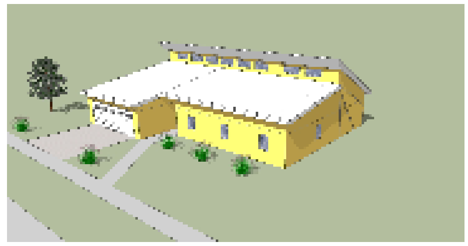
Equinox House Project

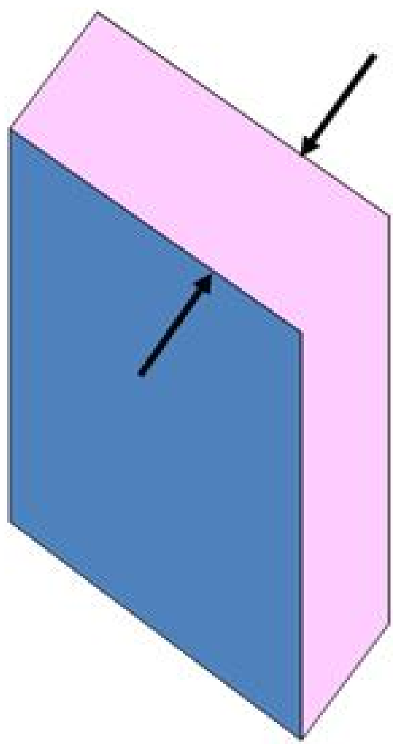
Topic 3 Walls and Roofs

Ty Newell – February 11, 2010



Walls and roofs. How thick should they be? What materials should be used? How do you determine the most economical wall thickness? And can anyone think of a more boring topic to write about? The answer to the last question is a definite “yes”, as I will demonstrate in future topics.

It would seem that after a few millennia of building shelter we would understand this, but the arguments go on….and they will continue because we cannot agree on the ground rules for determination of “optimal” insulation. For example, what is the economic “lifetime” that should be used for such a calculation? Should it be the length of the mortgage (~20 to 30 years), the expected lifetime of the house (100 years), or the time you expect to live in the house (5 years)? My view is the expected lifetime of the house is most appropriate. While this may cost me a bit more now, over the lifetime of the house it will result in the lowest cost for all involved. Assuming the lifetime is about 100 years, this decision is spread over 4 or so generations (ie, you are making a decision bigger than yourself that impacts your children, grandchildren, great grandchildren and beyond). We will explore the effect of the economic lifetime. The basic problem we want to address is illustrated below.



- Thin wall/roof insulation requires more energy to keep a house comfortable, resulting in greater energy cost
- Thicker wall/roof insulation results in higher building cost

We are in the midst of a revolution in the development of new materials that allow us to construct buildings that can be very energy efficient, structurally sound, safe, and long lasting domiciles. A myriad of insulation choices abound including fibrous materials (eg, cellulose, fiberglass, rock wool, straw), foams (eg, urethane, Styrofoam, "bio-foams"), and VIPs(vacuum insulation panels). Most insulation consists of a low thermal conductivity gas (air or other gas) that is stagnated in some manner to restrict its movement within a fibrous or cellular structure. When air is the gas in the insulation, such as in fiberglass or Styrofoam, the "R" value or thermal resistance value will be about 3 to 4 per inch thickness (don't worry about units …for R values, bigger is better). A low thermal conductivity gas is sometimes encapsulated in an insulation, as is common in urethane foams. The "R" value of such insulation with a low conductivity gas may be in the range of 7 to 8 per inch thickness.

VIPs are hi-tech materials usually available in a panelized form. Small particles, such as "fumed silica" (think of very tiny sand particles), are packed in the panel, and a vacuum drawn. Fumed silica particles are spherical, so as they are compressed together, they barely touch each other, which causes a high thermal resistance. Some materials are often added to reduce radiation energy transfer within the panel. Also, the panel packaging is quite sophisticated with various layers of plastic/metallic films that impede gas transfer into the package over time (think vacuum pack coffee bag technology). R values exceeding 30 per inch thickness can be achieved, but generally at high cost. Approximately 8 to 9 inches of fiberglass or Styrofoam would be needed to reach this R value. But, no one yet knows if they will last 100 years.

