless of insulation within the stud cavities. A building envelope is most effective against operational energy losses when thermal bridging and air infiltration are relatively low, while insulation value is relatively high. Furthermore, these three elements need to be considered as interrelated and complementary components of the whole envelope. For example, thick and expensive insulation matters little if gaps are left for easy air infiltration, or if thermal bridging conducts heat through the envelope.

Of the three principles targeted to reduce heat transfer through the building envelope, reducing air infiltration has the largest impact on performance and is also one of the least expensive areas to address. Relatively small investments--in both dollar cost and embodied energy--to seal the envelope of air infiltration will pay large dividends over the long life of the building. We strongly recommend a blower door test *just before* insulation is installed, to identify and seal air leaks in the structural envelope. Low cost (dollar and environmental) sealants such as caulk, spray foam, and tape can be applied to air gaps in the outer shell before they are covered by insulation and inaccessible. Note that this practice applies to *any* envelope system, and the investment of a few hundred dollars will pay off in a few years with both environmental and economic benefits. Furthermore, the embodied energy of this task and material pales in comparison to commensurate reduction in operational energy over the life of the structure. With very few resources and materials used for a pre-insulation blower door test and seal, this is more of a process inclusion than a materials or systems upgrade to the building envelope, most of which have much higher costs (in both dollars and embodied energy) and diminishing returns. Let’s now apply these principles to each of the building envelope elements; foundations, roofs, and walls.

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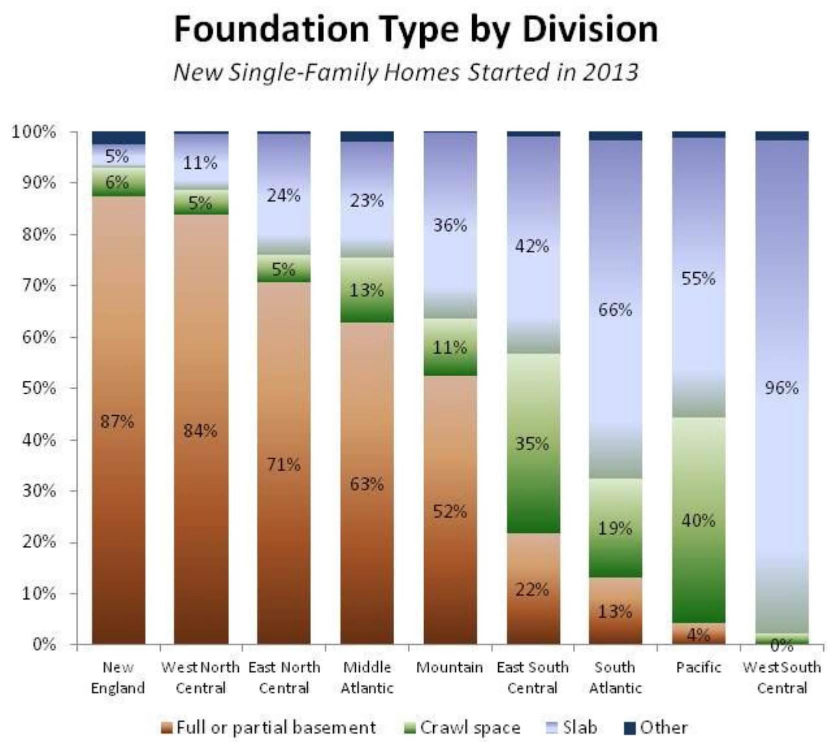
[2] Total weight of three solar installations in 2018; this includes modules, racking, inverter, and switchgear: 3.4 KW system 652 lbs., 5.8 KW system 1,600 lbs., and 9.1 KW system 1,897 lbs.

[3] See https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html

Three predominant foundation methods are used in the United States. The National Association of Home Builders (NAHB) reports that 54% of houses are built on concrete slabs, 30% on full or partial basements, and 15% over crawl spaces; the small remaining balance (about 1%) are built on stilts, pilings, or use other methods (Siniavskaya, 2014). The optimal choice is based on many factors, but primarily weather conditions, local geology, and cost; see Figure 5.1 for the U.S. breakdown by region.



Source: Survey of Construction, 2013, NAHB Estimates

Colder climates benefit from envelope contact with the earth, since soil is an effective insulating buffer in extreme cold, and it also blocks air infiltration. The regions with the coldest winters are the five in Figure 5.1 using mostly basements. Ground temperature at the surface varies (though lags) with air temperature changes, but that variation modifies below grade, and progressively with distance from the surface. In many areas of the U.S., ground temperature below the frost line hovers near 50-55° Fahrenheit year round; this is fantastic insulation in the winter when air temperatures drop well below 50° in many parts of the country, and this is one reason basements are common in colder climates. Standard construction practice for concrete floors on soil include four to eight inches of gravel, then plastic sheeting as a vapor barrier, before pouring a four-inch concrete slab. Concrete has relatively high thermal bridging properties, which draws the coolness of the earth onto the surface of the slab; many homeowners lament the cool/cold surface of concrete basement floors, which also cools surrounding air and increases the indoor heating load. One upgrade we advise is installing two inches of foam (either spray or rigid) between the gravel and plastic to both insulate and break the thermal bridge from the soil to the slab; this adds minimal cost in both dollars (about $1.30 per square foot) and materials, makes the concrete more comfortable to live on, and will reduce heating costs and energy use in the winter. Rigid foam also works well for slab edge insulation, in this case to break horizontal thermal bridging from adjacent earth to the slab.

Crawl spaces work best when they are within the conditioned envelope, but that requires energy to heat and cool unusable space. Unconditioned crawl spaces are very tricky to get right, since they need a measure of air exchange to control moisture and prevent mold growth, but this further weakens the insulating value of the envelope. Since conditioned areas over a crawl space are not rammed against the earth, substantial insulation is recommended in the floor system, and great care should be taken to seal any gaps or penetrations through the floor to minimize air infiltration. Crawl spaces often have an advantage over slab floors in thermal bridging; floor joists are less conductive (if wooden) than concrete. Builders should consider breaking the thermal bridge below floor joists, but only in consultation with an integrated strategy to control condensation and moisture. Since the complexities of crawl spaces are many, we strongly advise consulting history, best practices, and engineered specifications outside of this resource.

Most residential roof structures in the U.S. are wood-framed. Wood is a better material for reduced thermal bridging than most other structural options[4]; by contrast, it is very difficult to isolate metal roof members from the thermal bridging problem. Additionally, metal expands and contracts more with temperature variation, and that has the potential for stressing building materials and opening cracks over time that allow air infiltration. If metal must be used for structural purposes, insulation should be placed between the metal and outside elements to reduce temperature variation of the metal and thermal bridging problems. While not as critical as with metal, insulating between structural members and outside elements is good practice for any structural material. This can be accomplished with a design that places the envelope ceiling below an upper structure for roofing, and then adding insulation on top of structural ceiling members. Figure 5.3 below shows loose cellulose being blown into truss cavities, then on top of ceiling joists; this forms an integrative solution to the top plane of the building envelope that reduces air infiltration and thermal bridging while providing substantial insulation from recycled material[5].

