Energy Consumption in Housing

John C. Bean

Outline

Our homes consume over 1/5th of U.S. energy

- 90% of which involves producing and moving heat

How that heat is moved:

- CONDUCTION = Transfer of vibrational energy between atoms/molecules
- CONVECTION = Movement of hot atoms/molecules to cooler places
- RADIATION = Flow of energy via electromagnetic waves (e.g., as infrared heat)

Detailed analysis of how each of these mechanisms affect our homes

- And the often simple & cheap things we can do to decrease their impact

Long term energy-saving strategies, including passive solar and smart(er) homes

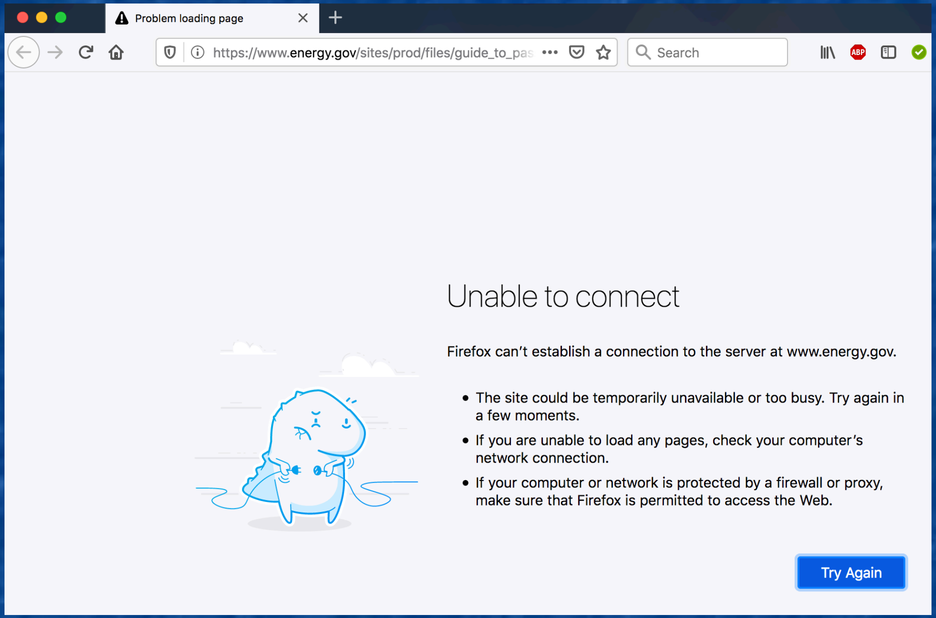
Versus big savings available NOW via things like "condensing furnaces" and "heat pumps"

(Written / Revised: February 2021)

A digression concerning many of the sources cited in this note set:

Early (pre 2017) versions of this note set drew heavily on **Department of Energy** data

But beginning in the Spring of 2017, the cited webpages began to disappear:



Unable to connect

Firefox can't establish a connection to the server at www.energy.gov.

- The site could be temporarily unavailable or too busy. Try again in a few moments.
- If you are unable to load any pages, check your computer's network connection.
- If your computer or network is protected by a firewall or proxy, make sure that Firefox is permitted to access the Web.

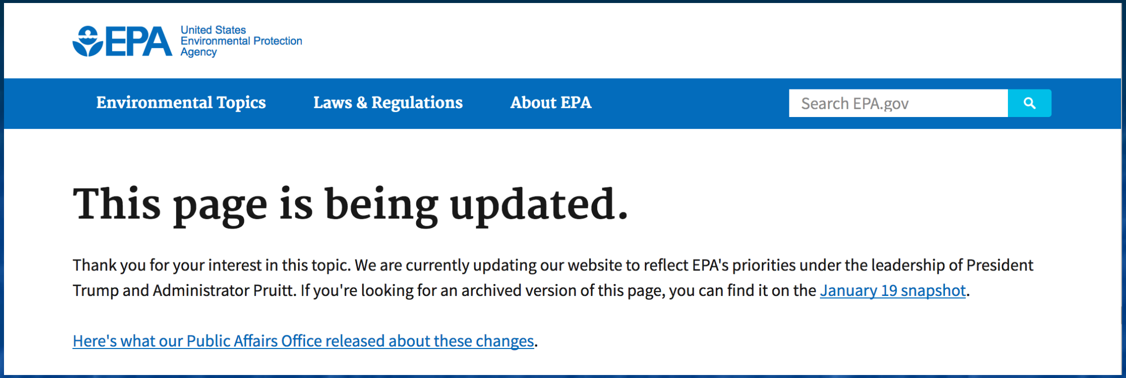
Searches using old webpage wording also turned up mostly broken links

As have searches repeated up to this day

Environmental Protection Agency webpages also began disappearing

But for those disappearances I found an unambiguous explanation:

Accessing the "Inventory of Greenhouse Gas Emissions" 29 April 2017, I instead got: [1]

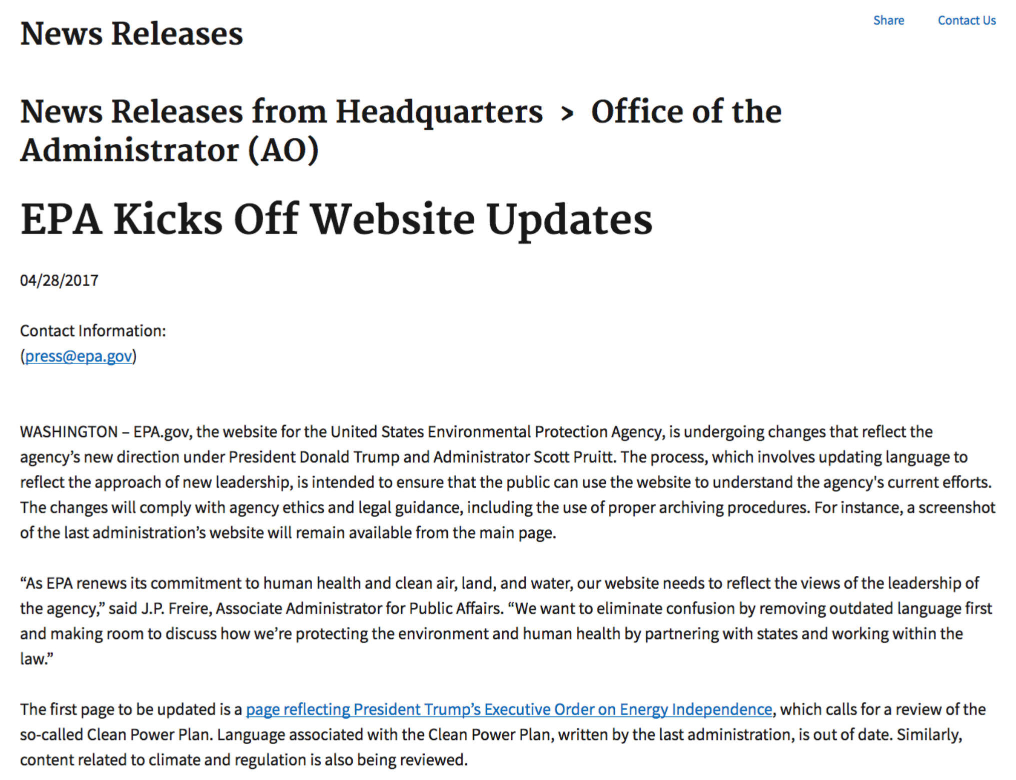


This page is being updated.

Thank you for your interest in this topic. We are currently updating our website to reflect EPA's priorities under the leadership of President Trump and Administrator Pruitt. If you're looking for an archived version of this page, you can find it on the January 19 snapshot.

Here's what our Public Affairs Office released about these changes.

The news release found at the preceding link:



News Releases

News Releases from Headquarters > Office of the Administrator (AO)

EPA Kicks Off Website Updates

04/28/2017

Contact Information:
(press@epa.gov)

WASHINGTON – EPA.gov, the website for the United States Environmental Protection Agency, is undergoing changes that reflect the agency's new direction under President Donald Trump and Administrator Scott Pruitt. The process, which involves updating language to reflect the approach of new leadership, is intended to ensure that the public can use the website to understand the agency's current efforts. The changes will comply with agency ethics and legal guidance, including the use of proper archiving procedures. For instance, a screenshot of the last administration's website will remain available from the main page.

"As EPA renews its commitment to human health and clean air, land, and water, our website needs to reflect the views of the leadership of the agency," said J.P. Freire, Associate Administrator for Public Affairs. "We want to eliminate confusion by removing outdated language first and making room to discuss how we're protecting the environment and human health by partnering with states and working within the law."

The first page to be updated is a page reflecting President Trump's Executive Order on Energy Independence, which calls for a review of the so-called Clean Power Plan. Language associated with the Clean Power Plan, written by the last administration, is out of date. Similarly, content related to climate and regulation is also being reviewed.

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1) http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf

Earlier, I'd not had to worry about disappearance of governmental data

If fact, my bigger concern was about the **persistence** of governmental webpages

which, once posted, were often left unaltered for years (or even decades)

Meaning that their information could often become obsolete and/or irrelevant

And that I didn't always bother caching those webpages (as I now do)

Thus, in this note set, a number of important cited sources can no longer be accessed

Mostly those from the U.S. DOE, its daughter labs such as NREL, and the EPA

But where I could not identify newer sources with comparably relevant data

I have retained my original summaries of those now lost pre-2017 sources,

as supported only by their footnoted original web links

(but followed, where I **could** find them, by links to cached copies)

ONWARD:

Energy Consumption in Housing

Every one of my (many) energy/environmental textbooks has a chapter on **autos**

Of course: they're one of the **biggest ways** we, as individuals, use energy!

But, strangely, only **one** textbook has a whole chapter devoted to housing

Despite it being the **other big way** that we, as individuals, use energy

To be fair, most of those textbooks DO have chapters on heating and cooling

Which DO turn out to be major contributors to household power use

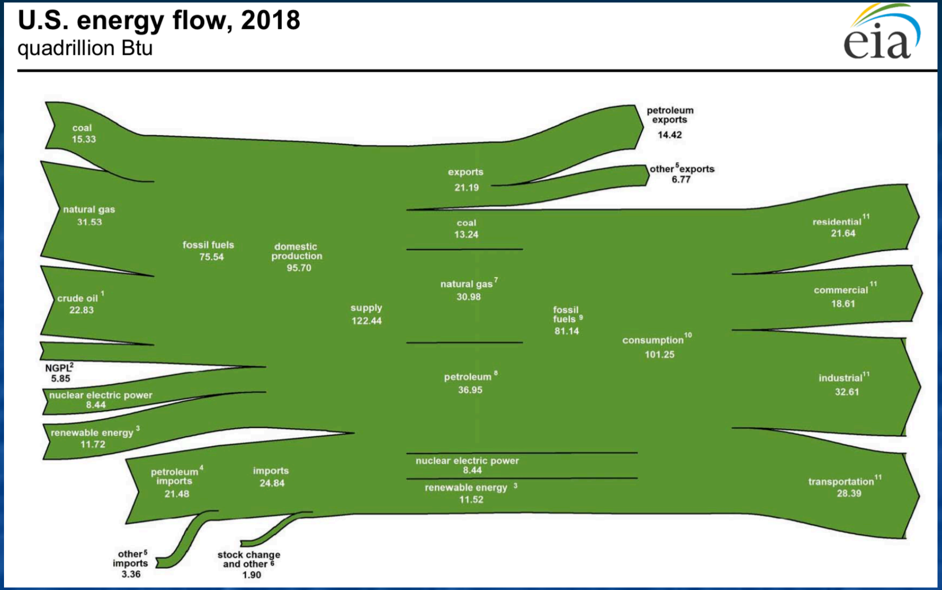
But heating & cooling power diminish **hugely** in a well built & well maintained home

So today I am **also** going to discuss our homes, themselves

Because, with a little **DIY**'ing (**do-it-yourself** 'ing),

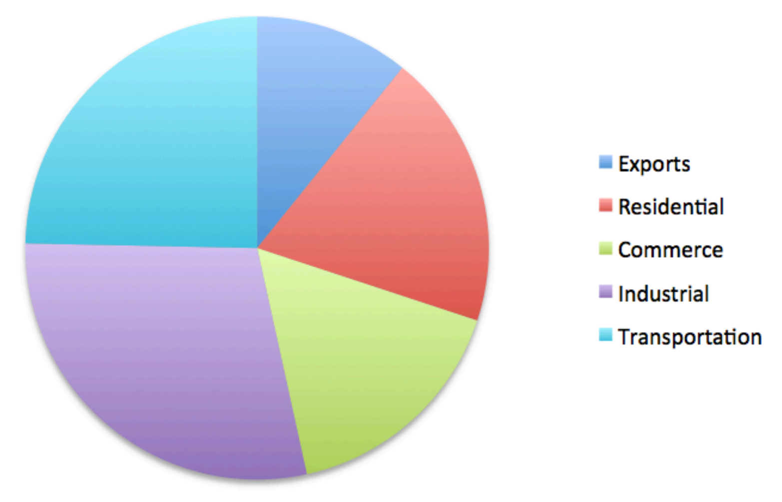
your home offers you your #1 way of saving energy

2018 "U.S. Energy Flow" according to our Energy Information Administration:



From which I generated this U.S. power consumption pie-chart:

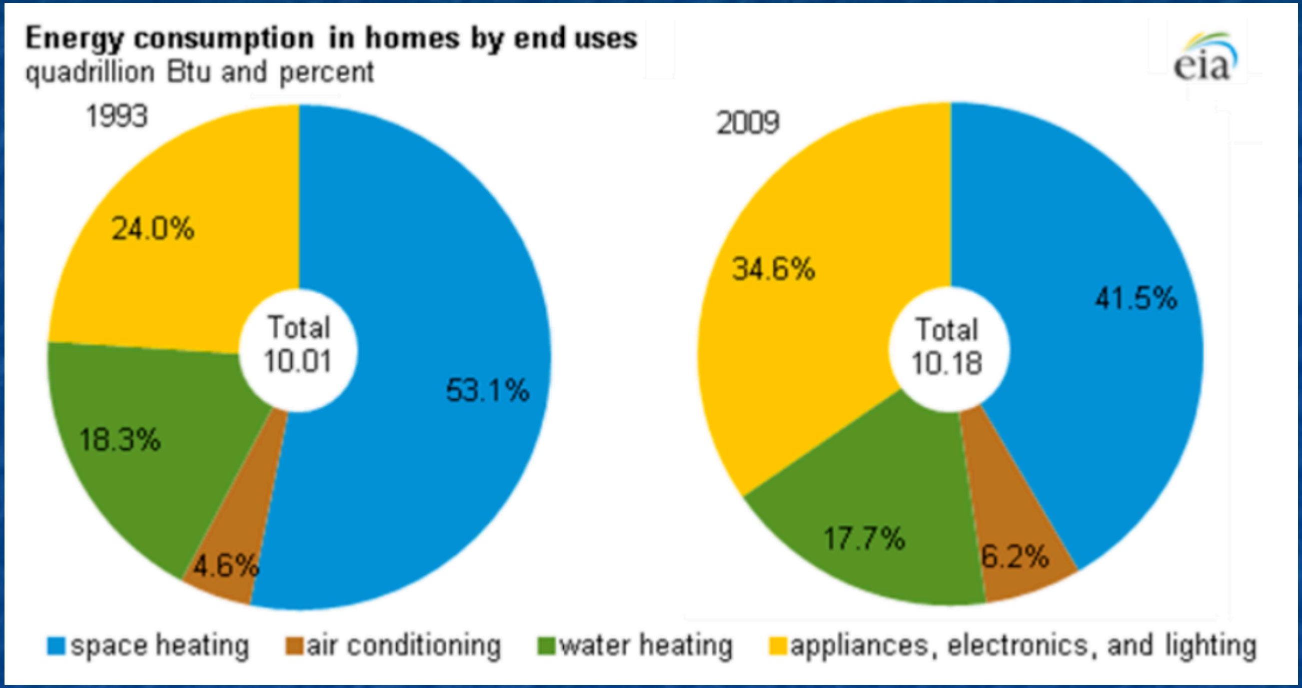
Exports (fuels):	17.3%
Commerce:	17.7%
Residential:	**15.2%**
Transportation:	26.6%
Industrial:	23.2%



EIA U.S. Energy Flow 2018: https://www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy.pdf

Where do we WE use that "residential" 15.2% of U.S. Energy?