There are many discussions regarding the sustainability and environmental "friendliness" of various insulation materials. On the bio-base material side, eel grass used to be a popular fibrous insulation used in walls in the early part of the 1900s….until some unknown malady nearly wiped out eel grass in the early part of the 1900s. Straw is often discussed as a good, durable insulation, and it is. And, soy-based foams are now available. Celluose insulation(chewed up newspaper) is one of the most popular choices today, but who reads the newspaper anymore? Celluose's future may be limited.

In terms of non-bio-based insulations, fiberglass, Styrofoam, urethane and others are common choices. Urethane, which generally has a low conductivity gas encapsulated, is often the subject of debate because the encapsulated gas has a high global warming potential (GWP) index. Current research directed toward a low GWP gas for foams will be available in the not-too-distant future. Styrofoam, the insulation in Equinox House, is currently made from petrochemicals, however its historic roots are bio-materials. Styrene, one of the earliest polymers, was derived from tree resin. Perhaps in the future, it will be bio-based again. We will be planting a styrax Japonicus tree in the spring at Equinox to celebrate the styrene resin and Equinox's roots in the Usonian, Japanese inspired architecture of Frank Lloyd Wright….whose Usonian homes were one of the earliest examples of SIPs construction.

I prefer to use foam insulations because of the difficulty of managing moisture in our Midwestern climate. Foam insulations are semi-impermeable, impeding moisture transfer. With our hot humid summers, and cold dry winters, moisture can come from either inside or outside. With fibrous insulations, moisture will find a place in the wall or roof where it would like to condense, and from there all sorts of problems occur from structural degradation to mold/mildew/fungus problems. I like the structural quality of Styrofoam and that it has no apparent nutrient attractant characteristics to various creatures. Of course, if someone sneezes on it, some type of biological growth could ensue, as it could on any other material (ok, maybe not on a panel made of plutonium). Also, because it is an air-encapsulated foam, one does not need to worry about a special gas diffusing out of the insulation over time. The cost per "R" value is good for Styrofoam and the extra thickness required for an equivalent thermal resistance to that of a low conductivity gas foam such as urethane results in a stiffer structure. When I go before the great Creator, possibly my choice of insulation, coupled with a time when I chose paper instead of plastic (or vice versa) will be the last straw that sends me to hell.

We will discuss moisture transfer and moisture's effects on a home's energy performance in a later discussion. At this point if you would like to learn more on this important topic, let me point you to some of Bill Rose's publications (see: http://www.arch.uiuc.edu/people/faculty/wrose/). Bill is a colleague at the University of Illinois and is an internationally renowned leader in building moisture effects. A second source of information is Joe Lstiburek, a principal of the Building Science Corporation (http://www.joelstiburek.com/). Joe's firm has conducted extensive research and written an excellent series of books on building construction in various climates.

Determination of Wall/Roof Insulation Thickness

The basic goal is to determine the optimal cost of a wall or a roof based on insulation thickness. There is negligible difference between insulation for a wall and a roof, however the construction method may dictate that the insulation is thinner or thicker for a wall or roof. For example, a truss roof construction allows three feet of chopped fiber insulation to be blown in, while typical wall construction would not.

Several factors enter into this analysis. The location is very important. In the tropics, the answer may be zero insulation. The cost of the insulation is very important, and different insulation materials have different costs. As previously mentioned, the economic lifetime is important as well, and this is something many people will debate. Currently, most financial lending institutions and real estate appraisers (at least in central Illinois) do not value the thickness of insulation.

So here is an equation that boils things down for determination of optimal wall/roof insulation thickness:

Optimal Insulation Thickness =

square root (**home lifetime energy cost per insulation thickness** divided by **the cost per volume of the insulation**)