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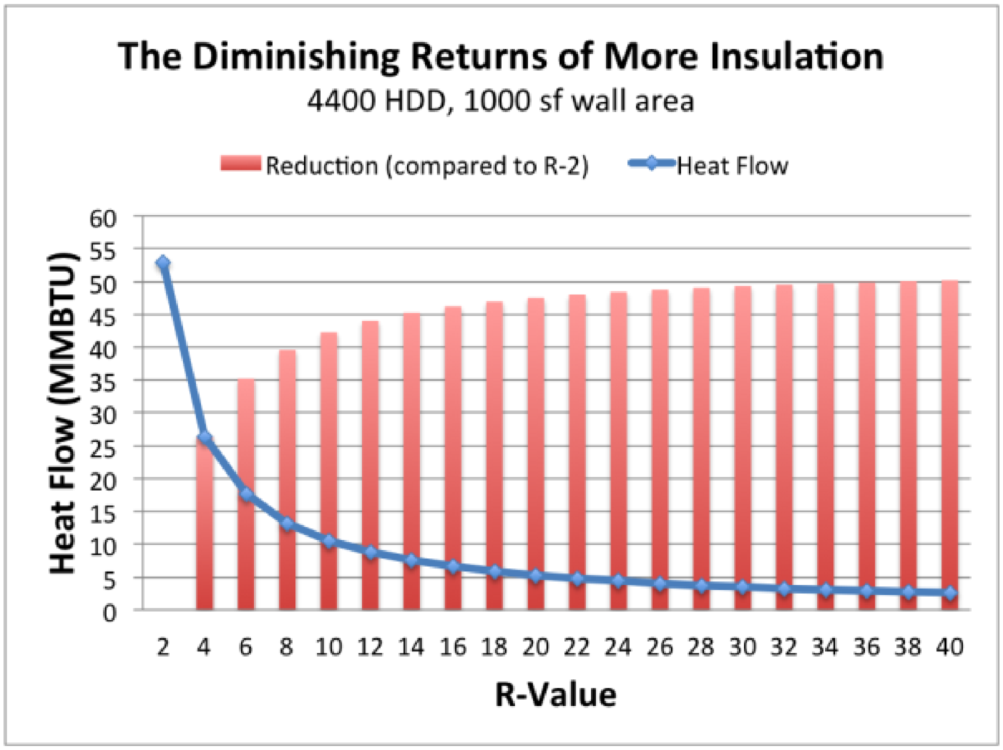
[4] See https://www.engineeringtoolbox.com/thermal-conductivity-d_429.html
[5] Cellulose has lower embodied energy than many other insulation options and is recycled material.

The upper plane of the building envelope encounters the most extreme temperature differences and therefore benefits from more insulation than walls; for example, R-38 is recommended or required in U.S. Region-4. Concentrated heat in the summer, either by direct sunlight on the roof or heat buildup in an attic space, encounter temperatures well above ambient outdoor air, and an insulation shield helps keep that unwanted heat out of conditioned spaces below. During colder weather, well-insulated ceilings helps reduce heat losses and energy use from within, since heat naturally convects to the highest elevations. For these reasons, building codes in the U.S. require higher R-value in ceilings than in walls and, for reasons detailed in the next chapter, we think adding more insulation than code requires is a poor use of resources and offers a poor set of tradeoffs. Due to the substantial value of insulation in the upper plane of the envelope, penetrations through ceilings and roofs should be minimized and, where necessary, sealed with spray foam, caulk, tape, or other sealing agent. Large housings, such as for recessed lights, should not be placed in the envelope structure; these become dramatic weak links in the overall system and prime areas for condensation to occur, which can lead to mold growth and/or structural damage. For similar reasons, skylights and solar tubes (natural light tubes) introduce weak points in all three compromising areas (air infiltration, insulation, and thermal bridging) and are best avoided.

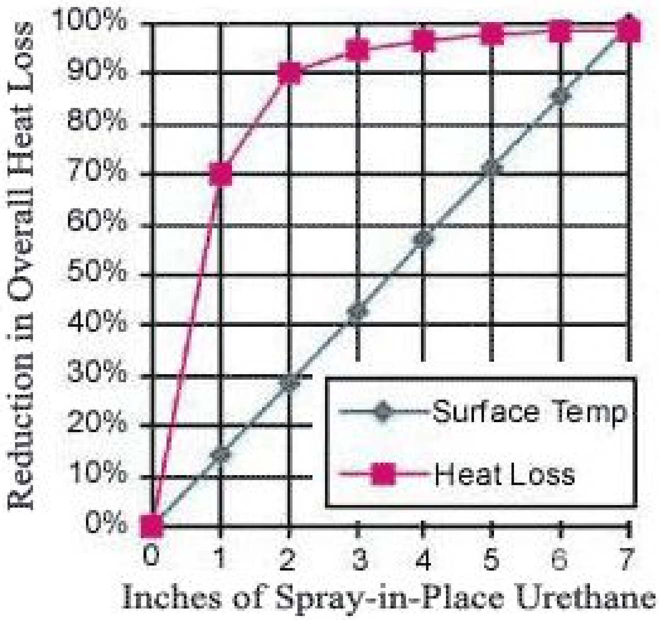
Before moving to the wall systems of the building envelope, a better understanding of the properties and benefits of insulation is instructive. Insulation is a critical component of the building envelope, but how much is needed and what insulation types and systems offer the best tradeoffs among cost, performance, and environmental impact? Performance of building insulation, of all types, offers progressively diminished returns (benefits) with each additional unit after the first; meanwhile, the costs of increasing insulation--on both environmental and dollar measures--are closer to linear. For example, installing insulation where none is present adds tremendous value in insulating performance, but each additional unit beyond the first--say, each additional inch--provides a declining additional performance benefit (see Figure 5.4 below). Meanwhile, on the cost side, doubling the thickness of insulation comes close to doubling the installed dollar cost[6] and the embodied energy in the material used.



Source: Bailes (2014)

Common insulating materials in building construction are fiberglass (blown and batts), mineral (rock) wool, cellulose, and foams, among others. As an example of the diminishing returns of additional insulation, Figure 5.4 below illustrates the reduction in heat loss (as a percentage) for each inch of polyurethane foam. Just one inch of spray-in-place urethane reduces heat loss by 70% compared to no insulation. Adding a second inch improves the insulating benefit, but by a smaller margin, combining with the first inch for 90% reduction in heat loss. Each additional inch will surely improve insulation performance, but at diminishing rates; in the case of polyurethane, the difference between six and seven inches is hardly discernible in performance value, both on the graph and in heat loss and energy bills.

[6] There are small efficiencies gained adding more insulation due to economies of scale, but not significant.



Source: South (2017)

This illustration on the performance rates of urethane foam shows that there is very little--and progressively less--gained in insulating value by installing more than just a few inches. Furthermore, the environmental damage of using more of any one type of insulation is largely linear, along with the dollar cost; this raises relevant questions about how much (how many inches of) insulation provides the best balance of insulating value vs. cost of product vs. embodied energy of installed material. This analysis has been attempted for a typical house and installation in the U.S., though many related factors influence whole house performance, such as the number and size of windows and doors, and of varying quality. Still, some sense of expected return on insulation upgrades is helpful to gain a sense of magnitude; Figure 5.5 offers such an analysis.

R-Value Reality Check

Insulation R-Value	Amount of heat flow reduced by this insulation	*Est. cost for this Insulation (per sq. ft.)	Extra cost for this Insulation (per sq. ft.)	Extra cost vs. R-8 Insulation (based on 4,000 square feet)	Improvement in Energy Efficiency vs. R-8 insulation	**Savings per year vs. R-8 insulation	Years it will take for more R-value to pay for itself
R- 8	90%	$0.60	-	-	-	-	-
R-12	93%	$0.90	$0.30	$1,200	+3%	*$22.50*	*53 years*
R-16	95%	$1.20	$0.60	$2,400	+5%	*$37.50*	*64 years*
R-20	96%	$1.40	$0.80	$3,200	+6%	*$45.00*	*71 years*
R-32	97%	$2.00	$1.40	$5,600	+7%	*$52.50*	*107 years*

Figures for amount of heat flow reduced are based on Fourier's Law of Thermodynamics.

*Costs provided are estimates only for conventional fibrous insulation. Insulation and energy costs could vary by region, type of insulation, type of home and type of heating/cooling equipment.

**Based on heating/cooling costs of $750 U.S./year. Source: Insulation Smart (2017)

Returns calculated for Figure 5.5 utilize a simple payback formula, dividing the investment value of each premium by its respective predicted annual savings in energy costs. That analysis is quick and simple, but it leaves out important financial realities that vastly change payback periods. To provide a more realistic return on investment, we include an expected inflation rate of energy and the cost of funds, or the opportunity cost of money spent on each upgrade. Since most homeowners finance their residence with a mortgage, we think a reasonable lower bound on cost of funds is 4.5%; those paying cash might consider a higher opportunity cost, such as against equity or fixed income investments. Overall inflation in the U.S. has averaged 3% in the modern U.S. economy (since WWII), and while energy inflation has been higher, on average, we believe that 3% is a conservative rate for this kind of analysis. Using the same underlying data as Figure 5.5 above, but correcting for energy inflation at 3% and variable rates (base of 4.5%) for cost-of-funds, Figure 5.6 shows realistic payback periods.