Also from the U.S. Energy Information Administration (EIA):



OLD HOMES:

53.1% air heating / 18.3% water heating / 4.6% air cooling / 24% appliances + electronics + lights

NEW HOMES:

41.5% air heating / 17.7% water heating / 6.2% air cooling / 34% appliances + electronics + lights

EIA Energy Data Facts - Residential: https://rpsc.energy.gov/energy-data-facts

From which one can conclude:

Home energy use is mostly about heat, its movement, or removal

Old Homes: Heating + Cooling = **76%** of their energy consumption

Suggesting: 15.2% x 76% => 11.6% of TOTAL U.S. energy consumption!

New Homes: Heating + Cooling = **65.4%** of their energy consumption

Suggesting: 15.2% x 65.4% => 9.9% of TOTAL U.S. energy consumption!

For MIX of OLD and NEW HOMES, let's take Heating + Cooling average ~ 70%

Accounting for 15.2% x 70% = 10.6% of TOTAL U.S. energy consumption!

Or is the heat component even larger?

To answer, look more closely at the "appliances" contribution of ~ 1/3:

U.S. Department of Energy data on power of appliances

Which I've converted to **energy** use based on approximate time used per day:

Device	**Power**	**Use/day**	**Energy/day**
Air Conditioner	0.6 kW	12 h	7 kW-h/d
Coffee Maker	1 kW	½ h	0.5 kW
Clothes Washer	0.4 kW *	1 h	0.21 kW-h/d
Clothes Dryer	4 kW *	1 h	4 kW-h/d
Cooktop range	3.3 kW	½ h	1.6 kW-h/d
Dishwasher	2 kW	1 h	2 kW-h/d
Microwave Oven	1 kW	1/3 h	0.3 kW-h/d
Oven	3 kW	½ h	1.5 kW-h/d
Refrigerator	0.7 kW	24 h	1.75 kW-h/d

* vs. implausible MacKay textbook statement (p. 51) that **Clothes Washer = Clothes Dryer** = 2.5 kW

http://energy.gov/energysaver/articles/estimating-appliance-and-home-electronic-energy-use (no cached copy)

Re-sorting those in energy consumption order:

Device	**Power**	**Use/day**	**Energy/day**
Air Conditioner	0.6 kW	12 h	7 kW-h/d
Clothes Dryer	4 kW	1 h	4 kW-h/d
Dishwasher	2 kW	1 h	2 kW-h/d
Refrigerator	0.7 kW	24 h	1.75 kW-h/d
Cooktop range	3.3 kW	½ h	1.6 kW-h/d
Oven	3 kW	½ h	1.5 kW-h/d
Coffee Maker	1 kW	½ h	0.5 kW
Microwave Oven	1 kW	1/3 h	0.3 kW-h/d
Clothes Washer	0.4 kW	1 h	0.21 kW-h/d

RED = All/mostly about heat

Pink = Partially about heat

http://energy.gov/energysaver/articles/estimating-appliance-and-home-electronic-energy-use (no cached copy)

Assuming my usage times are ballpark correct:

And that every home has one of the above appliances

The RED appliances are ~ 100% about heat

The PINK appliances are ~ 50% about heat

Fraction of "appliance" energy consumption due to heating (or moving heat) is then:

$$\frac{(7 + 4 + 2/2 + 1.75 + 1.6 + 1.5 + 0.5 + 0.3)}{(7 + 4 + 2 + 1.75 + 1.6 + 1.5 + 0.5 + 0.3 + 0.21)} = 93.6\%$$

Multiplying by earlier fractions of home energy use due to appliances (24% or ~34%)

Adding home energy percentages due to air & water heating, and air cooling:

Heating + Cooling + Appliance/Electronics/Lighting Heat => **~ 90% of Home Energy**

~ 14% of TOTAL U.S. energy consumption!

Did I leave some things out?

Sure! Huge TV's and HiFi systems can be big hitters, as can personal computers

Especially as these combine **high power** with **high use** times

But the **energy** that goes into these things **must be conserved**

And in our homes, almost no energy is being added to chemical bonds

Nor is very much energy being put into sound, light, radio waves

Which means that almost all of the input power **ultimately** ends up as HEAT

In fact, for almost all appliances & electronics: Power input ~ HEAT output

So to McKay's rant in "Sustainable Energy - Without the Hot Air" that:

"It's NOT about every little thing, it's about every big thing!"

Let me add my rant that:

"If it isn't producing (or moving) HEAT, don't worry about it!"

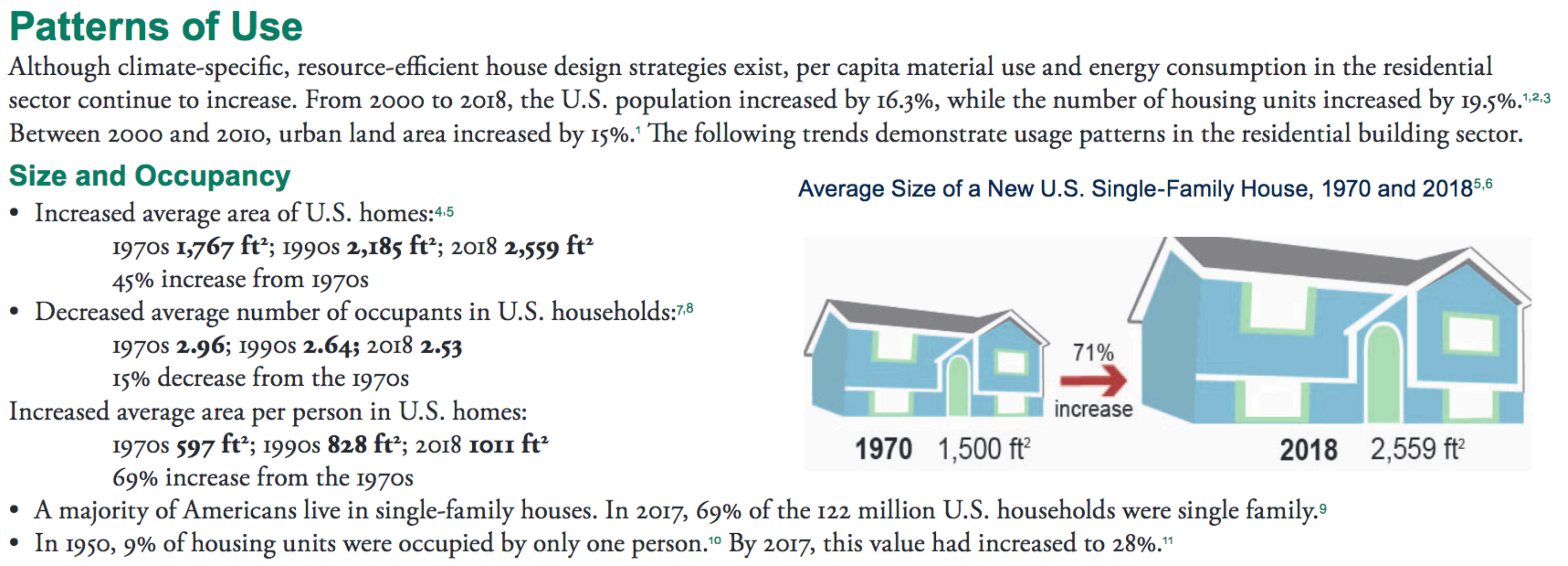
*But rather than **percentages** of total U.S. energy consumption, what about the **actual levels** of U.S. residential energy consumption?*

In 2018 the University of Michigan's Center for Sustainable Systems released a Fact Sheet about U.S. Residential Power [1]

It noted that, since 1950, U.S. residential power use increased 16 fold,

(while the U.S. population only slightly more than doubled [2])

The Fact Sheet also reported these trends:



Patterns of Use

Although climate-specific, resource-efficient house design strategies exist, per capita material use and energy consumption in the residential sector continue to increase. From 2000 to 2018, the U.S. population increased by 16.3%, while the number of housing units increased by 19.5%.[1,2,3] Between 2000 and 2010, urban land area increased by 15%.[1] The following trends demonstrate usage patterns in the residential building sector.

Size and Occupancy

- Increased average area of U.S. homes:[4,5]
  1970s **1,767 ft^2**; 1990s **2,185 ft^2**; 2018 **2,559 ft^2**
  45% increase from 1970s
- Decreased average number of occupants in U.S. households:[7,8]
  1970s **2.96**; 1990s **2.64**; 2018 **2.53**
  15% decrease from the 1970s

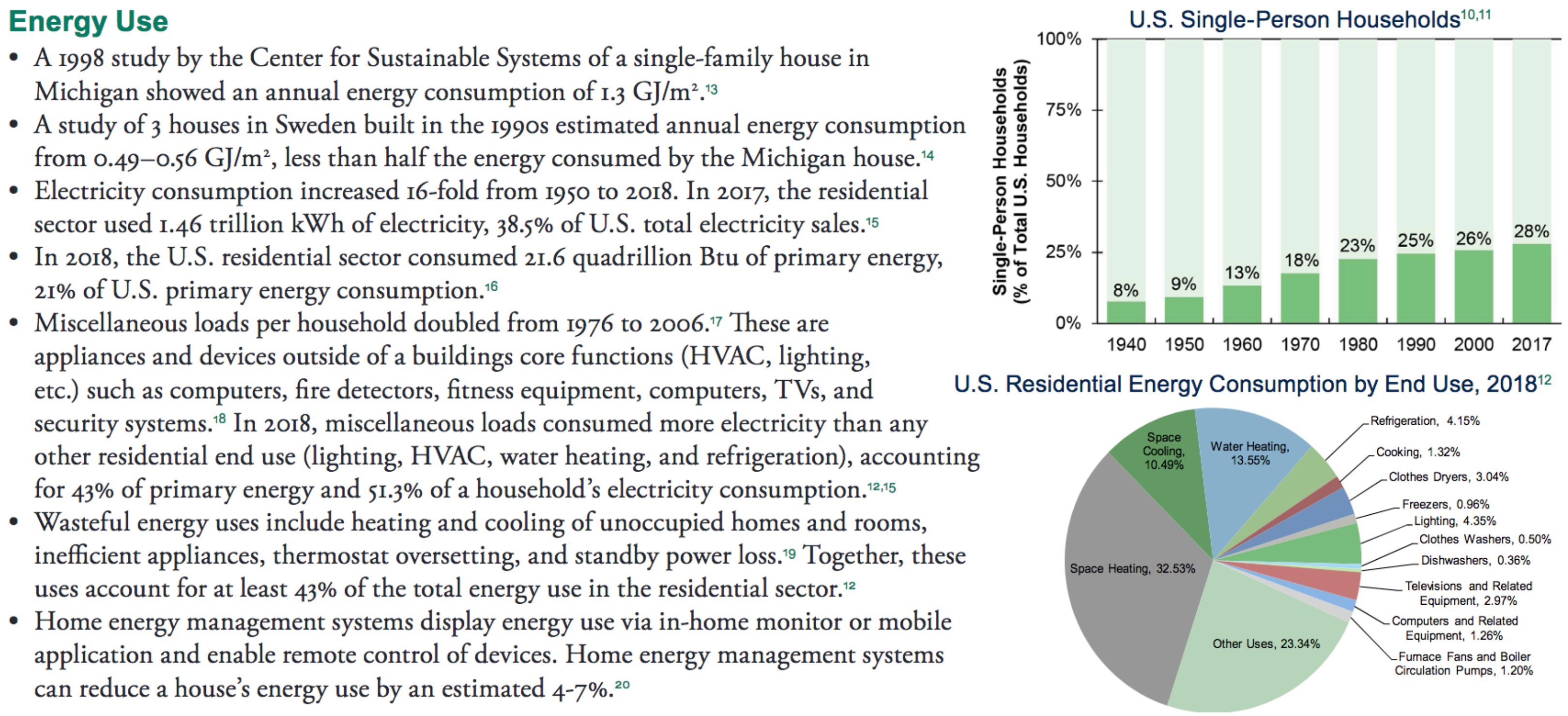
Increased average area per person in U.S. homes:
1970s **597 ft^2**; 1990s **828 ft^2**; 2018 **1011 ft^2**
69% increase from the 1970s

Average Size of a New U.S. Single-Family House, 1970 and 2018[5,6]