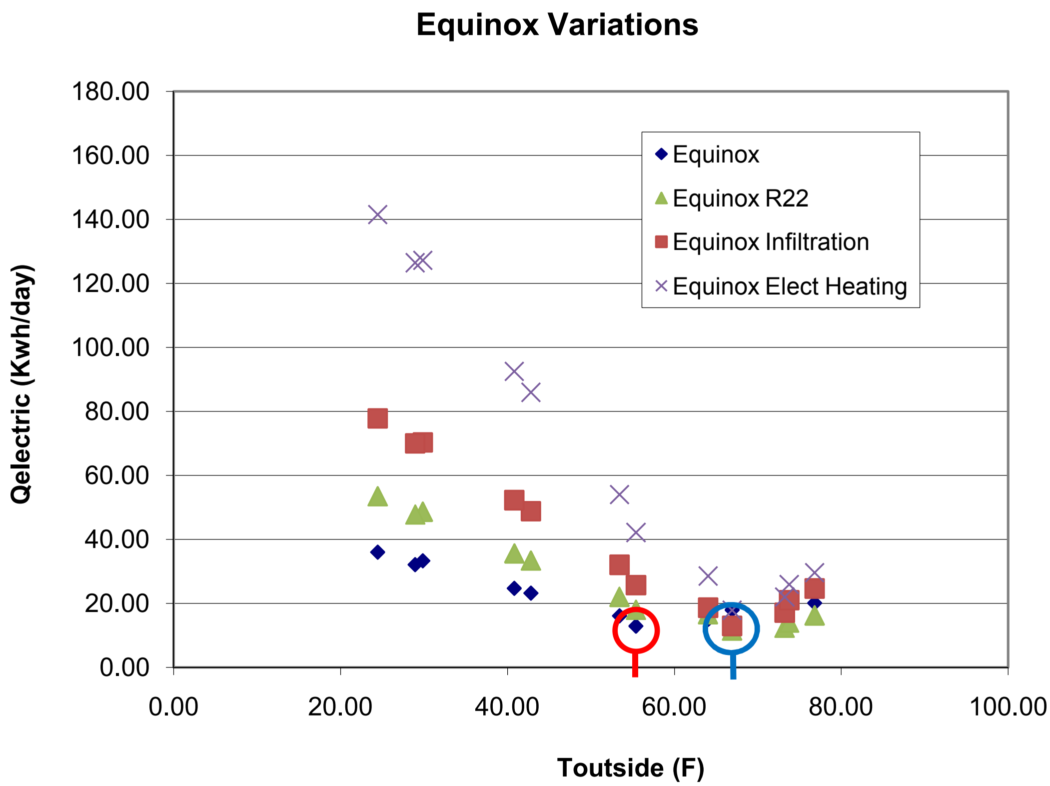
This equation is a deceptively simple result. I developed this relation for optimal design of refrigerator cabinets, and class lectures covering its derivation are deadly. If you think about it, there is a similarity between a refrigerator cabinet and a house. Keeping you at a comfortable temperature in your house is the same as keeping tofurky or roast beef at a proper storage temperature.

In order to use the above equation, we need to find the energy cost per insulation thickness, which is easy to do, and to determine the cost of insulation, which is also easy to do. We need some weather data, which we can get for free from the National Climatic Data Center (part of the Department of Commerce: http://lwf.ncdc.noaa.gov/oa/documentlibrary/clim81supp3/clim81.html).

At the end of this paper I have attached copies of the climatic weather maps showing "heating degree days" and "cooling degree days", which are measures of the time (days) and difference in temperature between the outside temperature and the temperature inside your house. For example, looking at the Heating Degree Day map, you will see that Chicago has about 6500DD. Assuming Chicago's winter season is roughly, mid-October to mid-April, or about 6 months (~180 days), and dividing this number of days into 6500DD, we find that the average temperature difference between the inside and outside of a conditioned building is approximately 36F. For the heating degree day calculation, an inside reference temperature of 65F is used. Assuming this reference temperature, subtracting the 36F gives us an average outside temperature of 29F for Chicago's winter period. Is this accurate? It doesn't matter. I arbitrarily used 180 days for the time base. If I had used 210 days (add an extra month), this results in an average outdoor temperature estimate of 34F. The reason it doesn't matter is that it is the combination of time *and* temperature built into the degree-day parameter, and separating it as above hopefully gives some semblance of its origin, but we don't need to separate it for our analysis

The 65F degree inside reference temperature is roughly the outside temperature at which one's house requires heating, but, as you build a superinsulated, supersealed house, the outdoor temperature at which you require heating (and cooling in the opposite direction) changes. Why? Because internal energy loads such as your metabolism, the refrigerator heat exhaust, energy powering your stereo and other powered devices are providing a contribution toward heating your home. Additionally, depending on the type and number of windows used, solar energy can be a significant source of heat that will skew when the outside temperature is cold enough to require heating. Reprinted below from the first discussion topic that provided an overview of Equinox is a plot that shows Equinox House energy needs versus the outside temperature. The red circle shows the Equinox House "balance point" where no conditioning energy for heating or cooling is required at an outdoor temperature of 55F. The blue circle shows a conventionally constructed house with less insulation, more air infiltration (red) and a less efficient heating/cooling system (purple)requires heating when the outdoor temperature drops below 65F.