R-Value Reality Check...now adding financial realities: Energy Inflation (annual rate escalator of 3%) Cost of Funds (opportunity costs at 4.5%, plus)					
Insulation R-Value	Examples of type and mass of insulation	Extra cost vs. R-8 insulation[7]	Annual energy savings vs. R-8	Payback with COF of 4.5%	Highest rate for any payback (years at rate)
R-8	2” of spray in place urethane	Baseline	Baseline	-	-
R-12	3.8” fiberglass batts or blanket	$1,200	$22.50	113 years	4.87% (331 years)
R-16	5.1” mineral wool batts	$2,400	$37.50	224 years	4.56% (430 years)
R-20	5.6” polystyrene beadboard	$3,200	$45.00	Never pays back	4.40% (403 years)
R-32	8.6” of loose, dry cellulose	$5,600	$52.50	Never pays back	3.93% (539 years)

Figure 5.6: insulation paybacks with financial realities

[7] Based on 4,000 square feet, in line with underlying analysis from Insulation Smart (2017).

Even at a relatively low rate for cost-of-funds (4.5% represents competitive mortgage rates for top-tier borrowers in 2018), it is hard to make a financial argument for upgrading insulation beyond R-8. However, if onsite renewable energy generation is not available, then increasing the R-value of insulation in the building envelope may be the responsible environmental choice (up to a point) to minimize energy use and the household carbon footprint from operations. This is where our three scenario classification is helpful again. SNAIL homes lack the ability to generate clean energy onsite, and given that operational energy far exceeds embodied energy over the lifetime of a building, the best environmental choice where the energy is derived from fossil fuels is to decrease energy use and losses, even though it nets a financial loss. Reducing air infiltration and thermal bridging should be priority before increasing insulation beyond what building codes require in cavity spaces between structural members. Even a SNAIL home will encounter insulation (and R-value) thresholds where the environmental impact of adding insulation in embodied energy exceeds the marginal performance and environmental impact of reducing energy use in operations; these will be discussed later in this chapter and the next. On the other end of our typology, SOAR homes are assured of generating sufficient and clean onsite energy, so they can use fewer resources, less insulation, and lower R-values (and embodied energy), and still achieve net zero energy. SORTA homeowners will add building envelope premiums only to the point of reducing energy use to within limits placed on solar PV or other onsite renewable energy generation, and reducing air infiltration and thermal bridging should be prioritized before any increases in insulation.

Most envelope structures already have insulation cavities deeper than necessary to achieve an R-value of 8, and most building codes require R-values higher than eight in each of the three envelope elements. Additionally, breaking thermal bridging and addressing air infiltration most effectively utilizes applications outside of the structure, and outside of the insulation cavity, which add further insulation and R-value. That aspect will be addressed further in the section on walls, but what is clear from a straight economic cost-benefit analysis is that building code requirements and structural cavity spaces already provision insulating values well beyond the economic-performance optimum. This gap between optimal and achieved R-values widens still further when thermal bridging and air infiltration are addressed. Walls are further complicated by weak(er) links in whole-wall sections from doors, windows, utilities within walls (e.g., electrical boxes and piping), and utility penetrations (e.g., bath fans, dryer vents). These weak(er) links render higher R-values in walls even less effective, both in terms of energy use and loss, and in economic return; discussion of these mismatched elements are taken up in the next chapter.

Before assessing wall sections of the envelope, a few more broad understandings of building insulation are needed. Figure 5.4 showed the insulation profile for polyurethane foam; this pattern is similar for other insulation materials, though each one has its unique performance profile. Keep in mind that these ratings are static for a cross-section of insulation material and does not account for quality of installation, integration with other systems, or the wall as a whole which will have lower ratings across structural members (e.g., studs) and other weaker links (e.g., windows, doors, utilities). Installation quality can significantly compromise effectiveness of insulation; for example, if fiberglass or rock wool batts are not cut with precision to fill an entire wall cavity, or if they are not notched carefully around impingements like electrical boxes, they leave insulation gaps, which quickly overwhelm the R-value rating of the insulation. Similarly, if cellulose is not blown to the correct density, it will settle over time and leave an uninsulated gap at the top of each cavity; again, this breach overwhelms much of the benefit of the insulation material. With those caveats in mind, the following table (Figure 5.6) provides maximum R-value ratings, by inch thickness, for many of the common insulation materials used in most residential construction in the U.S.; these relative values may be helpful in comparing different insulating materials, and in helping to inform wall thickness and wall system decisions.

Insulation Type	Approx. R/Inch	**Approximate Inches Needed:**					
Loose Fill Machine-Blown		R-11	R-19	R-22	R-30	R-38	R-49
Fiberglass	R2.25	5	8.5	10	13.5	17	22
Mineral Wool	R3.125	3.5	6	7	10	12.5	16
Cellulose	R3.7	3	5.5	6	8.5	10.5	13.5
Loose Fill Hand-poured							
Fiberglass	R2.25	5	8.5	10	13.5	17	22
Mineral Wool	R3.125	3.5	6	7	10	12.5	16
Cellulose	R3.7	3	5.5	6	8.5	10.5	13.5
Vermiculite	R2.1	5.5	9	10.5	14.5	18	23.5
Batts or Blankets							
Fiberglass	R3.14	3.5	6	7	10	12.5	16
Mineral Wool	R3.14	3.5	6	7	10	12.5	16
Rigid Board							
Polystyrene Beadboard	R3.6	3	5.5	6.5	8.5	10.5	14
Extruded Polystyrene	R4-5.41	3-2	5-3.5	5.5-4	7.5-5.5	9.5-7	12.5
(Styrofoam) Urethane	R5.4-6.2	2	3	3.5	5	6.5	8
Fiberglass	R4	3	5	5.5	7.5	9.5	12.5

Figure 5.6: insulation materials and performance

Wall sections of the building envelope have more variables than foundations and roofs. Some walls may be below grade, and above-grade sections have windows and doors. People enter and exit through walls, which exchanges air, as do vents from bath and exhaust fans and dryers. Walls tend to have more utility incursions, especially electrical boxes, in addition to piping and wiring. All of these complicate options and selections of wall systems and insulation. Let's start with below-grade wall systems where structural strength and moisture control are preeminent, along with thermal bridging and insulation. Most below-grade wall systems are engineered for greater strength because they bear the weight of the whole house above and lateral pressure from bermed earth. Moisture control is critical because these wall sections either abut, or are in close proximity to, soils that absorb and hold water that would dam against the wall system if drainage is not intentionally and carefully provided.

Wood structures are commonly used in residential construction above grade, but they are not optimal below grade for the potential of water penetration and structural compromise. Wood could also be more accessible to termites or other bugs in some regions if used below grade. Masonry block was common in basement walls in many regions of the U.S. That system relied on effective and durable waterproofing as a thin membrane on the exterior surface to keep moisture at bay; unfortunately, too many of these systems failed, leaving basements and crawl spaces damp and musty, and potentially unhealthy from mold colonies. Fortunately, there are better and improving products on the market today, both for wall systems and waterproofing. Insulated concrete forms (ICF), Superior Walls, and poured concrete walls all add greater structural integrity than masonry block and more comprehensive moisture control, but all still require effective waterproofing applications on the exterior surface up to grade.

Most critical for avoiding moisture intrusion into below-grade walls is an effective drainage system that wicks water away from the wall and foundation. Gravel or other porous material installed between walls and adjacent earth will allow gravity to pull water down and away from the surface of the wall, and into a foundation drain that channels it away from the building. Soil is a very heavy encumbrance against below-grade walls, and wet soil can add magnitudes more weight, not to mention constant water pressure if the drainage is not sufficient. An engineered system and quality installation is paramount in the exterior drainage system around below-grade walls, then an effective waterproofing application hopefully keeps incidental moisture out of the wall material. Finally the wall system should be carefully selected for each unique application, and constructed with care and quality. Cutting corners is short-sighted in any phase of building construction, but the integrity of below grade structures is unforgiving. Compromises or shoddy construction of wall, waterproofing, and drainage systems below grade will result in problems over the life of the building, and possibly severe enough to shorten the useful life; there is zero tolerance for errors with these components.