- A majority of Americans live in single-family houses. In 2017, 69% of the 122 million U.S. households were single family.[9]
- In 1950, 9% of housing units were occupied by only one person.[10] By 2017, this value had increased to 28%.[11]

1) http://css.umich.edu/factsheets/residential-buildings-factsheet
2) https://en.wikipedia.org/wiki/Demographic_history_of_the_United_States

That "Fact Sheet" also included these figures & factoids:



Energy Use

- A 1998 study by the Center for Sustainable Systems of a single-family house in Michigan showed an annual energy consumption of 1.3 GJ/m².[13]
- A study of 3 houses in Sweden built in the 1990s estimated annual energy consumption from 0.49–0.56 GJ/m², less than half the energy consumed by the Michigan house.[14]
- Electricity consumption increased 16-fold from 1950 to 2018. In 2017, the residential sector used 1.46 trillion kWh of electricity, 38.5% of U.S. total electricity sales.[15]
- In 2018, the U.S. residential sector consumed 21.6 quadrillion Btu of primary energy, 21% of U.S. primary energy consumption.[16]
- Miscellaneous loads per household doubled from 1976 to 2006.[17] These are appliances and devices outside of a buildings core functions (HVAC, lighting, etc.) such as computers, fire detectors, fitness equipment, computers, TVs, and security systems.[18] In 2018, miscellaneous loads consumed more electricity than any other residential end use (lighting, HVAC, water heating, and refrigeration), accounting for 43% of primary energy and 51.3% of a household's electricity consumption.[12,15]
- Wasteful energy uses include heating and cooling of unoccupied homes and rooms, inefficient appliances, thermostat oversetting, and standby power loss.[19] Together, these uses account for at least 43% of the total energy use in the residential sector.[12]
- Home energy management systems display energy use via in-home monitor or mobile application and enable remote control of devices. Home energy management systems can reduce a house's energy use by an estimated 4-7%.[20]

U.S. Single-Person Households[10,11]

U.S. Residential Energy Consumption by End Use, 2018[12]

Which included these highlights:

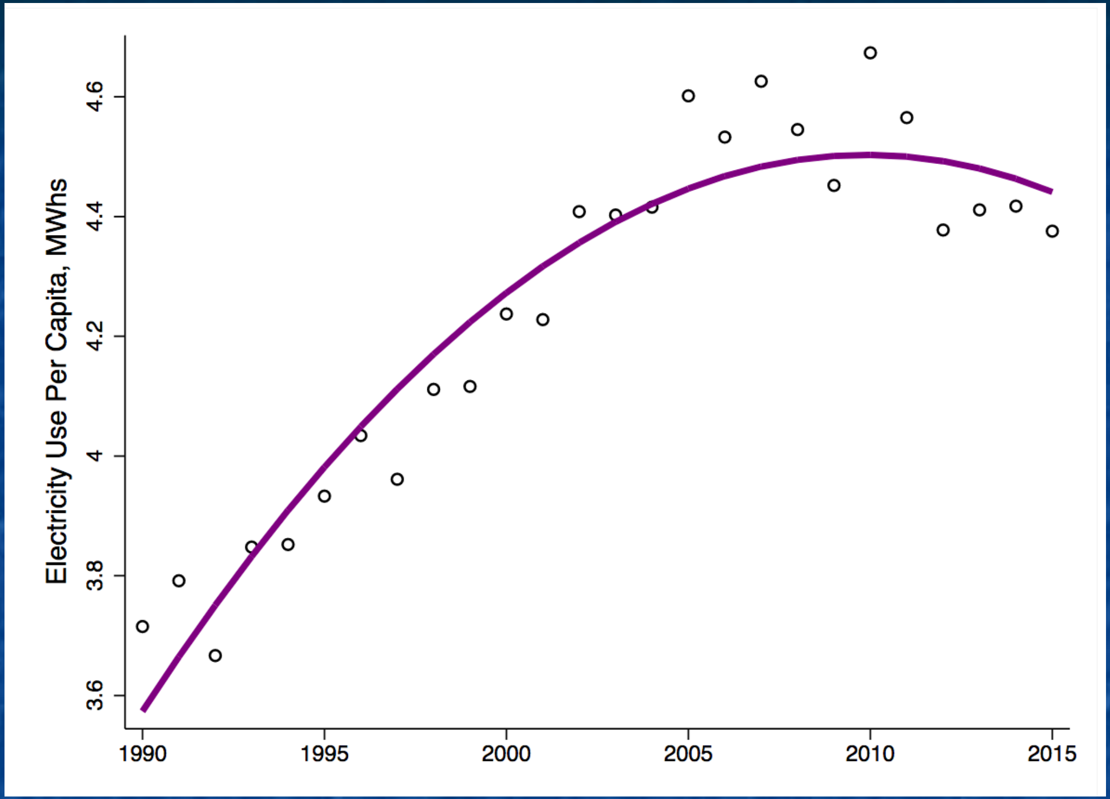
U.S. homes are both larger AND consume 2.5X the energy per area of Swedish ones

"Miscellaneous" electronic devices are now the major U.S. home energy consumers

Wasteful / avoidable home energy use accounts for 43% of total home consumption

Energy monitoring & management devices alone could reduce that by up to 7%

But another study DID suggest recent flattening in U.S. home energy use:



This non-peer reviewed study (out of University of California Berkeley) also estimated the energy likely saved by recent increased use of LED lighting in U.S. homes, and concluded that LED use alone might account for the observed rolloff [1]

1) https://www.haas.berkeley.edu/wp-content/uploads/WP279.pdf

The statistics indicate that home energy use is almost all about heat

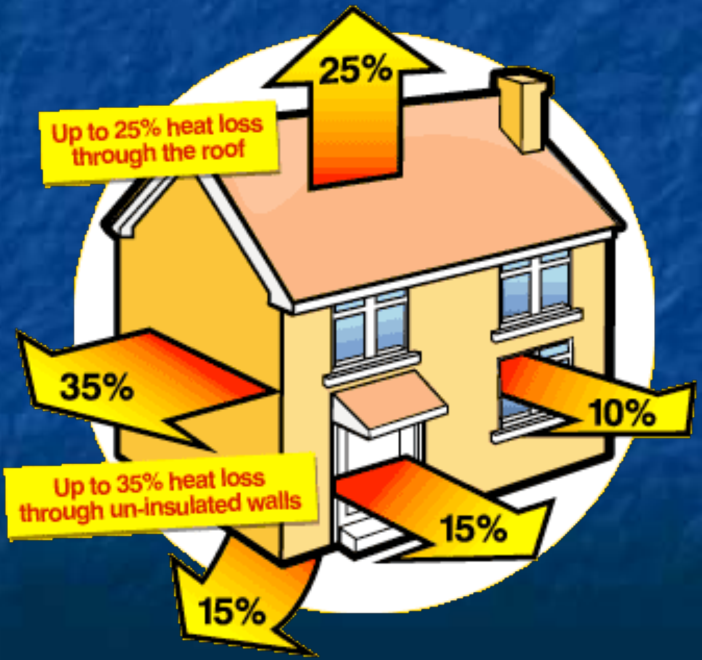
And that half of this energy use has to do transfer of air heat in and out of our homes

So how DO U.S. homes loose and gain heat?

On this topic, the U.S. Department of Energy maintains its almost unbroken record

of offering minimally useful/detailed educational or consumer information!

But **I did** find this figure used on several **UK government websites**:



It has the unfortunate shortcoming that:

1) UK homes are built differently than in U.S.

Mostly with thermally conductive brick & tile

2) Figure shows WHERE heat exits, but not HOW

By heat conduction?

By air air leakage?

By something else?

http://www.newcastle-staffs.gov.uk/housing_content.asp?id=SXBC10-A780DDF0&cat=1403   (no cached copy)

So let's dig into heat transfer mechanisms on our own:

From high school physics: Heat energy can be transferred in one of three ways

1) **Conduction = Transfer of vibrational energy between atoms/molecules**

2) **Convection = Movement of hot atoms/molecules to cooler places**

That is, by gravity pushing cooler (denser) gases below hotter gasses

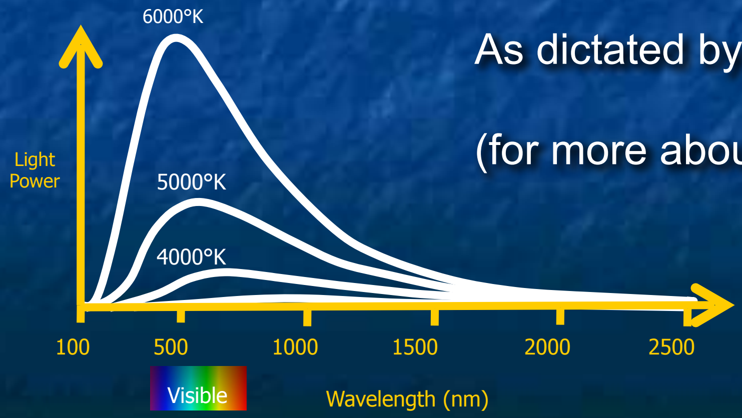
3) **Radiation = Flow of energy via electromagnetic waves** (e.g., infrared light)

With that radiation **emitted from** vibrating atoms & molecules:

More intense the vibration (= hotter) => More intense the radiation

As dictated by the "Black Body Radiation" laws

(for more about them see: **Greenhouse Effect** (pptx / pdf / key))



1) Conductive Heat Transfer:

"Transfer of vibrational energy between atoms/molecules"

Which transfers heat through the walls, ceilings and floors of our homes

Consider one wall/ceiling/floor: How much heat moves through it?

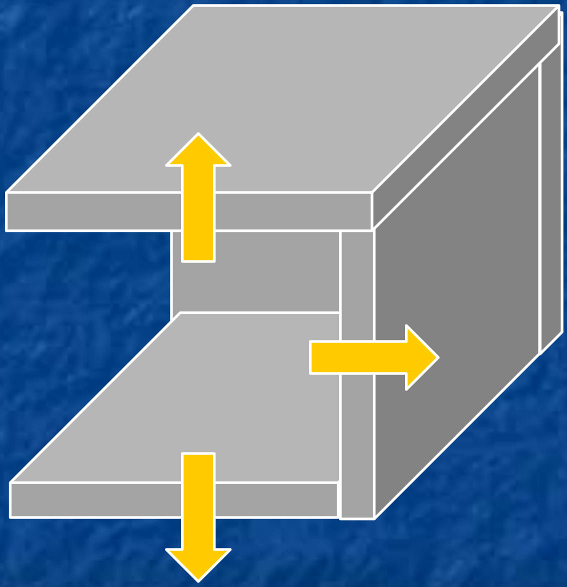
1) It scales with the difference in temperature across it: ΔT

2) It scales with its area: **A**

3) It depends on how wall/ceiling/floor is made

Its thickness, composition, detailed design . . .

Which is sometimes lumped into a number, κ



Yielding an equation for **Heat flow =** κ **A** ΔT

Higher κ, larger area, greater temperature difference: All => Greater heat flow

It's rewritten a bit differently when applied to buildings & housing:

1) In Europe and in engineering textbooks:

Heat flow = U A ΔT where U must be the same as κ

Lower U values => Lower heat loss!

The units of U? Inverting the equation, U = (Heat Flow) / A ΔT = (Power) / A ΔT

= (Watts) / (Area) (Temperature difference) = **Watts / m^2 - °C**

2) Or in the U.S. where, in housing, we're still cursed with antiquated British units:

Heat flow = A ΔT / R where the **"R value"** must just equal 1 / κ

Higher R value => Lower heat loss!

The units of R value? R = A ΔT / (Heat Flow) = **ft^2 - °F / (Btu / hr)**

= **ft^2 - hr - °F / Btu** where Btu = a "British Thermal Unit" = 1055 Joules

To convert: Metric "U value" = 0.176 / (U.S. "R value")

Some R and U values for housing (plus their cross conversions):

Material	**Thickness**	**R** (ft^2-hr-°F/Btu)	**U** (W/m^2-°C)
Solid wood door[1]	2"	(0.067)	2.6
Wood[1]	1"	(0.063)	2.8
Hard/Soft woods[2]	1"	0.9 – 1.25	(1.95-0.14)
Plywood[2]	½"	0.62	(0.28)
Sheetrock (Gypsum)[2]	½"	0.45	(0.39)
Fiberglass insulation[2]	3 1/2" / 6"	10.9 / 19	(0.016 / 0.0093)
Polyurethane foam[2]	1"	6.3	(0.028)
Cellulose insulation[2]	1"	3.7	(0.047)
Single pane glass[1]		(0.0347)	4.7
Single pane glass[3]		(0.035)	5.0
Double pane glass[1]		(0.0628)	2.8
Double Pane glass[3]	20 mm gap	(0.10)	1.7
Solid brick wall[1]	10"	(0.088)	2
Solid brick wall[3]	9"	(0.08)	2.2
Insulated brick wall[3]	11"	(0.29)	0.6
Timber framed floor[3]		(0.25)	0.7
Solid concrete floor[3]		0.22)	0.8

1: http://www.engineeringtoolbox.com/heat-loss-transmission-d_748.html

2: "Energy – Its Use and the Environment," Hinrichs & Kleinbach, Chapter 5, Table 5.1, page 128 (Brooks/Cole 2013)

3: "Sustainable Energy without the Hot Air," McKay, Chapter E, Table E.2, page 290 (UIT Cambridge 2009)

Warning / Disclaimer:

The preceding table took me hours to compile!

Not because I could not find data sources

But because they so often disagreed . . . even radically!

I ended up gathering data from three or more sources, for virtually all materials

And then tossing the outliers

Nevertheless:

Seek out additional verification before **relying** upon any of those data!

http://www.designingbuildings.co.uk/wiki/U-values

*But how would you then **use** such (verified) data?*

You'd **add** all the heat flows, as calculated from **Heat flow = U A ΔT = A ΔT / R**

So for **each** wall, ceiling or floor, you'd need its R (or U) value

What if you couldn't find U/R data for your particular wall/ceiling/floor?

If you knew it consisted of ½" sheetrock + 3.5" fiberglass insulation + 1" plywood

You'd ADD the R values for each of its layers (e.g., from table above):

$R_{\text{total}} = R_{\text{sheetrock}} + R_{\text{3.5" insulation}} + R_{\text{0.5" plywood}} = 0.45 + 10.9 + 0.62 = \mathbf{11.98}$

While U's are a bit harder to use because:

$U_{\text{total}} = 1 / \text{Sum} (1/U_{\text{1st layer}} + 1/U_{\text{2nd layer}} + . . . + 1/U_{\text{last layer}})$

Above would be a "timber frame" wall built to minimal current U.S. standards

Which is still **hugely** better than traditional British $R_{\text{solid brick wall}} = \mathbf{0.08}$!