The end result is that the optimal insulation value is somewhat of a moving target. As you increase insulation on a house, you now have an easier time conditioning your house. It can get colder outside without needing heat to stay comfortable. It can be cooled more easily in the swing seasons (spring and fall) by using more outdoor air for ventilation, and more insulation results in less active cooling in the summer. Ignoring the "moving target" nature of a house's balance point, and using the standard degree-day values given by the weather service without any corrections will result in a "conservative" determination of optimal insulation (yes, you can do this calculation without regard to your political philosophy). The conservative estimate for wall insulation thickness will not be overly optimistic (ie, cost you more than it should). In a later topic where we will put everything together (walls, roof, windows, people metabolism, refrigerators, water heating, etc) we will show this to be a good estimate.



Equinox House versus similar houses with less insulation, more air infiltration, and less efficient conditioning systems typical of current, conventional house construction practices.

Ok, so enough with that. Let's determine insulation thickness. The last things we need are the cost of insulation and cost of energy. For insulation cost, we will use $5 per cubic foot for the cost of "EPS" (expanded polystyrene) insulation. I obtained this cost from the Home Depot website. A 4' by 8' sheet of 2 inch thick EPS costs $25, or about $5 per cubic foot. Fiberglass is quite a bit less expensive at $0.4 per cubic foot. Urethane foam costs about $10 per cubic foot. For the 2007 University of Illinois Solar Decathlon house, we paid $12 per cubic foot for "spray foam" applied urethane foam (people in moonsuits spray the walls, roof, etc).

For the cost of energy, all we need to know is how much it costs for electricity from solar energy, and that is simple. Forget about the cost of natural gas or a utility's electric rates. If you've been following the Equinox House project, you know by now that we are focused on living on our daily solar allowance and that we are in a time where solar energy is affordable for all energy needs of a residence. This includes buildings in which solar may not be suitable, but would tap solar or wind derived energy from the grid. The solar energy system for Equinox House has an installed cost $35,000. In central Illinois weather, the system provides 10,000kW-hr per year of energy. The 30% tax credit reduces system cost to $25,000. The system lifetime is projected to be 20 years based on the solar collector warranty (yes, some parts such as inverters (converts the solar panel DC electricity to the household AC electricity) might need to be replaced at some interval, but let's not complicate things with escalation, discount factors, maintenance, etc…..yes, those things are important, but no one knows these factors with any accuracy). So, $25,000 divided by (10,000kW-hr per year times 20 years) gives us an electric energy cost of $0.125/kW-hr. Ok, let's say that inverter is replaced halfway through the panel life at a cost of $4000. This gives us an electric cost of $0.15/kW-hr. We can use this cost range to see the impact on insulation thickness.

The electricity we use to condition our house has an "efficiency" based on the type of house heating/cooling system we use. If an electric resistance heating system is used, the "efficiency" is 1.0, which is crappy (electric resistance heater manufacturers, such as the Amish fireplace folks, like to tout this as 100% efficiency....but thermodynamically this is the lowest efficiency level and we can do better). The energy efficiency factor (related to the "EER" and SEER" tag numbers you see on air conditioners and heat pumps) for a heat pump or air conditioner will average about 2 to 3 for most locations and applications. We will use an efficiency factor of 2.0. This means that for every unit of electricity used from our solar energy system, we get 2 units of heating or cooling energy from the home comfort conditioning unit. Equinox's CERV unit has an average value of 2.0 for heating and cooling.