With rigid foam built into the formwork of ICF walls, there is no additional step to insulate. Precast concrete walls have a pre-formed cavity for insulation, and poured walls require an additional application on the inside surface; this is often accomplished with a 2x4 stud wall with cavity insulation. The insulation component of poured or Superior walls cannot improve either air infiltration or thermal bridging, so almost any certified insulation material is adequate. In cases like this, embodied energy may be the best guide from a sustainability perspective, and cellulose is one of the better choices on that basis because it is recycled material. Cellulose is also very effective as an insulator; it does not effectively block air infiltration, but that is not valued in below-grade walls. We've offered some important principles of walls and systems below grade; however, optimal solutions involve so many factors unique to location and design. We recommend working with trusted local professionals to determine a suitable system for each site and building; this team may include, among others, the building contractor, building inspector, and architect.

[This would be a good place for a BB or AA, and maybe some examples of failure and success]

Above-grade wall systems really get complicated. Building science provides us with tested performance data on insulation and R-value, as in many of the charts and graphs in this chapter, yet those metrics are for a static cross-section of the insulation material. Whole wall R-values are far lower than the insulation metrics for a variety of reasons, including thermal bridging across structural members, air infiltration, and the presence of windows and doors that have very low R-values relative to wall insulation. While infinite in possible permutations, some basic principles can be drawn from this complexity. The diminishing returns of better insulation, either because of material selected or thickness of the application, is further diminished by any breaches or weaker links in the wall system, or building envelope. Breaches from air infiltration or thermal bridging, and weak links from doors, windows, vents and utility penetrations, all compromise the building envelope regardless of R-value in the walls (or floors and ceilings, for that matter). This principle suggests that better insulation (material or thickness) improves heat loss performance, but by progressively smaller amounts than the static R-value ratings might suggest; this further diminishes the marginal effectiveness of heavier insulated wall systems. Even the best energy modeling software cannot predict overall performance with precision because there are so many elements beyond the control of the systems, such as poor quality of construction, a window that doesn't latch well, or a door that loses its seal.

The basic above-grade wall system used across much of the U.S. is 2x4 wood structure, with studs at 16-inch centers, half-inch OSB sheathing and wrap on the exterior, and fiberglass batt insulation in the stud cavities. Using this wall system as a base, and considering a number of upgrades using cost of funds rate of 4.5% and energy inflation of 3%, we found very few upgrades that offered reasonable returns, both on economic grounds exclusively, and even when adding ecological impact. However, adding insulation on the exterior of the base wall system is one upgrade worth making because it both adds R-value to the whole wall (except where there are windows and doors) and it breaks the thermal bridging through the solid wood members (studs and plates) of the wall structure. Adding exterior insulation, however, can complicate the trapping and drying of moisture in the wall, potentially causing structural damage and/or mold growth. Let us look at this specific issue of moisture in and through walls and then return to exterior insulation.

Sheathing on the exterior of walls will get wet, or moist. Moisture can encroach from the exterior through any defects or breaks in the water-resistive barrier (WRB); poor workmanship, or quality problems in installation, can allow this breach from the outset, but gaps will also open over time as building materials cure, shift, and degrade. Moisture can also arrive from forces inside the house. In the winter, warm inside air can leak into the wall via cracks or gaps, such as through wall switches and outlets, poorly fitted insulation, and under the lower edge of the drywall and the lower wall plate. When this warm moist air meets the sheathing, which is cold from low outdoor temperatures, the vapor in the warm air is condensed and absorbed by the sheathing; a process called 'sorption' (Holladay, 2010). This was less problematic in the past with basic wall systems, which allowed enough warmth from livable space to infiltrate the wall and warm the inner side of sheathing, but thicker and more insulated walls allow the sheathing to become colder, thereby exacerbating the sorption condition on the inside surface. As this condition led to mold growth and rotted sheathing, building codes began adding requirements for exterior insulation in cold climates to protect the sheathing from getting too cold. Figure 5.X indicates minimum R-values of exterior insulation, with examples if using expanded polystyrene (EPS).

	2x4 wall		**2x6 wall**		**Any wall**
	Minimum R-value of foam sheathing	Minimum thickness of rigid foam (assuming EPS is used)	Minimum R-value of foam sheathing	Minimum thickness of rigid foam (assuming EPS is used)	Minimum percentage of the wall's total R-value that needs to come from the rigid foam layer
Marine zone 4	R-2.5	1 inch	R-3.75	1 inch	16%
Zone 5	R-5	1.5 inch	R-7.5	2 inches	27%
Zone 6	R-7.5	2 inches	R-11.25	3 inches	36%
Zones 7 and 8	R-10	2.5 inches	R-15	4 inches	43%

Figure 5.X - Climate Zones in the U.S. (Source: International Residential Code, 2015)

Note that the thicker wall (2x6, in this case) requires higher R-value insulation on the exterior; this is because thicker wall cavity insulation keeps the inside surface of sheathing colder from interior warmth. Note also that R-value requirements increase for colder zones, and there are no requirements in the warmer Zones 1-4 (areas of Zone 4 not in the Marine region). The map below shows the climate zones across the U.S.

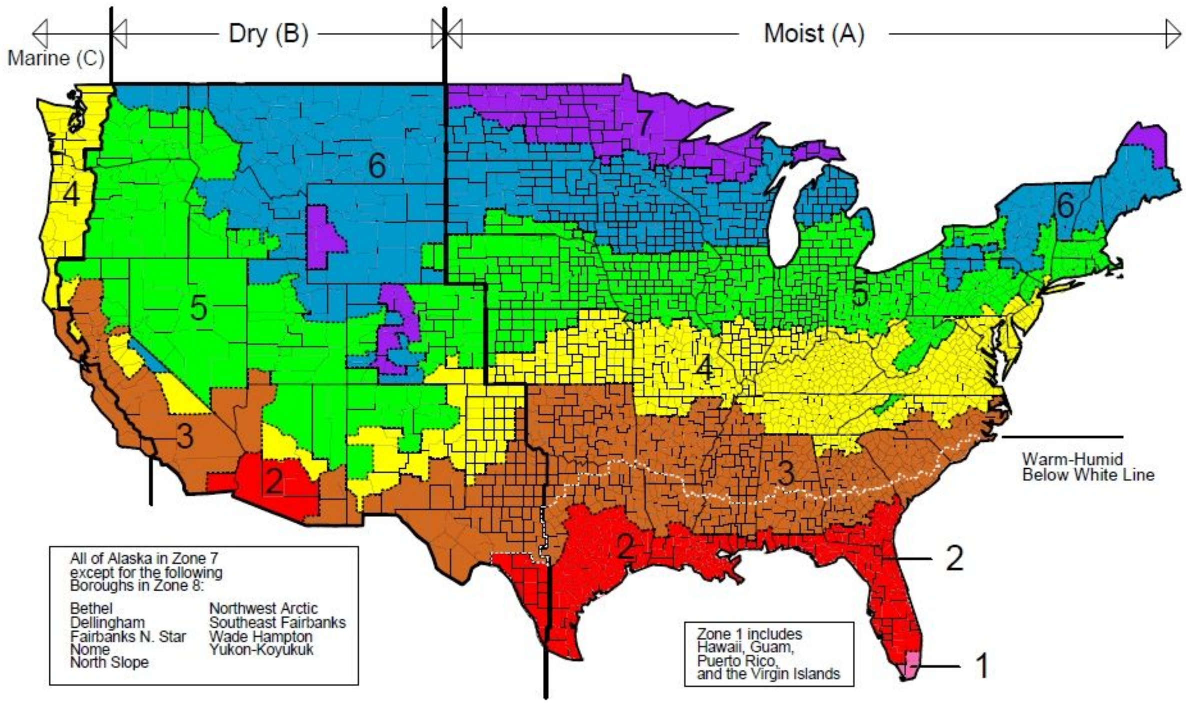


Figure 5.X - Climate Zones in the U.S. (Source: International Residential Code, 2015)

It is not advisable to expect that water/moisture will never be present inside a walls. The presence of moisture is not problematic if the wall system is designed to facilitate drying and, ideally, a wall should be able to dry both to the interior and exterior. Drying will occur to the inside when outdoor temperatures moderate and inside air is dehumidified. Drying to the outside will take place naturally when the ambient air is dryer, but the sun's energy driving against the wall is the most effective drying agent. In the northern hemisphere, north-facing walls dry more slowly; another reason to buffer the north side of a residence with the garage or other semi-conditioned or unconditioned space. To permit drying, the other materials in the wall system must be vapor permeable. For example, closed-cell foam insulation is a vapor barrier, whereas open-cell foam is not; both are effective air barriers.