Next you'd need areas through which the heat is flowing

Which you'd get by measuring the areas of the exterior walls/ceiling/floors

Subtracting out the area of any doors or windows

(and later calculating their heat flows separately)

FINALLY, you'd need the temperature difference across those barriers

Which you could measure at a particular time . . . or much better:

To get heat flow over a full season, consult "degree day map"

Those maps integrate the **following quantity** over a **whole** heating season:

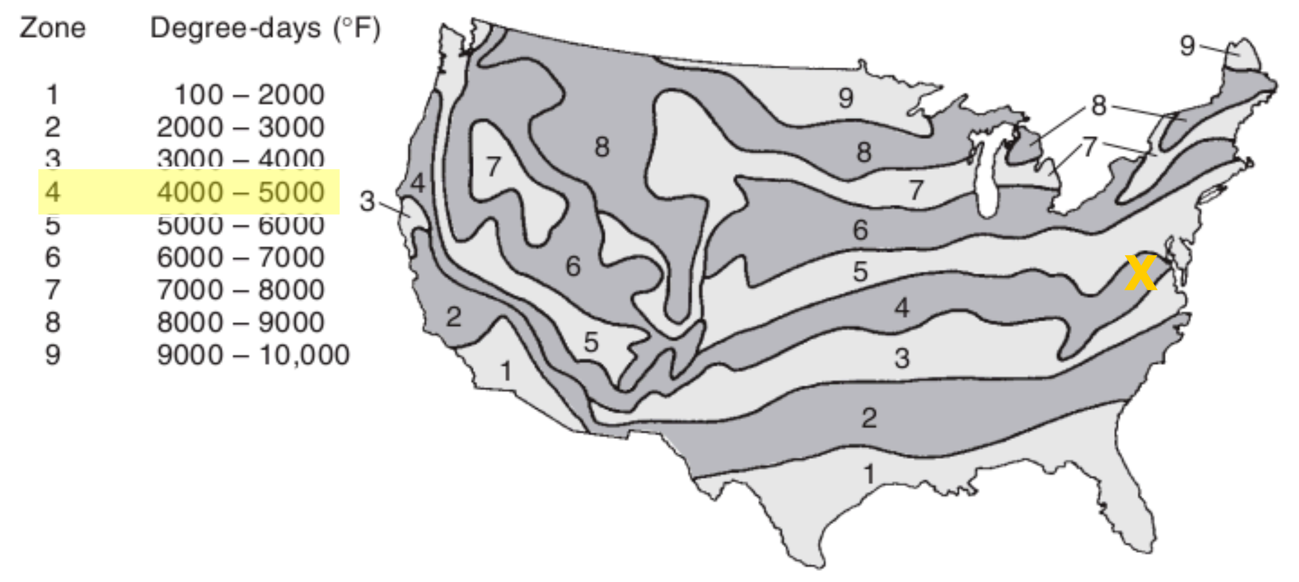
(Average inside temp. - Outside temp.) x (Net time spent at that difference)

With a "**heating season**" defined as part of year when it's colder outside

And a "**cooling season**" defined as part of year when it's hotter outside

Yielding degree-day maps such as this:

A **heating season degree day map**:



Zone	Degree-days (°F)
1	100 – 2000
2	2000 – 3000
3	3000 – 4000
4	4000 – 5000
5	5000 – 6000
6	6000 – 7000
7	7000 – 8000
8	8000 – 9000
9	9000 – 10,000

So for central Virginia, a house's total cool season **conductive** heat loss would be

For ONLY walls/ceilings/floors/doors/windows exposed to outside temperature:

$$= \text{Sum}\ [\, A_{\text{wall } i}/R_{\text{wall } i} + \ldots + A_{\text{floor } j}/R_{\text{wall } j} + \ldots + A_{\text{door } k}/R_{\text{door } k} + \ldots + A_{\text{window } l}/R_{\text{window } l}\,]$$

$$\times\ [4500\ °\text{F days}]$$

Figure: "Energy – Its Use and the Environment," Hinrichs & Kleinbach, page 135 (Brooks/Cole 2013)

*How big a deal **is** such **conductive heat loss / gain** ?*

As noted above, I found little information on housing energy in textbooks and online

But we can look back to that **British** figure to make an estimate:

There homes make much heavier use of bricks and ceramic roof tiles

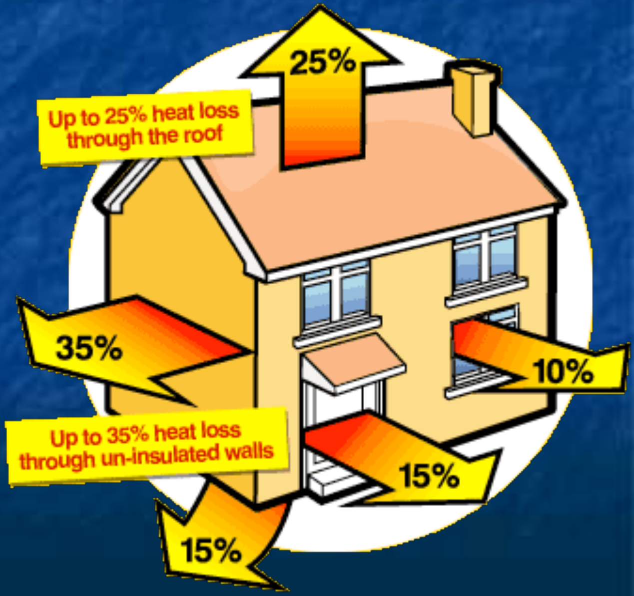
Which makes their walls & attic/roofs MUCH more thermally conductive

In such homes, these outside surfaces account for 60% of the total home heat loss

But I'd be surprised if U.S. homes cut this below 20%

Leaving another ~ 80% of energy loss to account for

Thus, moving on to our next candidate:



http://www.newcastle-staffs.gov.uk/housing_content.asp?id=SXBC10-A780DDF0&cat=1403 (no cached copy)

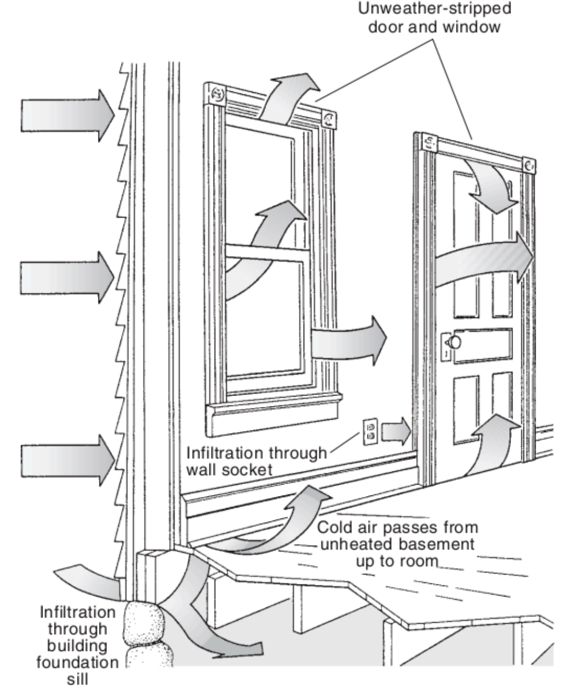
Convective Heat Transfer

"Movement of hot atoms/molecules to cooler places as driven by

gravity pushing cool/dense air below hotter/less-dense air OR by winds"

The MANY, MANY paths by which outside air can be driven into our homes

But how important can these tiny cracks/holes be?



It is estimated that a typical U.S. home experiences

1 complete home air exchange PER HOUR

In other words, **every hour** your furnace must:

Heat, from outside to inside temperature,

the air volume of your entire house

=> ~ 1/3 of U.S. home heating energy [1]

Which can **double** when outside wind speed rises to just 20 mph!

Figure: "Energy – Its Use and the Environment," Hinrichs & Kleinbach, page 133 (Brooks/Cole 2013)

1) http://en.wikipedia.org/wiki/Infiltration_%28HVAC%29

*But don't we **need** some fresh air?*

Won't we suffocate otherwise? Or be poisoned by household chemicals?

Amer. Soc. of Heating, Refrigerating & AC Engineers (ASHRAE) had a standard of:

7 cfm/person + 1 cfm/(100 ft^2 of floor space)   ("cfm" = cubic foot / min)

Assume 4 people living in a 2000 ft^2 home (with typical 8' ceilings):

Required air exchange: 7 x 4 cfm + 1 x 20 cfm = 48 ft^3/min

Air volume of home: 2000 x 8 ft^3 = 16,000 ft^3

Required home air changes/hour = 60 x (48/16,000) = 0.18

In 2013, the standard was changed to 7 cfm/person + 3 cfm/(100 ft^2 of floor space)

New required air exchange: 7 x 4 cfm + 3 x 20 cfm = 88 ft^3/min

New required home air changes/hour = 0.33

Both are a **lot less** then the 1 full exchange/hour you're likely getting now!

http://www.greenbuildingadvisor.com/blogs/dept/musings/how-much-fresh-air-does-your-home-need

My (confirming) experience with leaky American homes

Our incredibly poorly designed U.S. doors / door frames:

Our doors DO have slender rubber weather-sealing gaskets for which:

~ 0 mm squeeze => Crack for air to funnel in

~ 3 mm squeeze => Medium Compression / Good air seal

~ 6 mm squeeze => Strong Compression requiring **slamming** of door

What determines the squeeze of these gaskets? The **door striker plate:**

Which determines the point at which the door latches

So this plate should be positioned with ~ 2 mm accuracy, right?

U.S. doors are mostly factory built, complete with hinges, in a frame

But the striker plates are NOT installed, nor are holes cut for them

Why? So that we can choose our favorite style of door latch ("lockset")

I've owned 3 homes and built ~ 40 Habitat for Humanity homes:

It is **almost impossible** to chisel out the recess required for the striker plate

And then drill the necessary screw holes

With the required ~ 2 mm accuracy

(particularly if you're **also** installing a deadbolt lock)

Further, because buyers DO immediately notice the need to **slam** a door closed

Builders err on the side of more loosely positioned striker plates

Meaning that door gaskets range from 0 to proper compression

You don't believe me?

On a windy day, run your hand down the edge of a door

Or at dawn/dusk look at the **sunlight** coming in at edges of some doors!

My response as a DIY homeowner?

I first tried chiseling new recesses + new screw holes for the striker plates

- But a NEW screw hole must be ~ 4 mm away from OLD screw hole
  - Meaning that new hole often => Over-compression / Need to slam door

I DID eventually find online ONE adjustable striker plate

- That, in my already chewed up doorframes only sort of worked

I finally enlarged the old screw holes, and glued in replacement wood plugs

- (which required buying a special "dowel/plug" cutting drill set)
  - And **then** tried to drill new properly positioned holes in the plugs

The ALTERNATIVE, RATIONAL, but still STILL CHEAP ($5 to $20) solutions?!

- i) Factory-installed latches/striker-plates (you could still choose doorknobs!)
- ii) Adjustable or pull-tight types of latches
  - (As already used in Scandinavia and other parts of northern Europe)

A further energy lesson taught to me by stink bugs:

After going through all of the above door repair/modifications

In a fairly new, fairly well built house, we were still plagued by winter drafts

Then I noticed a **trail** of stink bugs crawling in at a door's corner

On hands and knees I figured out HOW they were getting past the door's seal:

Proper door seals:

My door seals:

To save the (miniscule) cost of

miter cutting the gasket corners

(i.e. "picture framing")

They just cut the pieces ~ 1" short

Leaving breezeways & bugways

At all four door corners

(continuing)

These weren't cheap doors (and I've seen **same** problem on other not-cheap doors)

My solution for **this** problem?

I spent an hour on the Internet identifying replacement gaskets, then

For $35 I bought enough to REGASKET every exterior door on my house

But I measured carefully AND made 45° razor blade cuts at their ends

Which took me a grand total of about 1 hour for six doors

(And would have taken door **manufacturers** trivial time & money!)

RESULT: My previously drafty house is no longer drafty

=> **Same winter comfort at 1-2°C cooler heating temperature**

WHY do we Americans put up with this pennywise / pound foolishness!

*Cutting **convective heat loss** is thus all about little things:*

Which, in its own way, is good news

Because for **conductive heat loss**, only thing a DIY homeowner can easily do is:

Install insulating sheets of fiberglass in attic or under crawlspace floors

Whereas for **convective heat loss** that same homeowner can:

Caulk cracks (anywhere and everywhere!)

Install rubber gaskets in electrical outlets located on exterior walls

Replace door and window seals

Or, if you are more ambitious, replace/repair door and window latches

=> Saving VASTLY more in heating costs than these DIY repairs cost you

Even saving money if you have to pay someone to do these repairs for you!