So, here is the equation for optimal wall and roof insulation thickness in more formal terms:

Optimal Thickness = square root [(DDh + DDc) x Years x E$/(1715 x R x COP x I$)]

Where: DDh = annual heating degree days….see map at end of paper

DDc = annual cooling degree days….see map at end of paper

Years = house lifetime (100 years for me; 0 years for developer who doesn't give a crap)

E$ = Energy cost per kilowatt-hr (solar electricity ~$0.125 to $0.15 per kW-hr)

R = thermal resistance value per inch thickness (R=3.5 for Styrofoam)

COP = energy efficiency parameter (=1.0 for crappy system, 2.0 for good system)

I$ = insulation cost per volume ($5/ft^3 for EPS)

1715 = a number that mushes all the unit conversions together

As an example, let's choose central Illinois:

From the two degree-day maps below, we find DDh~5000 and DDC~1000 for heating and cooling seasons. Using the above values with these degree-day values, we find that the optimal Styrofoam thickness would be 1.12 to 1.22 feet (13.5 to 14.5 inches) with a total R-value of 46 to 50. The lower value is based on the lower solar electric price and the higher value is based on the higher solar electric price. Notice that we can play around with things a lot. If electricity is more expensive (or more inefficiently used), the insulation thickness will increase. If you live in a tropical paradise with zero heating and cooling degree days, the answer will be zero insulation thickness. The figure below shows a plot of the optimum thickness for a range of degree-days (total of heating and cooling) with conditions other conditions as used in this example.

If you use a lower lifetime (say 30 years), the thickness will decrease because this is only assuming a building's operational energy to be 30 years rather than its projected lifetime energy. If you're a developer, you want the lifetime as low as possible because once you sell the house, you'll never have anything to do with it. This is where energy policy and regulations are important, in order to apply standards that benefit society as a whole (in both cost and quality of life) that individual businesses will not use due to the need to be competitive with others.

How thick is the insulation in Equinox House? It is 1 foot (actually, the EPS SIPs are 12 5/8 inch thick, minus 7/8inch for the OSB panels, leaving an insulation thickness of 11 ¾ inches). In terms of the optimum thickness value, it is a pretty "shallow" optimum, and one should not get anal about the exact value. If you use insulation thicker than the optimum, you are weighting toward a level dominated by insulation cost, and if you use a somewhat thinner insulation, you are weighting toward an energy cost dominated region. But, more important things factor in once you calculate this value. Using standard insulation thicknesses and determining the cost to support and install the insulation are important. Fiberglass, for example, is very inexpensive which will result in a thicker insulation layer (the optimum calculation shows 3.8feet). For a truss type attic space, adding 3 feet or so of chopped fiber is reasonable, but building a wall 3 feet thick along with the support structure for holding fibrous insulation will dominate the cost.

If I haven't put you to sleep by this point, let me try one more thing that's sure to knock you out. The above simple analysis is all you need to figure out the cost of the insulation for your home, as well as the energy requirements of the wall and roof per year. For the EPS insulation example, let's say that we put 1 foot of insulation thickness in the walls and roof. Based on a cost of $5/cubic foot for EPS, this results in a cost of $5 per square foot of wall and roof using the EPS. A 2000sqft house like Equinox will have about 4000 square feet of wall and roof area (yes, depends on roof pitch, floor plan, one or two stories….adjust as needed), showing that the insulation will cost about $20,000. A conventional house with 3 feet of chopped fiber in the attic and a regular 2x4 stud construction with fiberglass batts would cost about $3500 for insulation. Is the difference worth it? In order to determine the energy cost, all we have to do is use the parameters we've already found, along with a chosen insulation thickness.

Lifetime Energy $ = [(DDh + DDc) x Years x E$/(1715 x R x COP x Insulation Thickness)] x Surface Area