Returning again to exterior insulation, which we suggest is a reasonable upgrade to the base 2 x 4 wall, though it's not critical if not required by local building code. Even a thin cover of insulation that breaks the thermal bridging of the structural members of the wall (studs, top and bottom plates, window and door frames, etc.) will return measurable benefits in reduced heat loss and energy bills. We like rockwool rigid board for this application, due to its properties of being a natural mineral, flame retardant, and advantages dealing with moisture and drying. Board as thin as half an inch would be ideal, but it more commonly sells in thicknesses of one inch or more. Rockwool in standard 1.25-inch thick rigid board adds an R-value of five to the whole wall, except over windows and doors, vents, or other penetrations. Thickness (and

R-value) of continuous exterior insulation should be guided by requirements for specific climate zone (see Figure 5.x above). Rockwool breathes, which is important for outbound drying of the sheathing; it also sheds (or drains) water effectively, and its structural integrity is not compromised by moisture. Exterior insulation that is not too thick allows fixing of siding to the structure without the additional step of adding furring strips, and rockwool in a thin rigid board package provides greater support than softer materials for exterior fixing through the material. The relatively thin depth also requires less labor and material for window and door extensions than thicker applications.

Homeowners with SOAR conditions, and who are able to install enough solar PV to meet their annual energy needs, will find that the most environmentally-friendly building envelope structure is simply complying minimally with local building codes. It bears repeating here, as at several other key places in this text, that quality and integrity in construction of the building envelope is paramount to maximizing sustainability objectives through longevity of use and life of construction materials. Building codes in the U.S. already require R-values well in excess of maximum cost-benefit gains from insulation, so there is no need to add more for economic reasons, and since SOAR homeowners are generating all of their (net) energy cleanly onsite, there is no need to add more insulation for environmental, or sustainability reasons. There may be other reasons a homeowners may wish to add wall thickness and more insulation, such as for greater indoor living comfort, but in our view that would be sacrificing environmental objectives for other personal concerns. Safety and security in areas at high risk to natural disasters provide a notable exception. Homes built in coastal regions susceptible to hurricane winds and possible storm surge will follow location-specific recommendations, and these most often require more extensive connecting hardware, and in some cases a more robust structure. The difference in these regions is that structural upgrades are required or recommended for personal safety and structural longevity rather than for energy use and loss.

Figure 5.x below offers the recommended wall system from our team for SOAR homes that utilize solar PV energy generation, for the first seven climate zones. There is some variability in local building codes, notably in natural disaster-prone regions, and those will legally supercede these broad recommendations by climate zone.

Figure 5.x Recommended Wall Systems for SOAR homes, for Sustainability, by Climate Zone

Climate Zone	Broad Assessment of Heating and Cooling Conditions/Needs	Recommended Wall System for SOAR homes, though adapt to meet local building codes
Zone 1	Very low heating needs, Lowest temperature differential (about 35℉ for cooling)	2 x 4 wood structure, studs on 16” centers, dry-blown cellulose in stud cavities, ½” OSB sheathing, and housewrap.
Zone 2	Relatively low heating needs, Low temperature differential (about 35℉ for cooling)	2 x 4 wood structure, studs on 16” centers, dry-blown cellulose in stud cavities, ½” OSB sheathing, and housewrap.

Zone 3	Low-moderate heating needs, Moderate temp. differential (about 60℉ for heating)	2 x 4 wood structure, studs on 16” centers, dry-blown cellulose in stud cavities, ½” OSB sheathing, and housewrap.
Zone 4	Moderate heating needs, Moderate-high temp. differential (about 70℉ for heating)	2 x 4 wood structure, studs on 16” centers, dry-blown cellulose in stud cavities, ½” OSB sheathing, wrap, and exterior 1¼” rigid rockwool.
Marine 4	Low-moderate heating needs Moderate temp. differential, but exceptionally wet/damp/moist	2 x 4 wood structure, studs on 16” centers, dry-blown cellulose in stud cavities, ½” OSB sheathing, wrap, and exterior 1¼” rigid rockwool.
Zone 5	Moderate-high heating needs, Moderate-high temp. differential (about 80℉ for heating)	2 x 4 wood structure, studs on 16” centers, dry-blown cellulose in stud cavities, ½” OSB sheathing, wrap, and exterior 1¼” rigid rockwool.
Zone 6	High heating needs, High temperature differential (about 80℉ for heating)	2 x 4 wood structure, studs on 16” centers, dry-blown cellulose in stud cavities, ½” OSB sheathing, wrap, and exterior 2½” rigid rockwool.
Zone 7	Very high heating needs, Very high temp. differential (about 90℉ for heating)	2 x 4 wood structure, studs on 16” centers, dry-blown cellulose in stud cavities, ½” OSB sheathing, wrap, and exterior 2½” rigid rockwool.

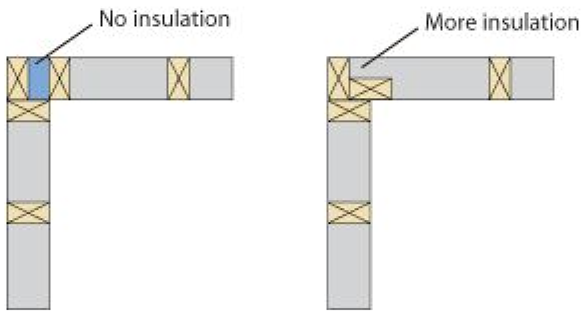
Note that the recommendation of exterior insulation is to meet minimum requirements of the International Residential Code (2015), and this is primarily for effective long-term management of moisture in wall systems rather than for energy use and loss. It is interesting that moisture management in some climate zones drives insulation requirements beyond what would be optimal from an economic and environmental cost-benefit basis for energy use and loss.

SORTA homeowners are working to reduce operational energy needs just to the limits of restrictions on solar PV, and we recommend addressing the weakest links in wall systems, but not the walls themselves, as we will explain in this chapter and the next. SNAIL homeowners may also wish to reduce operational energy needs, and we again recommend a priority of addressing the weak links of windows, doors, and utility incursions; more on that later. There are too many possibilities, in an evolving and dynamic industry to make specific recommendations, but these principles can be applied with the counsel of an architect, builder, and energy modeler.

To gain as much value as possible from the insulation cavity, we recommend minimizing incursions of utilities in exterior walls. This starts at the design stage with careful thought given to where plumbing fixtures are located, preferably adjacent to interior walls where piping can run without compromising the insulation envelope. Even where plumbing fixtures need to be placed against an exterior wall, as is often the case with a kitchen sink, the supply and drain pipes can be routed through conditioned floor and cabinet spaces rather than stubbed out from exterior walls. Design work should include locating light switches on interior walls, where practical, and we advocate for surface-mount electrical boxes where placement is necessary on exterior walls, either by owner preference or by code (see Figure 5.x below). Surface-mount wall outlets can be integrated with the baseboard to minimize intrusion into room space (see Figure 5.x below). While there are surface-mount electrical boxes and fittings on the market, we would like to see more attractive and integrated options; outlets and switches integrated with trim as factory-finished products. Electrical wiring may need to route through exterior walls in order to meet code requirements. Those lines do not compromise the insulation cavities in a significant way, but if batt insulation is used in the cavities, it is very difficult to notch perfectly around cables, and that typically results in gaps and compromise. This is one reason we advocate cellulose over batt-type wall insulation.