Bringing us to: ***Radiative Heat Transfer***

"Flow of energy via electromagnetic waves (e.g. infrared light)"

With radiation **emitted from** vibrating atoms & molecules:

More intense the vibration (= hotter) => More intense the radiation

From the physics of "Black Bodies," materials naturally radiate an amount of energy:

$\varepsilon\ \sigma\ \mathbf{T}^4$ where T is their absolute temperature (in degrees Kelvin, K),

σ is the "Stefan-Boltzmann Constant" = 5.670×10^{-8} W/m^2-K^4

and ε is the material's "emissivity"

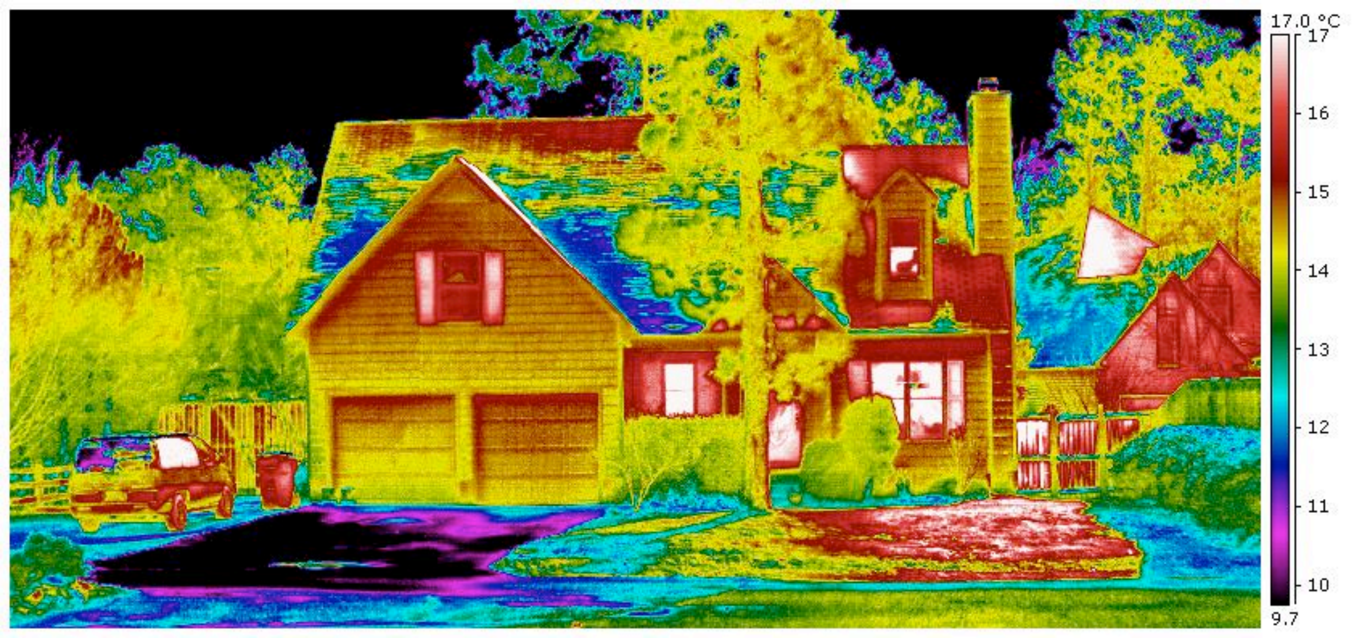
Which, for most organics, including wood & paints, is about 0.95

For an **opaque** material, the relevant temperature is its **surface temperature**

But earlier convective heat transfer cools **outside** surface temperature

of a well insulated wall to **almost the surrounding air temperature**

Yielding infrared images like this for well-insulated homes:



Wall surfaces are at almost the surrounding temperature (above, ΔT~ 1-2°C), thus:

Radiation **FROM walls TO environment** ($\varepsilon\ \sigma\ T_{wall\_surface}^{4}$) is only a bit higher

than radiation **FROM environment TO walls** ($\varepsilon\ \sigma\ T_{environment}^{4}$)

So there's little NET radiative heat transfer from a well insulated wall

But apparent window temperatures are right off the top of the scale!

Image: http://www.nicolascretton.ch/Astronomy/Spitzer_IR_space_telescope/Spitzer.html

"Apparent window temperatures" because:

The outside surface temperature of the window glass itself is also ~ $T_{\text{environment}}$

But because glass is transparent, it **passes** radiative heat out from the hotter interior

Let's run some numbers from temperatures given in preceding image:

$T_{\text{environment}}$ ~ 14°C, $T_{\text{wall surface}}$ ~ 15.5°C, T_{interior} ~ 21°C translating to °K:

$T_{\text{environment}}$ ~ 287.1°K, $T_{\text{wall surface}}$ ~ 288.6°K, T_{interior} ~ 294.1°K

Net heat loss per square meter (assuming all emissivities ~ 0.95):

Heat thru **wall** to environment: $\varepsilon\ \sigma\ (288.6^4 - 287.1^4)$ W = 7.7 W / m^2

Heat thru **window** to environment: $\varepsilon\ \sigma\ (294.1^4 - 287.1^4)$ W = 37 W / m^2

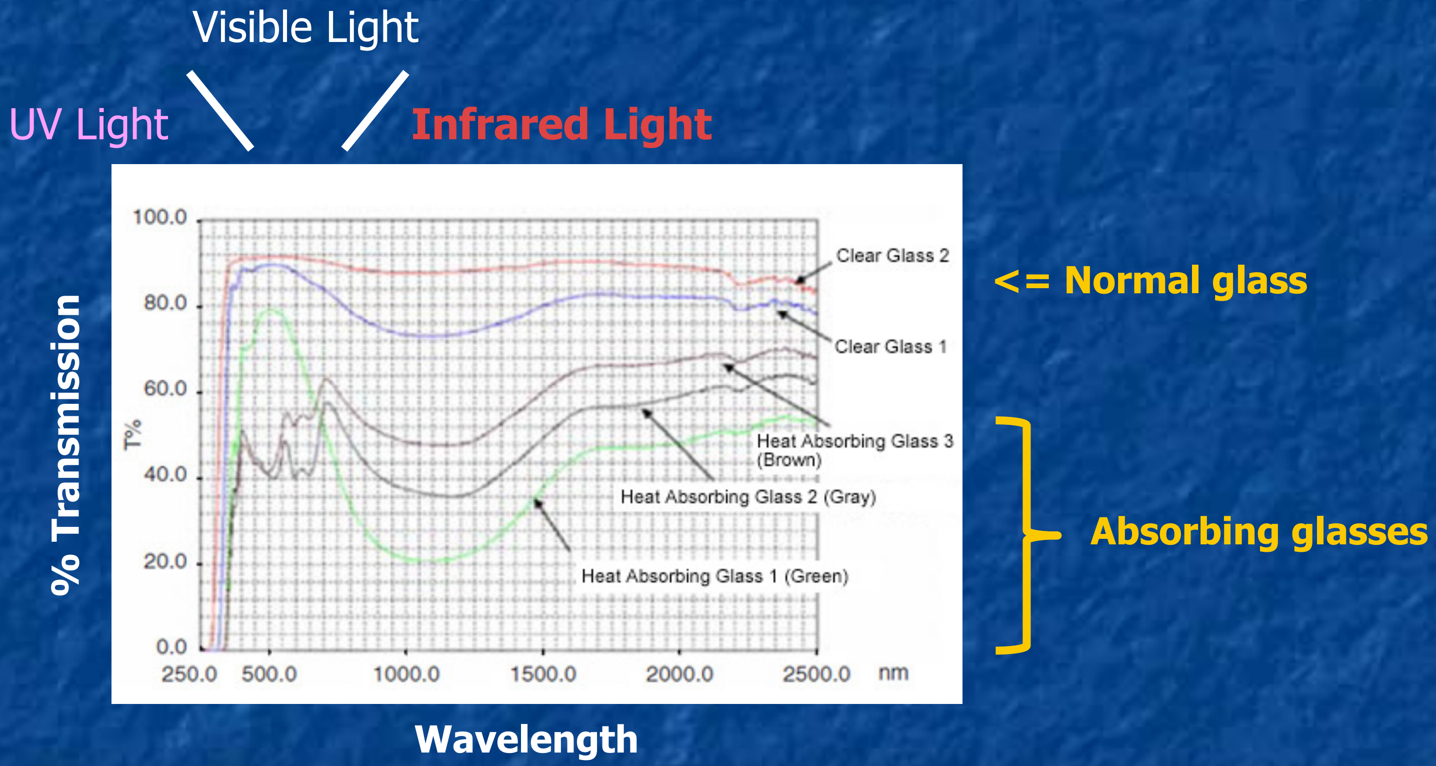
5X more radiative heat (per area) from windows than walls!

So radiative heat transfer is almost all about windows

*Windows are **intended** to pass visible light:*

But most **radiative heat transfer** occurs at invisible infrared (IR) wavelengths

Do normal plate glass windows transmit infrared light? **Yes!**



Some glasses do **absorb** IR: Summer sun would then heat outer glass

Which **would** help if you still had cooler inner pane(s) of glass

https://www.shimadzu.com/an/industry/ceramicsmetalsmining/chem0501005.htm

*But you can also **reflect** part of **all** light colors:*

By making your windows into partial mirrors (that are, for instance, 25% reflective)

During the day you'd hardly notice if light from the outside was 25% dimmer

And if you did notice, you'd probably end up appreciating it

A night, from outside, your inside lights would appear 25% dimmer

But optical tricks can ALSO produce **stronger** reflection in **only** the infrared:

It's done by setting up destructive or constructive interference of light waves

from surfaces of additional, very thin, **metal coating-layers**

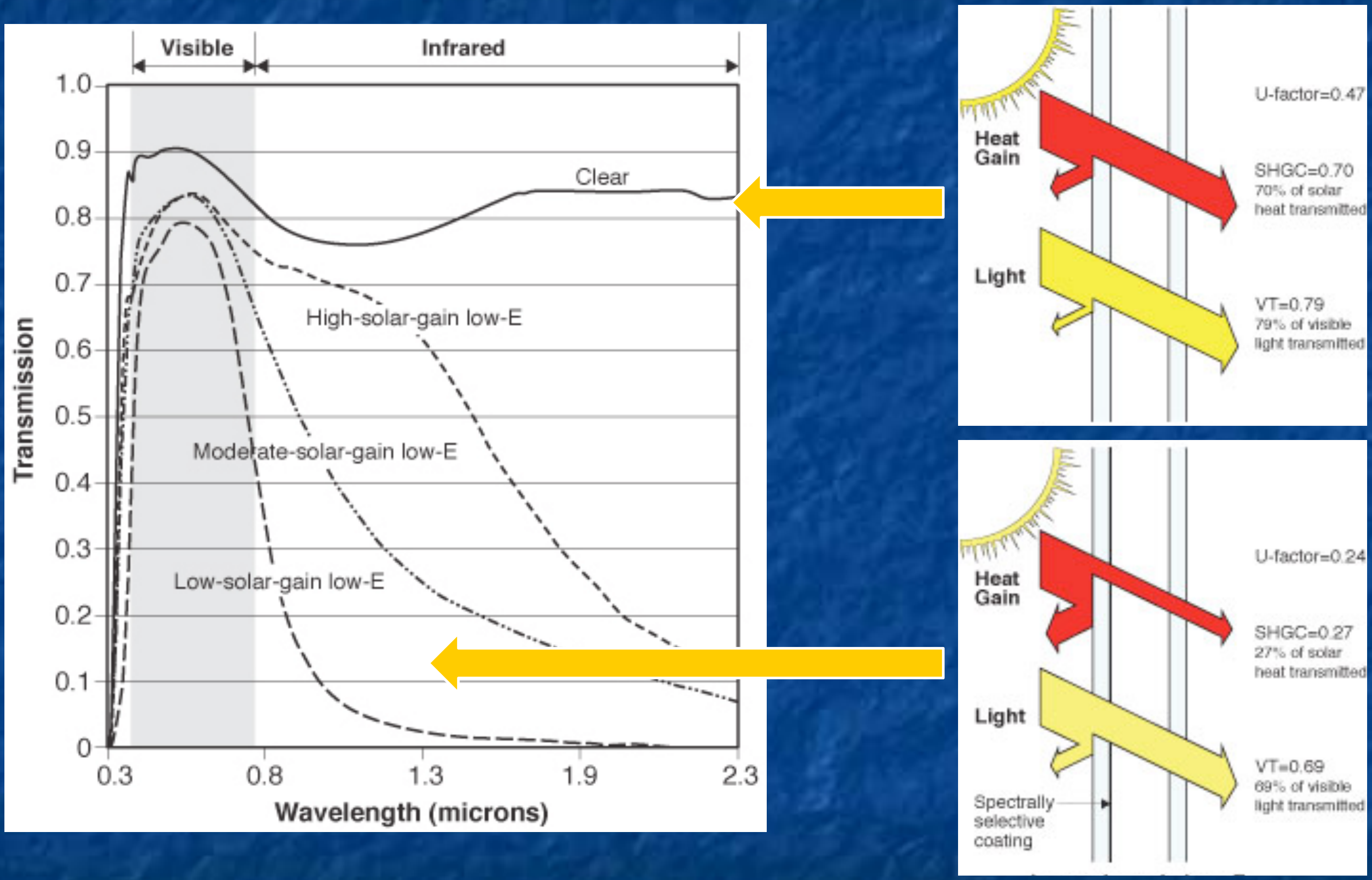
Sum of all 3 tricks (absorption + all color reflection + enhanced IR reflection)

=> **"Low E" Glass & Windows**

Where "E" again stands for emissivity = surface's efficiency at emitting light

Transmission of Low E glass / windows:

Now based more on changes in reflection, rather than absorption:



https://www.efficientwindows.org/lowe.php

Energy savings with low-E windows?

Here I (finally) found some semi-useful info from the U.S. Department of Energy: [1]

> "On average, low-e storm windows can save you 12%–33% in heating and cooling costs. This Equates to **$120–$330 in annual savings**, assuming a $1,000 annual heating/cooling bill."

Then working a bit with the Home Depot purchasing app:

Home Depot brand double-hung NON Low-E windows ran ~ $200 each

Anderson brand double-hung windows, all Low-E, started at ~ $400 each

I doubt that simple low-E process cost more than $50 of the added $200 per window

IF Department of Energy's "typical" U.S. house had 15 such windows:

- To **replace** with Low-E windows => 15 x $400 = $6000 => 20-40 year payback

- To **build with** Low-E windows (assuming my $50 ΔP is correct) = $750 cost

Which would mean an energy savings payback in as little two years

1) http://energy.gov/energysaver/projects/savings-project-install-exterior-storm-windows-low-e-coating (no cached copy)

*So that's how **normal homes** loose/gain heat*

But what about **abnormal PASSIVE SOLAR HOMES** ?