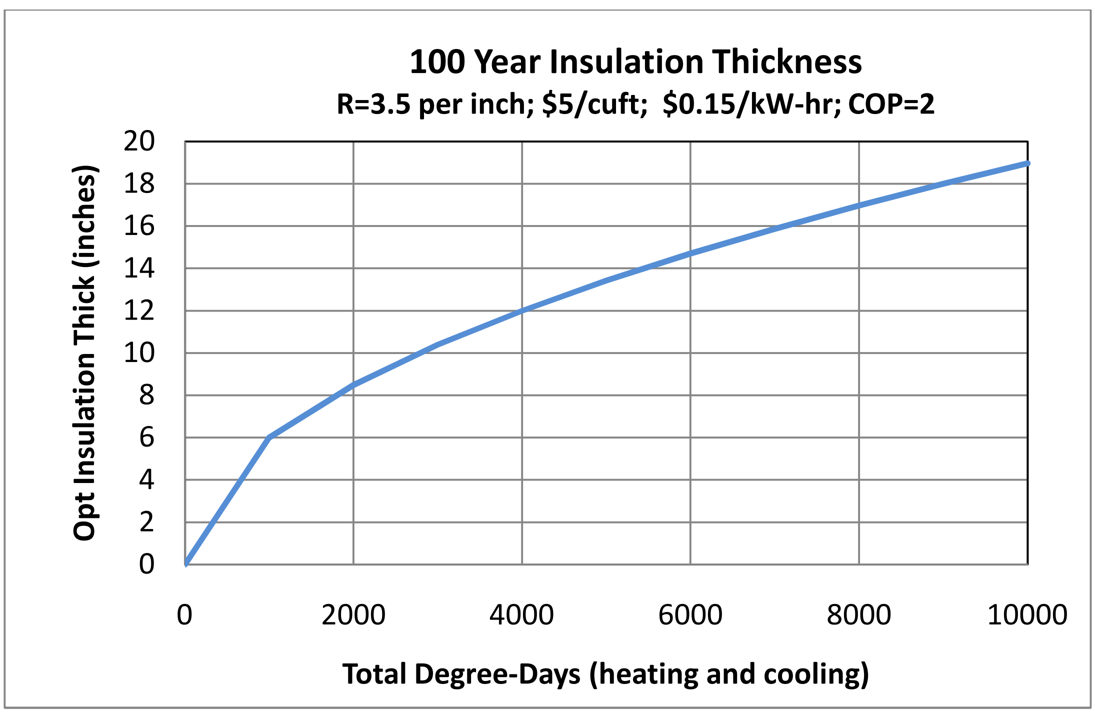
Where Insulation Thickness = either optimal thickness or any thickness in "feet"

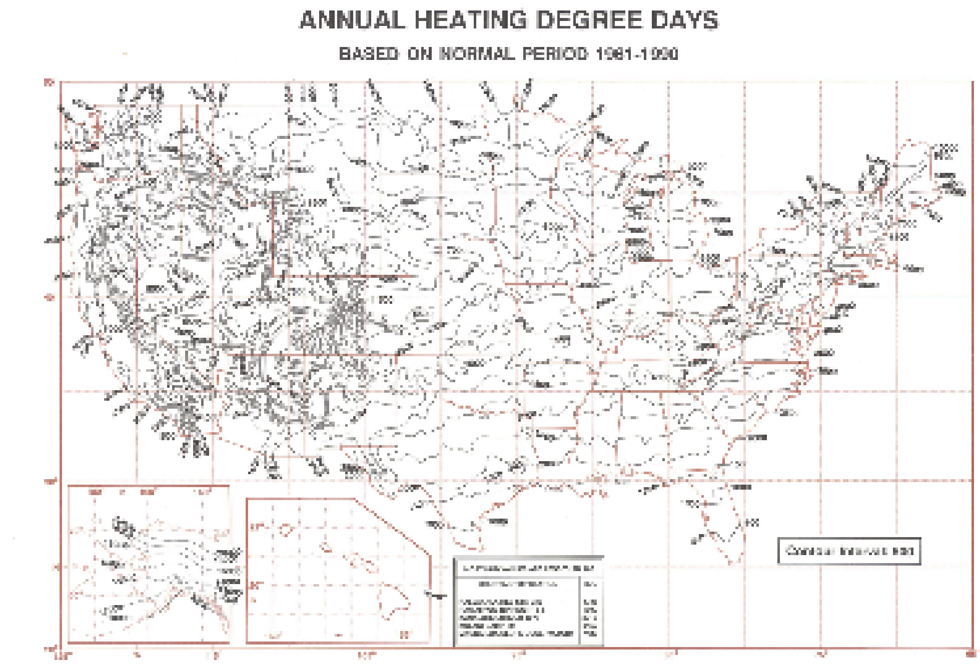
Surface Area = wall and/or roof surface area of interest in "square feet"