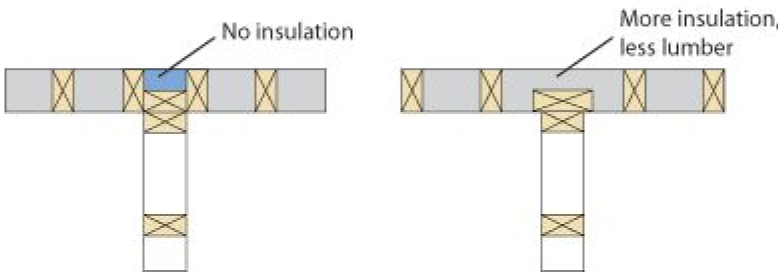
At both the design and construction phases, it is worth paying special attention to insulation and thermal bridging at the connecting points between building envelope elements. Where walls join and where walls meet ceiling and roof structures are areas often neglected from an insulation and heat loss perspective. The wall-roof connection needs to be considered first in the design stage, with sufficient space to retain the R-value of the wall through the corner and into the roof/ceiling insulation plane. Too many designs either pinch the corners, allowing less depth for insulation to match the R-value of the walls, or the design makes it a challenge for installers to reach and effectively fit the requisite insulation. The insulation challenge where walls intersect is more of a concern for the builder than designer. Figures 5.x and 5.x below show typical installations on the left, where a section of the wall is left without insulation, whereas the image on the right side demonstrates an alternative framing design that avoids insulation gaps and provides more space for stud cavity insulation.

Figure 5.x - Insulation challenges and solutions at corner sections of wood-framed walls



Source: Nuwool.com (2017)

Figure 5.x - Insulation challenges and solutions at T-sections of wood-framed walls



Source: Nuwool.com (2017)

A chain is only as strong as its weakest link is one of this chapter's opening quotes because it is a helpful metaphor to think about the whole building envelope. Weak links in the thermal envelope can appear in unintended ways such as from air infiltration or thermal bridging, as noted above, but they also come from intended design elements, such as windows and doors which can have insulating values significantly lower than the walls they are mounted in. The insulating value of windows and doors is represented as a U-factor, or U-value, and commonly ranges between 0.07 and 1.20. U-factor is the inverse of R-value, meaning that dividing U-factor into 1.0 provides an equivalent R-value to compare against other insulation profiles. Using this formula, some of the best windows on the market have an equivalent R-value of about 14, and some of the worst examples have an R-value below ONE! Lower U-factor (higher R-value) windows and doors are clearly preferable; however, they sell at a very high price premium, which requires a long-term cost-benefit analysis.

The best performing windows have triple-pane glazing, fiberglass framing, and casement style, whereas typical standard windows today are often double-pane glazing, vinyl framing, and double-hung style; there are also many other variations. One of the most reliable studies on window performance was conducted by the Department of Energy's Pacific Northwest National Laboratory (PNNL), which looked at the specific difference between double and triple-pane glazing. While the PNNL study showed a whole-house energy savings of 12.2% from triple-pane versus double-pane glass, the price premium for the better insulated windows provided very long payback periods of between 23 and 55 years (DWM Magazine, 2013). The Family Handyman estimates payback in "a few decades" (see sidebar). Furthermore, if cost of funds and energy inflation are added to the analysis, which again is more realistic, triple-pane windows likely never return a financial payback. Still, SNAIL homeowners wanting to make the most sustainable choices for overall ecological impact may wish to upgrade on the weak links of windows and doors. However, rather than jumping to triple pane glazing, we recommend starting with type (casement over double-hung), then to frame material (wood over vinyl), and then inspect meticulously for proper installation and air-gap sealing. The best window installed poorly will perform worse than the worst window installed well. Since SNAIL homes cannot generate onsite renewable energy, and if they receive energy directly or indirectly from fossil fuels, then the sustainability goal is to reduce operational energy demand in the home, and this needs to begin with the weakest links. Even for SNAIL homes, we do not recommend bulking up wall systems with structure and insulation beyond code minimum because the performance benefits are slight, yet the ecological impact from materials use is significant; we explain this over the next two chapters. Furthermore, when premium walls are coupled with windows, which are always weaker in resisting heat flow, the heat loss breach through weak-link windows overwhelms the benefit of increasingly robust wall systems, further jeopardizing the benefits and investment of a premium structural envelope. The weaker the weakest link, the weaker the chain, and the less value derived from the strongest elements. This leads to a principle of matching and integrating various elements of the thermal envelope, a topic explored in the next chapter.

> ### Are Triple-Glazed Windows Worth the Extra Cost?
>
> In cold regions, such as New England, triple-glazed windows can save 2 to 3 percent of your heating bill, compared with double-glazed windows. From a cost standpoint, it'll take a few decades to recoup the 10 to 15 percent upcharge to go from low-e double-glazed windows to triple-glazed. For example, if you pay $1,000 per year in energy bills, have 20 windows in your house, and 22 percent of your energy is lost through your windows (which is average), then each window is losing $11 worth of energy per year. A triple-glazed window will reduce that loss by about $1, so it'll take 35 years to cover a $35 upcharge for triple-glazing. Of course, if your energy bills and energy loss are greater, you'll recoup the cost sooner.
>
> However, the investment may be worth the cost in terms of comfort. Triple glazing will reduce condensation, which will allow you to maintain a higher indoor relative humidity in cold weather. These windows also reduce cold drafts. If you don't want to pay for triple-pane windows throughout the house, get them for the north- and east-facing rooms, where you'll get the biggest payoff.
>
> Source: The Family Handyman (2017)

Fortunately, there is helpful independent data available when researching and selecting windows and doors. The National Fenestration Rating Council (NFRC) provides independent energy ratings as a consumer service. Manufacturers display performance ratings in product specifications and on a window label (see below). Air leakage would be the worst compromise for a window or door, but there is little variance in that metric across brands and models. U-Factor, then, becomes the most salient performance and comparative data point. Solar Heat Gain Coefficient and Visible Transmittance will be addressed in the chapter on energy. NFRC also does this testing on doors; see www.nfrc.org for more information. However, the same principles outlined above for windows apply to exterior doors.

Energy Performance Ratings of Windows

The National Fenestration Rating Council (NFRC) is an objective third-party reviewer that tests windows and doors and provides performance data that manufacturers use in their data specifications; several performance metrics are printed on labels affixed to windows of participating manufacturers. In addition to metrics typically provided on window labels (see example at right), NFRC also has a condensation rating that is optional for manufacturers to include; it may not be on the label. The higher the number, the better a product resists condensation.	
U-Factor: Measures how well a product can keep heat from escaping from the inside of a room. The lower the number, the better a product is at keeping heat in. Range: 0.20-1.20 Look for: Low numbers	**Solar Heat Gain Coefficient:** Measures how well a product can resist unwanted heat gain, which is especially important during summer cooling season. The lower the number, the less you'll spend on cooling. Range: 0-1 Look for: Low, unless for passive solar design
Visible Transmittance: Measures how effectively the window lets daylight into the room, potentially saving on artificial lighting. Higher numbers let in more natural light. Range: 0-1 Look for: High numbers	**Air Leakage:** Measures how much air will enter a room through a product. The lower the number, the fewer drafts you'll experience. Range: 0.1-0.3 Look for: Low numbers

Source: www.nfrc.org (2017)

As with wall insulation, the U-factor rating on windows refers only to the glass; it does not include heat loss performance of window frames or assemblies, nor does it provide qualification about air seals and infiltration from installation quality. Just as full-wall R-values are lower than the R-value performance of just the insulation in the wall, whole-window R-values are effectively lower than just the glass component rated in U-factor, and unfortunately whole-window R-value ratings are not available. Fixed windows are both less expensive, and they perform better on heat loss than operable windows. In rooms that have more than one window, consider making only one operable for egress and ventilation, and the rest can be fixed glass.