These attack home heating and cooling losses point by point:

To deal with **CONDUCTIVE Heat Transfer**:

WALLS: Go from 2x4 wood-framed walls to 2x6 or 2x8 framed walls

Space for insulation goes up by ~ 50-100%, as does R value

Cutting wall heat loss by 33-50%

CEILINGS and FLOORS: Just pile on more fiberglass insulation blankets

WINDOWS: Move from double to triple pane glass

To deal with ***CONVECTIVE*** ***Heat Transfer:***

Passive solar homes:

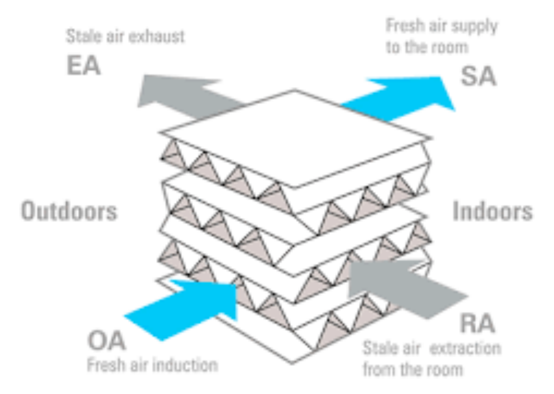
Use ultra-tight-latching doors and windows

Seal all remaining cracks and holes

Wrap whole house in wind impermeable "house wrap" (e.g., "Tyvek")

Potential Problem: House's air changes may fall below desirable 1/3 per hour

In which case you add an "**air-to-air heat exchanger**"



Which pushes inside air out, and outside air in:

Forcing them to pass closely, ~ averaging temperatures

So incoming air gets ~ **halfway** to inside air temperature

Thus ~ halving load to furnace/AC/heat pump

Top: http://www.nachi.org/housewrap-inspection.htm   *Bottom: http://www.celsiusair.co.uk/projects/callcentres.htm*

Finally, to deal with ***RADIATIVE Heat Transfer****:*

Passive solar homes reduce heat absorbed from sun by painting walls light colors

And similarly reduce heat to roof by abandoning black shingles for lighter shingles

But then passive solar homes make bigger changes:

They add south-facing rooftop passive water heaters, saving most of the 18% of residential power now used for water heating

But they DON'T use low-E windows - Instead they size and locate windows to:

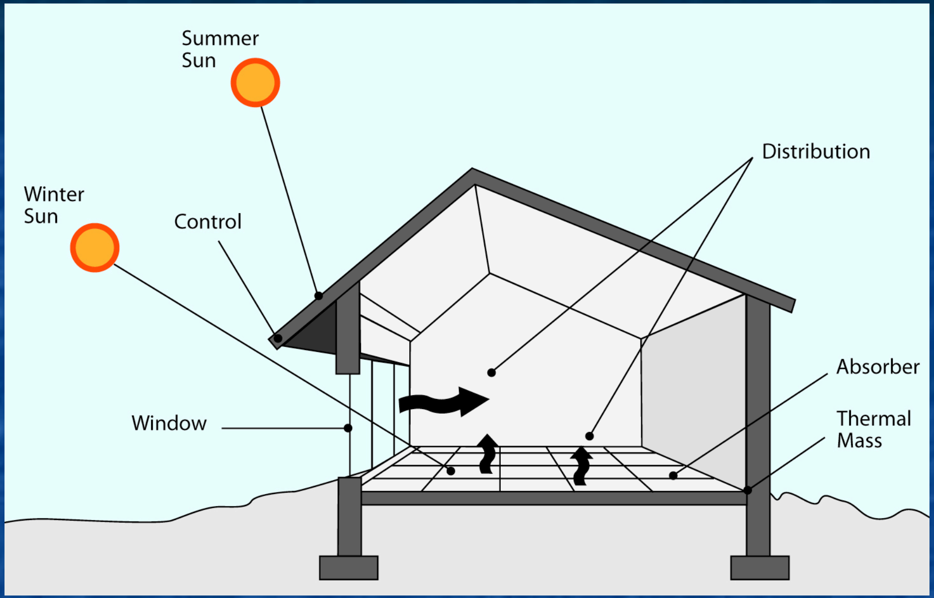
Capture solar heat in the winter, but **avoid** it in the summer

How? Some new type of selectively mirroring window? No (at least not yet)

Instead, they just redesign window overhangs and re-orient house:

Figure: http://environment.nationalgeographic.com/environment/green-guide/buying-guides/water-heater/shopping-tips/

The U.S. DOE's "five elements of passive solar design:" [1]



1) Vast majority of window **APERTURES** should be on home's south face (in U.S.)

2) **CONTROL** the entry of solar radiation into those windows via roof overhangs

allowing only low winter sun to reach the window, but not higher summer sun

(and **don't** use Low-E glass to block infrared heat from that winter sun!)

3) Inside those windows install dark **ABSORBER** surfaces to collect that winter IR

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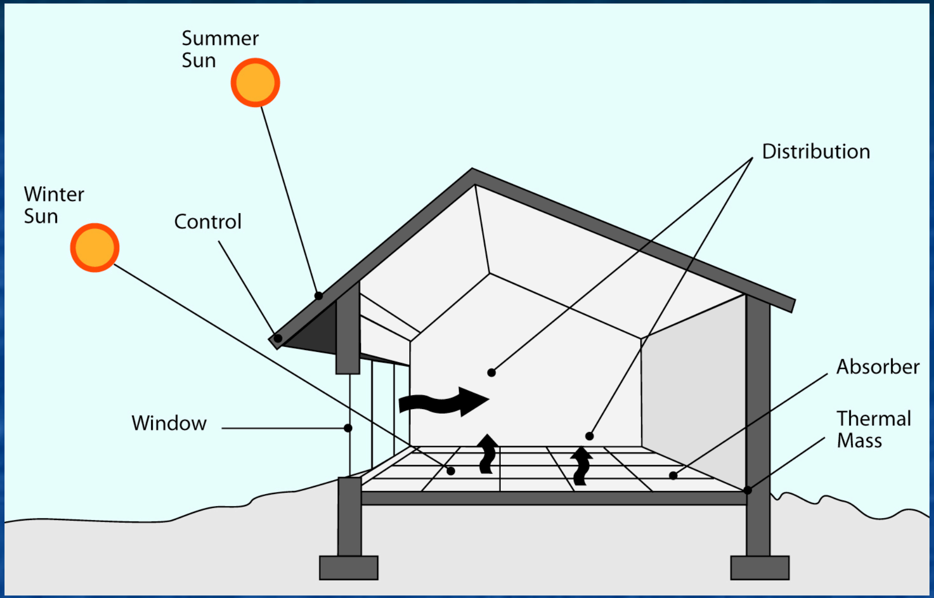
1) http://energy.gov/sites/prod/files/guide_to_passive_solar_home_design.pdf (cached copy)

The "five elements of passive solar design" (continued) [1]



4) Beneath those absorbing surfaces install **THERMAL MASS**

Things like stone or concrete that **absorb a lot of energy** as they heat up

5) Then provide for **HEAT DISTRIBUTION** from those thermal masses

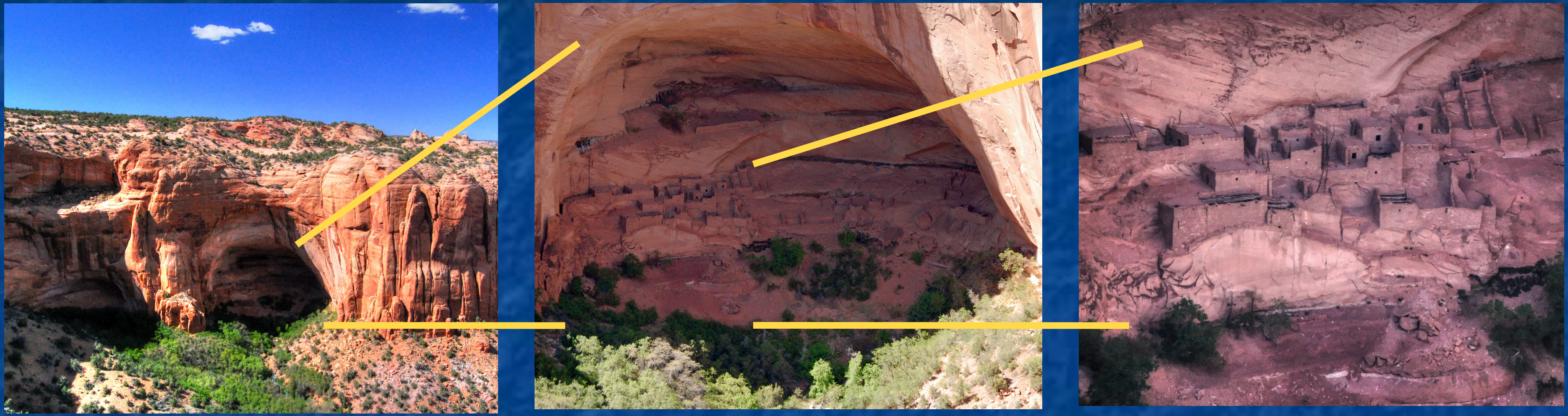
so that when sun sets, heat from the thermal mass is distributed throughout home

---

1) http://energy.gov/sites/prod/files/guide_to_passive_solar_home_design.pdf (cached copy)

An early example of U.S. passive solar homes:

The “Betatakin Cliff Dwelling” I photographed on a late May afternoon in Arizona:



Built by the Anasazi's ~**1000 years ago** (all across Arizona & New Mexico)

Not generally **in** a cliff (as for defense), but at the **base** of an **overhanging** cliff

- Facing to the south (or sometimes southwest)
  - Where houses would ONLY get DIRECT sunshine in the winter
    - Which would then heat the houses AND the surrounding stone

In other words, they **nailed** the whole idea of passive solar design!

*So why can't **WE** now "nail" the use of passive solar design?*

You DO need to aim most of your windows southward:

Which, if you didn't want to be staring at the side of your neighbor's house

Means that houses should probably lie on ~ east to west streets

So south would be out toward either front yard or back yard

But the rest is really easy (simple and cheap):

- Overhanging roof on south face of house
  - Dark light/heat-absorbing stone or concrete floors in south facing rooms
    - Air circulation to share stored heat with other rooms
- Plus well insulated and light-colored roof and W/N/E walls to shed summer heat

Which could give many/most of us low to no heating & cooling houses

Saving 2/3 of residential (~ 21% of U.S. total) power consumption!

But what about the homes we NOW mostly buy or live in?

We can still shop for homes implementing **some** of today's **best practices**

or, as owners, make certain best practice changes ourselves,

while also making better choices when home appliances are replaced

This note set's Resources Webpage includes a list of "Best Practices" sources

Of particular note are step-by-step webpages from the **Zero Energy Project:**

Step 1 - The Design Process
Step 2 - Use Energy Modeling
Step 3 - Super Seal the Building Envelope
Step 4 - Super Insulate the Building Envelope
Step 5 - Heat Water Wisely
Step 6 - Specify Highly Insulated Windows and Doors
Step 7 - Choose Solar Tempering
Step 8 - Create an Energy Efficient Fresh Air Supply
Step 9 - Select Energy Efficient Heating and Cooling System
Step 10 - Select Energy Efficient Lighting
Step 11 - Select Energy Efficient Appliances & Electronics
Step 12 - Use the Sun

Drawing from that and other Best Practice sources:

Air Heating & Cooling (and their minimization) are always a top priority

Recall the governmental data I cited at beginning of this talk:

Winter heating alone => 30-40% of U.S. residential power consumption

And how do we typically produce such heat?

By passing electricity through "resistor" heating elements

OR by burning hydrocarbon fuels in furnaces

How efficient are these processes (and how might they be improved)?

Resistive heating elements already convert electricity to heat VERY efficiently

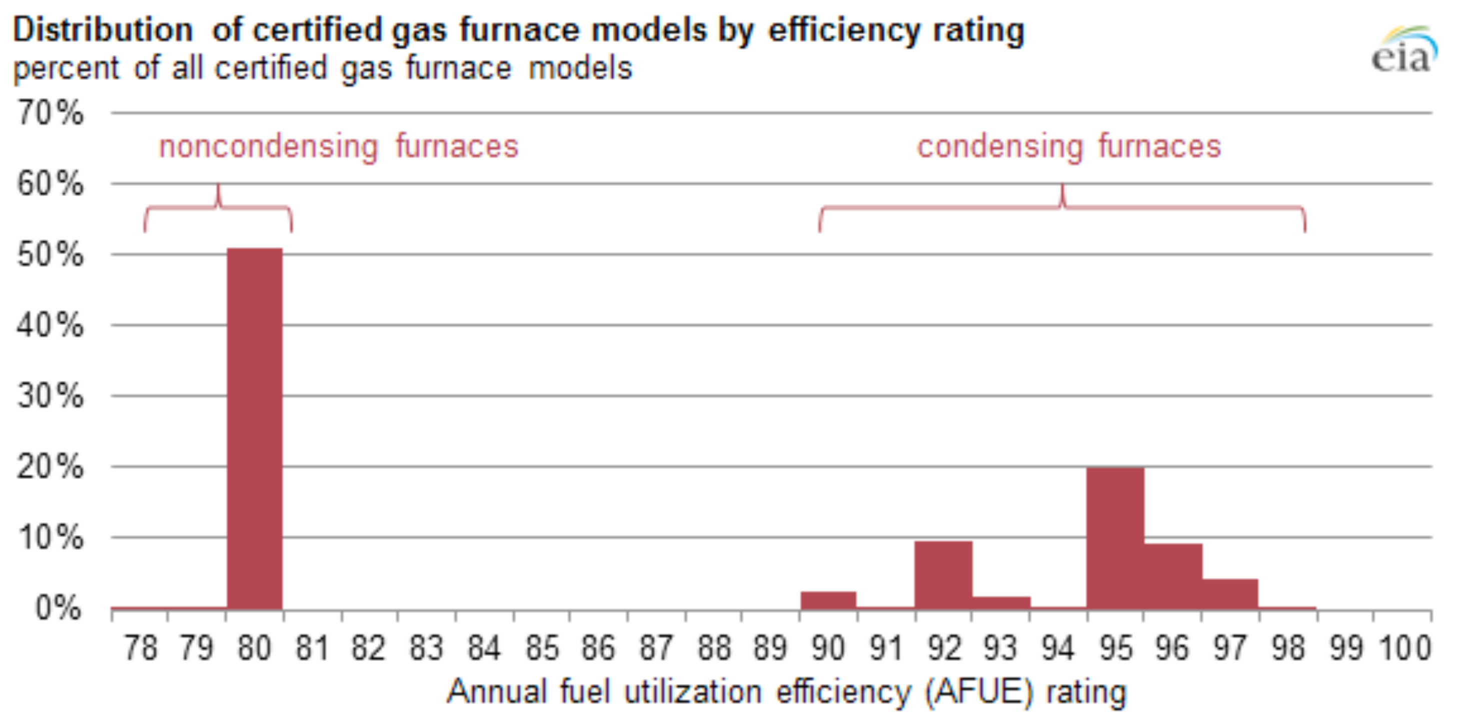
But the problem is then that our still dominant fossil-fuel power plants

convert fossil fuels to electrical energy at only 1/3 - 2/3 efficiency

What, instead, about furnaces burning fossil-fuels right in our home?