For Equinox, the lifetime energy cost for 4000 square feet of walls and roof will be $30,000 assuming one foot of insulation thickness along with the other parameters previously used. For a conventional house with 3 ½ inches of fiberglass in the walls (2000 square feet of wall) and 3 feet of chopped fiber in the ceiling (2000 square feet of ceiling), we find $55,000 of lifetime energy cost ($5000 for roof energy and $50,000 for wall energy). Overall, the optimal insulation example wins, with a total of $50,000 for insulation cost and energy cost over 100 years lifetime, compared to $58,500 for a house with fiberglass and conventional stud walls. But, the big hurdle is somehow incentivizing the movement of capital from being spread over the lifetime of the house for energy to the present such that $20,000 can be invested in insulation instead of $3500.

Let's say that between the "conventional" example above and the Equinox design, that the two came out the same, or that the lifetime economics favored the conventional. Are their other aspects that still favor (or disfavor) Equinox design? I think yes. First, more money spent on construction related materials requires more labor (both on site and in a manufacturing plant) rather than expended on energy. Notice that almost 95% of the conventional house cost of the walls and roof went to energy cost rather than fabrication of materials (insulation) as in Equinox. "Conventional "energy industries such as oil companies and coal companies employ very few people, and generally export a lot of the dollars outside your community. Reducing the house energy by investing more in insulation employs more people. In addition, the reduction in energy requirement coupled with solar energy creates a demand for jobs involved with building and installing solar panels. Is this a big deal? Yes. In 2009, the top revenue generating companies in the world were led by Shell, Exxon Mobil and you can guess the rest. Approximately 10 of these megacompanies had revenue of ~$400billion each, while only providing 0.2 jobs per million dollars of revenue. Manufacturing companies, such as the appliance industry, typically produce 2 to 4 jobs per million dollars of revenue. Shifting from an energy dominated economy to an efficiency and renewable energy dominated economy will result in 10 times or more jobs without added cost. And, we regain our freedom from a monopolistic fossil fuel industry.

Are you asleep yet?





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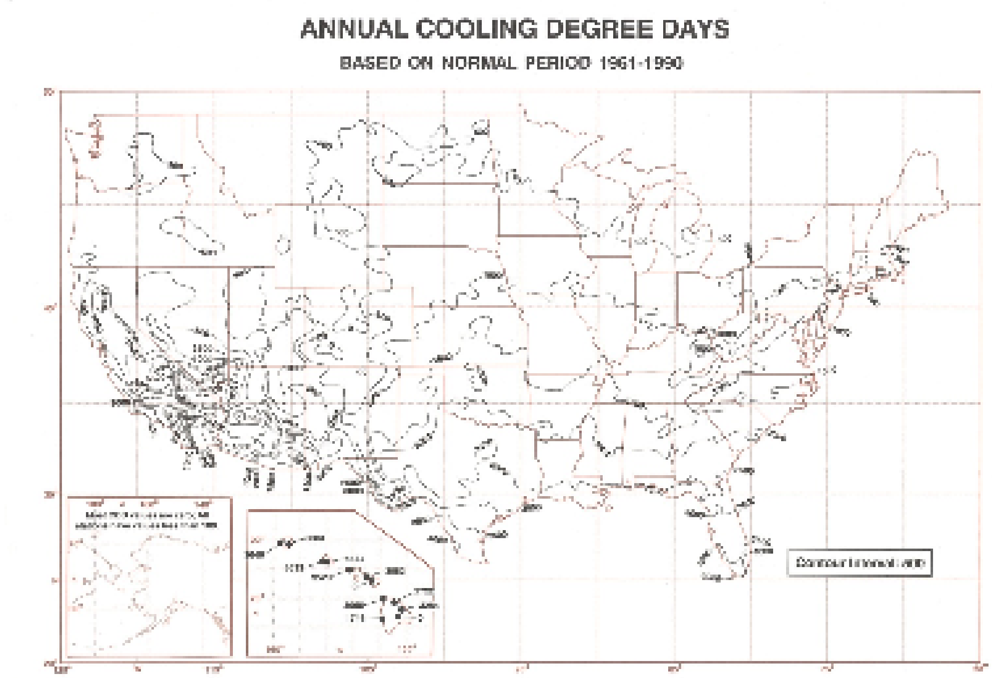

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