One question often asked about a robust building envelope is whether it can be built too tight. Before the days of advanced building science, precision tools, and durable sealants, it was impossible to build a house too tight. However, as methods and materials improved, tighter building envelopes reduced heat loss and energy use, but they also trapped more moisture and stale air, both of which may be unhealthy for inhabitants. Opening windows is a low-tech solution to this problem, but it's not recommended when outdoor temperatures or humidity could cause more harm, or more energy to run HVAC equipment. In those conditions, mechanical ventilation is recommended to exhaust stale air and replace it with fresh outdoor air, though through a mechanism to scrub humidity and temperature differences. The most common solutions today are the energy recovery ventilator (ERV) or the heat recovery ventilator (HRV); both of these are effective in exchanging air, and they offer about 90% efficiency in heat loss, but they also require energy to operate, and the outdoor air they bring in often requires more energy in HVAC operations. These trade-offs are discussed more in the energy chapter. Any house built with integrity, and detailed attention to air infiltration, should plan for mechanical ventilation. Even a standard code-minimum house can be just as tight as a home with a premium building envelope, and any tight house will suffer unhealthy levels of CO_2, among other risks. Most code-minimum homes in the U.S. today would benefit from an ERV, but they are not required by code and are still quite rare. Our research showed that new and recently-built homes in the U.S. have an undiagnosed CO_2 problem if there is no mechanical ventilation; we'll address this concern over the next two chapters. Most custom homes built with a robust envelope do include mechanical ventilation; however, the operational energy needed to power this equipment works against the objective of minimizing operational energy use and loss from a premium envelope.

Another factor to consider in building envelope upgrades is the opportunity costs; that is, what could be done with the same funds if not for the upgrades. Bolstering structural elements of the thermal envelope and upgrading windows and doors can quickly add tens of thousands of dollars to construction costs, and even into six figures; that is well more than would fund a solar PV system that could provide 100% of the home's energy needs. For an average size American home, the cost of a premium envelope, with premium windows and doors, could purchase two new (long range) electric vehicles plus a solar PV system large enough to power the home and transportation. Shifting housing and transportation to clean renewable energy would cut the average American's greenhouse gas emissions by at least 50%. If the homeowner laments the social and global injustices of climate change, a premium envelope forgone would fund enormous and perpetual relief to keep many from starving, or help thousands of poor people adapt to changing climate conditions. The possibilities for opportunity costs are endless, with just a few mentioned here. Stepping back from the homeowner's tree (their home) to view the forest of global implication and consequence can help keep these choices in perspective.

One final note before our case study to briefly address durability and longevity of the structure. Our data and analysis favors a lighter building footprint, especially when onsite renewable energy generation is available, as in a SOAR home. However, too many houses built to code minimum standards are also built with poor craftsmanship. The industry, as it works in practice, generally incentivizes short-term outcomes for the initial sale and warranty period, but it does not incentivize long-term durability and structural longevity. We strongly recommend that homeowners employ an independent, third party inspector to maintain quality control. This could be an architect or a trusted and independent builder. Our research found that homes built to U.S. code minimum standards can last indefinitely with careful use and effective maintenance, but that requires initial integrity and quality in every aspect of the construction process.

Case Study:

All three of us researching this project had a common goal at the outset to make the best decisions for overall sustainability in designing and building a new *American-style* home, though modest in size and appointment. The homeowner studies and teaches environmental and energy economics, and from the beginning planned for overall carbon-neutrality (or better) through onsite renewable energy generation by solar PV. The architect's specialty is building science and sustainable design, and the builder is known for environmental stewardship and constructing earth-friendly homes. Each of us had been following trends and recommendations in the building industry for years and, on that basis, designed a highly robust building envelope for the case study home: thick ICF walls, 12-14 inches of open cell spray foam insulation in the ceilings, 2-inch rigid foam under the slab, fiberglass-frame triple-pane casement windows, and some of the best insulated exterior doors on the market. The house was built to premium thermal envelope specifications, combining thick and well-insulated structural elements with some of the highest performing windows and doors available. Expecting the building envelope to be super-tight, the design included for an ERV to mechanically ventilate the home.

Unsurprisingly, the pre-loan appraisal was 28% below construction estimate and final cost, confirming our general assessments about how *sustainable homes* are valued in appraisal and finance markets. This also confirmed our judgement that prototypical *energy-efficient homes* seemed to be accessible only to wealthy homeowners, requiring them to infuse personal funds well in excess of the typical 20% downpayment to avoid private mortgage insurance (PMI). In this case, the homeowner would need to contribute 28% of the constructed cost *in addition to* 20% of the assessed/financed value, with the balance financed by a mortgage; very few Americans have sufficient resources for this level of investment. Still, in the interest of building sustainably the best we knew how, we marched on with an enthusiastic commitment to crack the code on this dilemma with a combination of critique on appraisal and financing practices and fresh calculations of full-cost pricing and long-term cost-benefit analysis. We would use this project (the case house) as an opportunity to review and analyze each decision in part, and the project comprehensively.

As we analyzed the economic and environmental implications and tradeoffs of specific choices and elements in the case study home, our findings began to crack our original assumptions that had distilled from our close and long-term following of the green building movement, which advocates more robust thermal envelope systems. When we expanded our analysis more generally beyond the case home, we found that very few envelope upgrades return good financial benefits, even when adding the implicit cost of environmental externalities. Ironically, it was our encouraging analysis of solar PV and its integration into a whole-systems and whole-life perspective that changed our assumptions. Indeed, it created a paradigm shift that led us to create a new three part classification scheme based on availability of solar PV. We could no longer endorse the conventional wisdom of thicker and more-insulated walls for both economic and environmental reasons. This is even the case for SNAIL homes that do not have availability for solar PV, and where upgrades should be made first to the weakest links of windows, doors, and utility penetrations (see next chapter). Further, even these limited upgrades are not likely to return financial benefits, even over decades, and appraisal/finance/market systems are likely to result in sunk cost asset losses for the homeowner. Further, as the electric grid continues to replace fossil fuel energy with renewables, any heavy investment in the thermal envelope will be stranded as assets, and unfortunate in materials impact.

The case house is located where solar PV is limited. There is a hard cap for residential solar at 20 KW, and the utility also employs a *soft cap* that adds a standby fee for systems between 10 and 20 KW; the extra charge degrades economic viability. This soft limit might classify a home in this utility as SORTA for some families, but the homeowner of the case study project had a long history of energy use in several code-minimum homes that could be generated with a solar PV system well below the 10 KW threshold. The case study home should have been designed and built to SOAR standards, which would have dramatically reduced financial cost and the embodied energy of construction. Complemented with a 7-8 KW solar array mounted on the roof, that SOAR package would meet all operational energy demand of the home and, in addition, power electric vehicle transportation. Specifically, and in retrospect, we would have constructed the same lower floor slab system (with under-slab foam insulation), but with insulated concrete form (ICF) walls just in below-grade applications. Above grade structure would have been 2x4 wood stud walls with continuous rigid rockwool exterior insulation[8] and dry-blown cellulose in stud cavities. Ceiling insulation would have been chosen to achieve the code minimum of R38 and the specific material selected by application area. Windows and doors would have been selected on criteria of durability and value (cost against energy performance), and this would have led to much less costly choices. Windows would have been double-pane instead of triple-pane, and frames likely wood or vinyl instead of fiberglass. We

[8] Rigid board rockwool exterior insulation at ½” to 1” thickness, depending on cost and availability.

would still select casement style windows, for both insulating value (U-Factor) and appearance, and have many of them fixed glass to limit weak links from those elements.

Without our classification scheme, and analysis on economic and environmental impacts of building envelope upgrades in combination with onsite renewable energy generation, the case home was designed and built for what we later termed, SNAIL conditions. It was only in the course of construction, and case analysis, that our findings uncovered the need for a new classification scheme, which then identified the mismatch of the case home to its conditions. We now believe that it is not the most sustainable home we could have built, and we disclose this transparently with significant lament. Rather, a SOAR home would have been energy net neutral (or positive) in operations, complemented with a 7-8 KW solar PV system, but with less embodied energy in construction. Furthermore, if the home had been built to SOAR recommendations, the cost savings (opportunity costs) of a lighter thermal envelope could have purchased a new long-range electric vehicle and still leave a six-figure balance to meet other needs or sustainability goals. With a broad look at the whole global picture (the forest), removing an additional 25% of the family carbon footprint by powering all transportation with onsite renewable energy (in addition to 25% eliminated from housing demand) would have been a much better sustainability choice than constructing a heavy building envelope. There is no doubt that the case home will be comfortable to inhabit for many years; the premium thermal envelope is not as drafty as homes with weaker windows and doors. From our previous knowledge, we understood that these comfort qualities were gratuitous byproducts of building sustainably, but in retrospect, we would have gladly sacrificed a small degree of personal comfort for a lighter impact on the World's poor and the Earth's natural resources.