They are now much more efficient than fossil-fuel power plants!

Types of furnaces (and percentage of such models) vs. heat delivery efficiency:



So what IS a condensing furnace, and why are they ~ 15% more efficient?

https://www.eia.gov/todayinenergy/detail.cfm?id=14051

Non-condensing (conventional) vs. condensing furnaces:

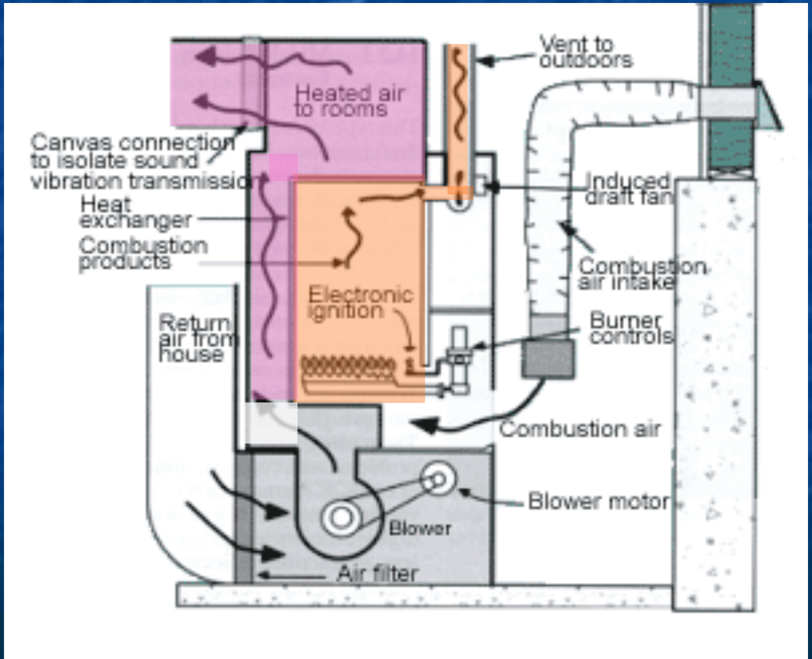
Both have a central chamber where fuel burns using inside house air (white)

Producing "exhaust" = very hot air + water vapor + byproducts = Orange

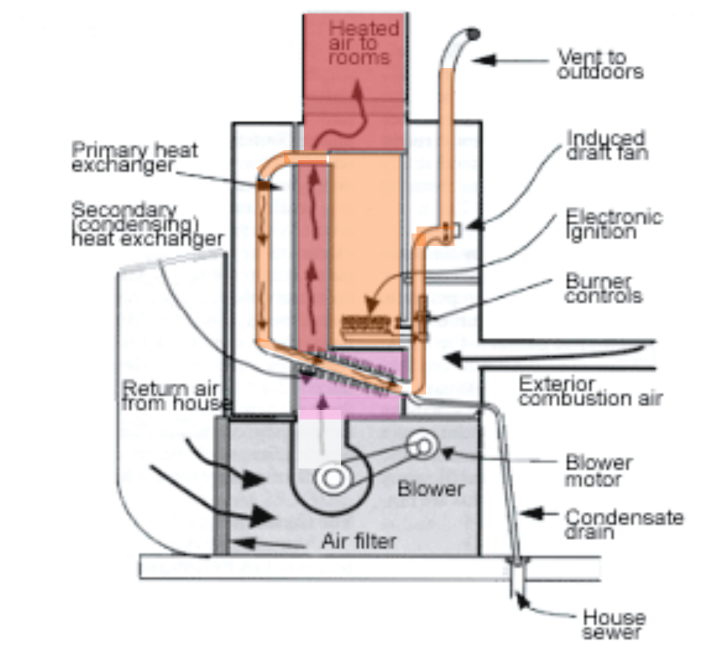
Adjacent to which, other house air passes, picking up some of this heat

Producing warm air to be returned to house = Pink (warm) / Red (warmer)

Non-condensing furnace:



Condensing furnace:



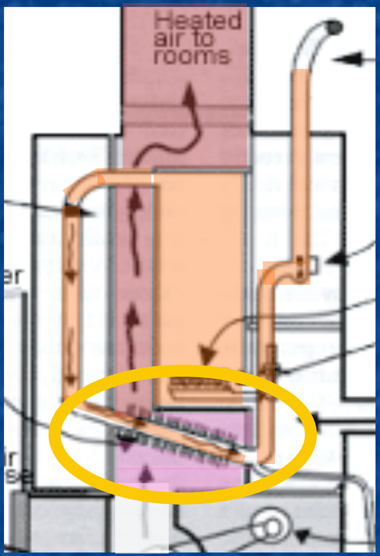
(colors added)

Original black and white figures from: http://www.r2000manitoba.com/heating_heat_dist6.shtml

But in condensing furnace, ***exhaust loops back*** *to pass by incoming air:*

That exhaust contains water vapor

Cooled by incoming house air, its water vapor **condenses** into liquid water



Water vapor then gives up its "heat of vaporization"

Which is partially absorbed by incoming house air

Pre-heating house air, before it passes burn chamber

This **also** cools the exhaust enough that a brick chimney is no longer required

It is replaced by small blower + PVC plastic pipe:

Elimination of chimney = Big cost reduction AND

PVC pipe allows furnaces to be placed in more efficient locations

But there is an even newer

and radically more efficient heating alternative!

Heat Pumps:

A LOOP of copper piping, with a very narrow segment at one point (capillary/valve)

Plus "heat exchanger" zig-zags inside house (left), and outside house (right)

Filled with "coolant" that normally boils at around room temperature

Purpose:

Pump pressurizes "coolant" gas entering house, causing it to condense into liquid

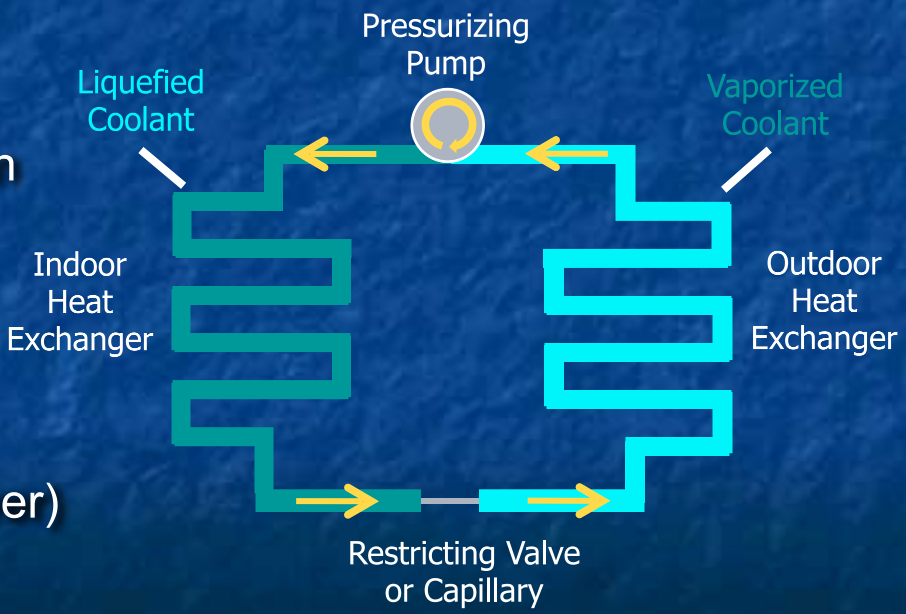
Losing heat TO inside air

Leaving house, liquid sprays thru restriction

Droplets **gain heat FROM outside air**

Converting coolant back to gas

(and process repeats over and over)



*But wait, doesn't that sound a lot like **Air Conditioners**:*

A LOOP of copper piping, with a very narrow segment at one point (capillary/valve)

Plus "heat exchanger" zig-zags inside house (left), and outside house (right)

Filled with "coolant" that normally boils at around room temperature

Purpose:

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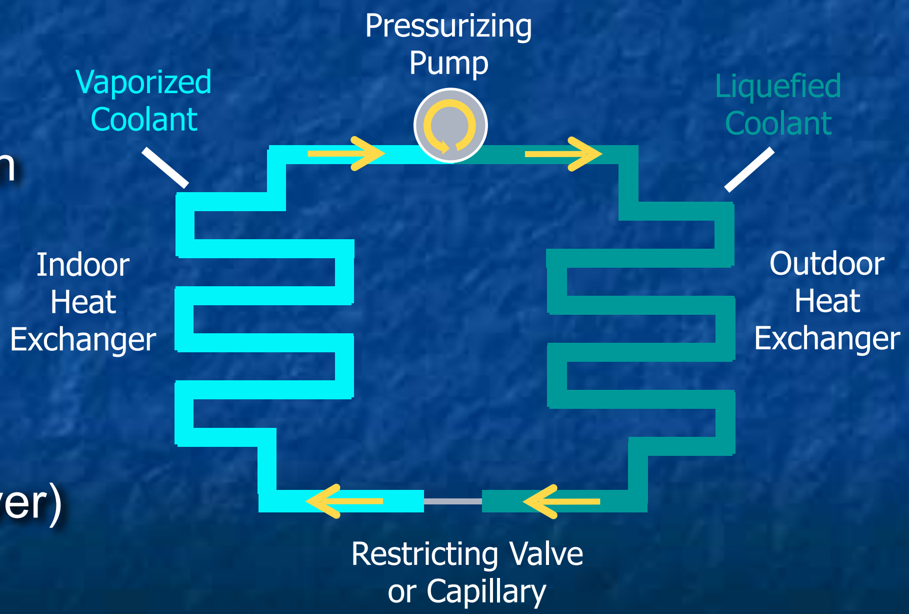


Yes, they are the same with just the pumping direction reversed!

"Killing two birds with one stone" by combining separate heating & cooling units

But it's even better when you look at the heating cycle:

A fuel-burning furnace produces 0.8-0.95 Watts of heated air per Watt of fuel energy

But a heat pump uses energy only in MOVING HEAT

That pump moves 3-4 Watts of heat per every 1 Watt it uses =>

80-95% furnace efficiency vs. **300-400% heat pump efficiency** [1,2]

Hold it! How can **anything** be 300-400% efficient?

Energy going into the pump is not <u>producing</u> the heat, it's just moving it

So think of a heat pump as a "heat transportation system"

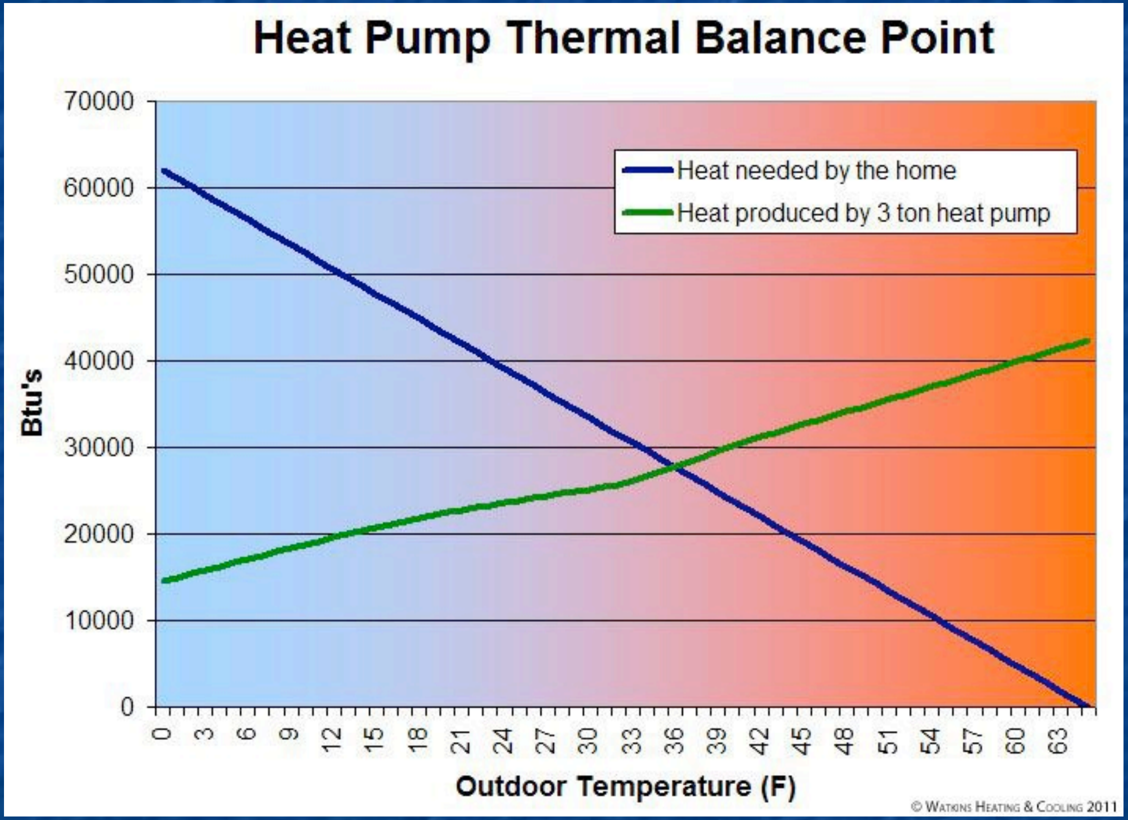
And, with optimized design, transportation systems can be quite efficient

1) http://energy.gov/energysaver/articles/tips-heat-pumps (no cached copy)   *2) https://en.wikipedia.org/wiki/Heat_pump*

Shortcomings?