Summary and Conclusions:

The big story of this chapter and topic is an upending of conventional wisdom on how to sustainably address the thermal building envelope. A new paradigm emerges from an integrated and whole-systems view of the impacts of building and operating residential homes, with a significant new variable of falling prices on solar PV across critical economic thresholds. Recall that it is now less costly in most regions of the U.S. to install onsite solar PV than not to install it. If a household can meet its annual energy demand by generating clean renewable energy onsite, the thermal envelope diminishes in importance from a heat loss and operational energy use concern, and increases in importance from a resource use and embodied energy perspective. That is because the ratio of embodied energy to operational energy is magnitudes better for solar PV--with both initial impact and/or increasing size--than for almost all systems and material upgrades of the thermal building envelope.

Process systems, such as a blower-door test before insulation to identify and seal gaps, will repay the investment quickly and many times over during the life of the building, but most material and systems upgrades to the envelope (beyond building code requirements) offer very poor financial and environmental returns, and many do more damage than good. For all homes, a premium building envelope actually worsens overall ecological impact, and upgrades become more about personal comfort than sustainability. SNAIL homes, however, do not have the good fortune to be able to install clean and renewable onsite energy generation; SNAIL homeowners who want to make the most sustainable choices within their unfortunate constraints may employ limited weakest-link upgrades to reduce heat loss and operational energy, knowing that most have poor financial return and increased impact in embodied energy. In the end, a SNAIL house is not sustainable unless or until grid-tied energy transitions to clean renewables. SORTA homeowners will plan for solar PV sized up to imposed limits, and then add thermal envelope upgrades to bring household energy demand down to that limit. The largest impact on heat loss will come from addressing the weakest links, first by sealing air leaks, for which we recommend a blower door test during construction, and then upgrading windows and doors to reduce the mismatch of elements (see next chapter). SNAIL and SORTA homeowners are advised that appraisals and financing will likely not value thermal envelope upgrades at installed cost, and market values may not approach prices that allow homeowners to recover their cost at resale.

Residential building codes in the U.S. already require insulation factors well in excess of thresholds that tip cost-benefit value; adding more insulation therefore provides minimal and diminishing benefit for increasing cost (both financial and environmental). Rather than adding more insulation, we recommend efforts to maintain the integrity of the insulation spaces throughout the thermal envelope. Particular egregious examples of encroachments and compromise of insulation cavities is plumbing pipes and electrical boxes and housings; we see market potential for attractive and practical surface-mount fittings where utilities are code-required on/in exterior walls. A design to meet code requirements on wall insulation in climate zones 4-7 should include a continuous exterior application to break the thermal bridging of structural members, such as wood studs and wall top and bottom plates. Adding R-value on the exterior surface of walls then allows a thinner wall structural assembly; 2x4 wood stud walls provide sufficient structural integrity, durability and longevity if the construction quality is strong, and we recommend a third-party quality control process to ensure integrity. A relatively thinner (2x4) wall has the lowest impact on the environment from a resource and embodied energy measure and, if built with quality and maintained adequately, it will likely have similar longevity to relatively thicker wall systems. If air infiltration is minimized via blower test sealing, and if insulation cavities are protected from utility incursions, the code-minimum wall will reduce heat loss at or beyond cost-benefit ideals.

Even a relatively thin (2x4) wall can be part of an overall thermal envelope constructed tight enough to warrant mechanical ventilation, though many other factors will determine the need, including quality of windows and doors, and practices and sensitivities of occupants. There is a large step in cost and commitment to opt for mechanical ventilation, which is discussed in greater detail in the energy chapter, but it includes initial costs for equipment and installation, and ongoing costs of operation. The energy use of operating an ERV or HRV should be weighed against predicted energy saved by upgrading the thermal envelope, but if indoor air quality is unhealthy, then mechanical ventilation is required regardless of energy and cost. Look for deeper analysis of this in the energy chapter.

Homeowners selecting building envelope upgrades in the name of sustainability might conduct careful analysis on the opportunity cost of those choices. Upgrading the thermal envelope can quickly build to tens of thousands of dollars in upfront cost, and most have higher environmental cost from embodied energy while returning minimal and diminishing benefits. What is the next best alternative for those funds? How could they be used to become more sustainable in other areas of life, or to meet acute human needs, or help the poor adapt to a changing climate? Economists like to remind consumers that every choice has opportunity costs, but it is too often an elusive concept that escapes rational consideration. In the case of sustainability, a step back to look at the forest instead of each tree can be instructive.

Our research and analysis strongly suggests building a SOAR home for both economic and ecological reasons; this starts by selecting a site, design, and building orientation for efficient solar capture. With active PV sized to meet the entire annual household energy needs, a basic wall structure is adequate, though we strongly advocate measures to ensure quality build and craftsmanship. A 2x4 wood stud wall with ½-inch sheathing provides sufficient structural integrity and longevity. Taped building wrap applied to the sheathing is an effective application to reduce air infiltration, and adding continuous rigid insulation (climate zones 4-7) on top of the wrap breaks the thermal bridging of structural members and contributes to code-minimum iinsulation levels. Our team has a preference for rockwool rigid board for continuous insulation, for reasons outlined in this chapter, but there are other good options on the market. With an inch (or more) of rigid exterior insulation, we prefer dry-blown cellulose to fill stud cavities; cellulose is relatively inexpensive, is made from recycled materials, and is an effective insulator when installed properly. Once again, we strongly recommend keeping utilities out of exterior walls. Building code insulation requirements in ceiling spaces is more than sufficient, though it may be advisable to add slightly more if it can break any thermal bridging. For lower ground floor slabs, we recommend at least 2-inches of foam under the concrete.

SORTA and SNAIL homeowners may need to begin upgrades from that base, and we would suggest starting with the weakest links, which are most likely windows and doors. Upgrading the weakest links will offer the best cost-benefit tradeoffs for those specific elements, relative to addressing walls or roof systems, and it will improve the benefit of structural elements if more of their benefit in reducing heat loss is not otherwise lost to relatively weaker links. SORTA homeowners should add upgrades to the base structure only to the point of reducing heat loss to fall within limited energy production levels. Ideally, SNAIL homes would be avoided but, if necessary, the weakest links of the thermal envelope should be given priority for upgrades.

Dos and Don’ts:

Dos related to the building envelope

1. Prioritize clean and renewable energy generation; select a building lot where solar PV is available, and then design and orient the home for solar energy capture.

2. Ensure build quality of the structure, air gap sealing, and insulating process by hiring an independent quality control agent to visit the site at critical points.
3. We recommend code-minimum structure, which in most regions is 2x4 wood stud walls. This wall depth is adequate if willing to surface-mount electrical boxes, otherwise 2x6 stud walls should be selected to minimize weak links/spots in the thermal envelope
4. Consider the opportunity costs for every upgrade considered and selected for the thermal envelope
5. When selecting windows and doors, consult chapters 5 and 6 for trade-offs and mismatched elements discussion
6. Select windows specific to their orientation for optimal insulating and solar heat gain properties

Don’ts related to the building envelope

1. Don’t build a new house with SNAIL conditions if there are SOAR or SORTA options.
2. Don’t build a new house with SORTA conditions if there are SOAR options
3. Don’t consider solar PV as an afterthought; build it into the design and plan
4. Don’t equate sustainable housing with thick walls and expensive construction
5. Don’t assume more insulation is always better, or the better choice overall
6. Do not assume thermal envelope upgrades beyond code minimum return on the investment or are better for the environment; most do/are not.
7. Do not fail to understand thermal envelope compromises from windows and doors, or the impact of mismatched elements
8. Do not select windows that have not been matched to their directional orientation
9. Don’t place compromising utilities in exterior (thermal envelope) walls or ceilings
10. Don’t expect appraisals to meet construction cost of building envelope upgrades

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