Heat pump heating efficiencies fall as outside temperature decreases

Because it's harder to pick up heat from that colder outside air

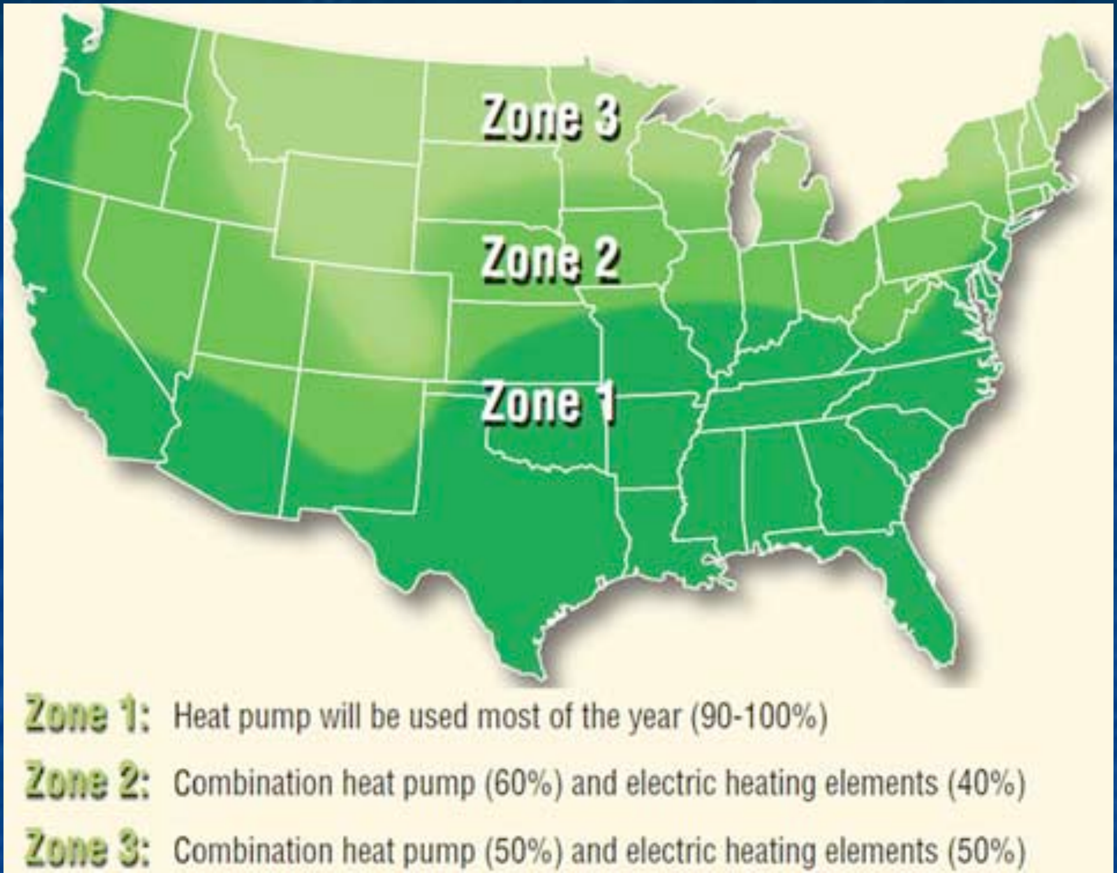


Note: Here a "ton" is antiquated U.S. way of rating heating/cooling capacities

Defined by cooling power once provided by melting 1 ton of ice

Figure: http://www.watkinsheating.com/blog/heat_pump_operation_102/

Leading to heat pump usage maps like this:



Zone 1: Heat pump will be used most of the year (90-100%)

Zone 2: Combination heat pump (60%) and electric heating elements (40%)

Zone 3: Combination heat pump (50%) and electric heating elements (50%)

Which recommended **adding** electric heating elements in colder climates

Despite low efficiency of those elements (due to 1/3 - 2/3 efficient power plants)

http://waterheatertimer.org/Review-GE-Heat-Pump-water-heater.html

But a more modern fix is to add back in a fuel burner

This produces what is called a **"hybrid" heat pump** in which:

For outside temperatures below ~ 45°F, heat pump shuts down

And fuel burner takes back over, continuing to heat the building

Remember: Fuel Burners are 80-95% efficient

My hybrid heat pump **also** has an **inside** heat exchanger that was

carefully optimized to condense out more water from humid summer air

This made that air **much** more comfortable

and led us to increase summer inside home temperatures by 2-3°F (~1.5°C)

When I replaced my Furnace + AC with a Hybrid heat pump:

My heating/cooling bills dropped by more than 1/3

A level of savings also cited on official / governmental websites

Other potential energy saving "big hitters?"

What about all of our appliances?

Which government figures say account for ~ 1/3 of residential power use?

Motors: They can be big energy users, but they are already highly efficient

So only alternative here is to settle for lower powered appliance motors

As Europe did in recent ban on high power vacuum cleaners

But most home motors are just not used enough to matter very much

"Vampire Chargers" as decried by UK politicians quoted in McKay textbook?

McKay: "It's NOT about every little thing, it's about every big thing!"

Chargers ARE now "little things" wasting very little power

Because, as explained in: **A Renewable Distributed Grid** (pptx / pdf / key):

Cool semiconductor AC/DC conversion circuits replaced hot transformers

Instead identifying heat-seeking targets based on my rant that:

"If it isn't producing (or moving) HEAT, don't worry about it!"

Eliminate hot incandescent light bulbs:

Wonder of wonders, the U.S. Congress has already banned them!

Buy "Euro" style front loading clothes washing machines:

Hold it! Earlier DOE data said these used only 400W, for short periods

Yes, but they are followed by dryers consuming 4000W, for longer

But to save water, those washers don't just drown clothes in volumes of rinse water

They add a little water, then spin like crazy to remove that water

As a result, clothes leave the washing machine MUCH less wet

Thus requiring ~½ the time in the energy hogging dryer!

In another of their almost useless, never more than one page long postings,

the U.S. Department of Energy cites a 70% energy savings for new washing machines.

But it's typically vague as to if this is for washers alone, or washers plus dryers [1]

[1] http://en.wikipedia.org/wiki/Induction_cooking

Continuing on our heat-seeking mission:

Induction cooktop ranges:

For normal gas ranges, hot air quickly passes by pots/pans, to be lost in the room

And the fraction of burner heat energy transferred TO the pots/pans is only ~ **44%** [1]

Induction ranges replace burners with embedded wire "coils"

Fed by pulsing electricity, these coils generate pulsed magnetic fields that excite electrical currents in nearby metals, thereby heating them

Energy transfer efficiencies thus approach **74%** (with manufacturers claiming up to **84%**)

But what about rings & watches (as carefully omitted in this marketing photo [2])

Won't their metal also be heated, burning hands & arms?

Most websites claim coils can **only** heat magnetic metals

Or, more specifically, iron or predominantly iron steels

RIGHT ANSWER BUT FOR THE WRONG REASONS!

1) http://en.wikipedia.org/wiki/Induction_cooking

2) https://www.appliancesonline.com.au/academy/wp-content/uploads/2012/10/Appliances-online-australia-induction-cooking-recipes1.jpg

*As explained in my note set about **Magnetic Induction** (pptx / pdf / key):*

Pulsed electricity flowing in an "induction coil" creates a pulsed magnetic field

- That field extends upward penetrating pots, pans (arms, rings & watches) above

But the **movement of magnetic fields** creates a force on electrons

- If those electrons are free to move (as they are in metals),
  - they will begin to flow back and forth (in time with the pulsing magnetic field)

This is the basis of both **electrical motors** and **transformers**,

- both of which get slightly warm as those moving electrons bump into things

Heating is reduced by use of "low resistance metals" in which bumps are less frequent

- Metals such as nearly pure and atomically-ordered gold, silver, copper or aluminum
  - (the sorts of metals we also favor in our jewelry)

But bumping (and heating) increase in less pure and more atomically-disordered metals

- Such as cast iron & steels, with are mixtures of iron, carbon, and other impurities
  - (making **them** the strongly-heating metals used in inductively-heated cookware)

Less dramatic, but nevertheless high impact ways of saving home energy:

Incrementally improved but particularly high use/energy appliances:

For instance, **Water heaters**, **refrigerators**, and **air conditioners**

As improved via better burners, insulation, coolant cycles, etc.

These are used so heavily (most of them almost constantly) that result is:

Water heaters alone now account for ~ 18% of our U.S. residential power

Air Conditioner's topped my estimated household energy list at 7 kW-h/day

Followed by clothes dryers (which I've already discussed above)

And below that, refrigerators at 1.75 kW-h/day

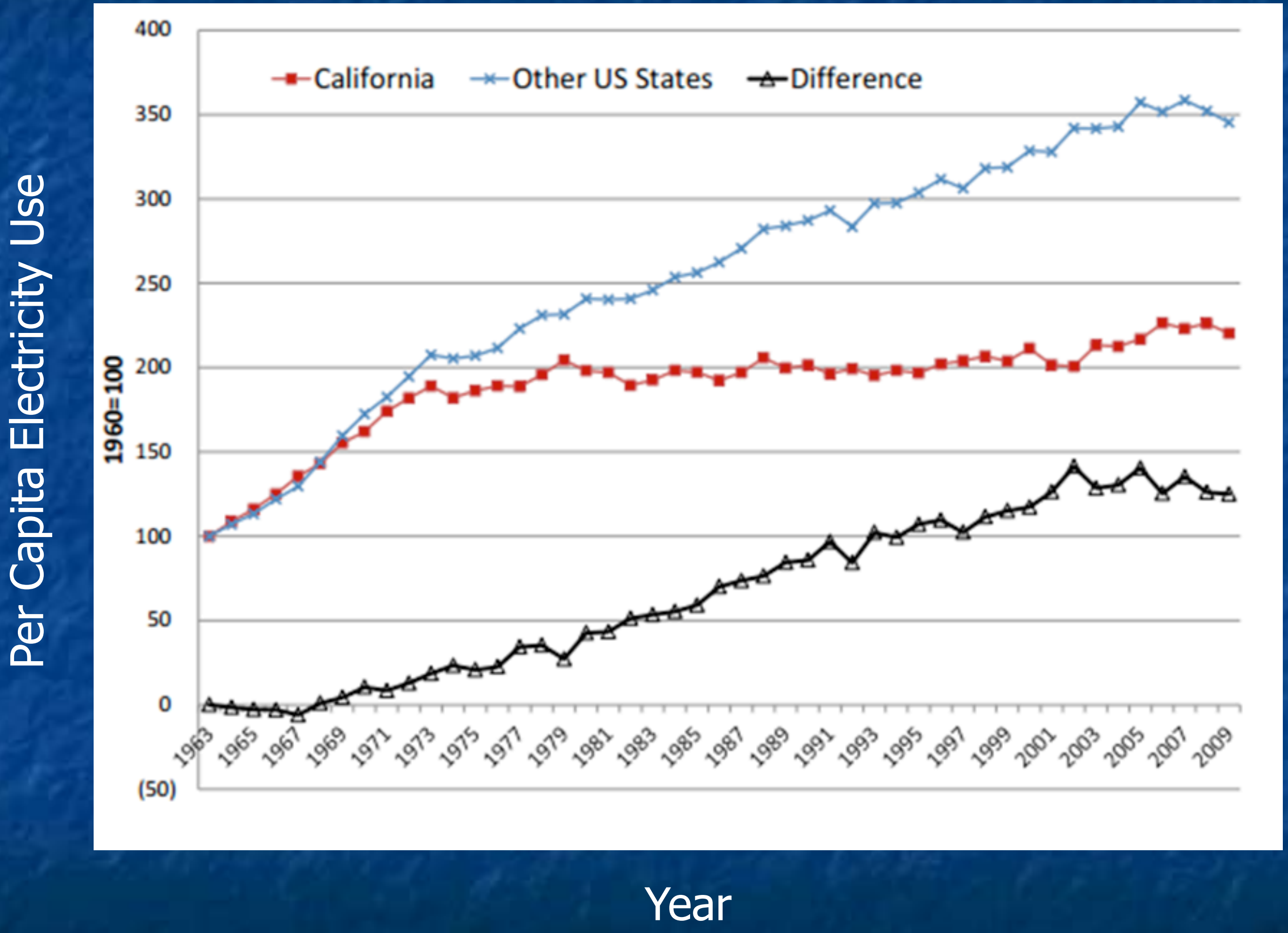
Dramatic energy and money savings can thus be achieved by replacing an old unit

with a newer "Energy Star" design that is only 10-20% more efficient

1) http://en.wikipedia.org/wiki/Induction_cooking

Figuring out appliance by appliance savings impact is difficult

But here is what California has achieved with incentives / regulations:



http://berc.berkeley.edu/californias-classic-chart-really-caused-energy-savings/ (no cached copy)

Federal government has also gotten into appliance improvement:

In the form of "Energy Star" labeling

Telling you how many $ you can save by buying a better appliance

AND in **new homes** builder's are required retain such labeling

So READ (and pay serious attention to) THESE LABELS!

However, did YOU know washing machine choice could save big dryer expense?

That still came as a surprise to me!

Suggesting HUGE energy saving opportunities via public education

Knock, knock, knock: U.S. Department of Energy, wake up (damn it)!

Even more could be done via state-mandated home building codes

Because:

1) We consumers seldom know enough to make such home construction decisions

Didn't parts of my long home-owning experience surprise you?

2) OR we lack the leverage over builder's choices to ensure that they choose well

Builder's often ignore single purchaser's requests or overcharge for them!

So despite prevailing anti-big-government / don't tread-on-me sentiments

I strongly suggest following the lead of states such as California:

Incorporating more energy saving requirements into **home** building codes

We could also require landlords to separately bill for an **apartment**'s energy use

Also requiring them to divulge recent charges to be would-be renters

Which would incentivize construction of energy-efficient apartments

Independent of saving energy, what about saving the planet?

For even the SAME energy use,

we could significantly reduce our CARBON FOOTPRINT

by shifting energy usage AWAY from peak evening hours

HOW/WHY?

Evening "peak power" requires special "peaking power plants"

Which, because they only produce power for a couple of hours a day,

must be both very fast-starting and very cheap ("low capital cost")

Today that means that they likely burn natural gas, and do so in the dirtiest way:

Via lower efficiency single cycle gas turbines ("OCGT")

See: **Generic Power Plant & Grid** (pptx / pdf / key) & **Fossil Fuels** (pptx / pdf / key)

Motivating & Facilitating such a Shift in Energy Consumption:

MOTIVATION can be provided just by forcing us to pay more for evening power

Which IS in fact considerably more expensive for power plants to produce

FACILITATION is commonly suggested via either:

1) Using **Smart Appliances** + **Internet of Things**

to **INFORM** us of costly evening power use (hopefully leading us to curtail it!)

OR:

2) Using **Smart Grid** + **Internet of Things**

to give **power companies** the ability to **CONTROL** our evening power use

But these raise serious efficacy, security, and privacy concerns

Leading me, in **Smart Grid** (pptx / pdf / key) notes, to make some alternative suggestions

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This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.