Residential Energy Use
Topics

- Energy use categories
- Winter heat loss
- Summer heat gain
- Annual heating and cooling costs
- Home energy systems
- Innovations in residential energy conservation
Home Energy Use Categories

- Space heating
- Hot water heating
- Air conditioning
- Lighting
- Electric appliances
  - cooking, laundry, refrigeration, other
- Gas appliances
Winter Heat Loss

- Heat loss, $q$, is proportional to $\Delta T$—the relevant $\Delta T$ is $T_{od} - T_i$.
- For analysis purposes, inside the home is a *thermodynamic system* (control volume) called the *conditioned space*, and outside air and earth are the *surroundings*.
- The system boundary of a building is called the building *envelope*.
- A home’s envelope consists of four parts: floor, ceiling/attic combo, walls and doors/windows.
Heat Loss Modes

- Typically, the home loses heat by convection from inside air at $T_i$ to envelope, conduction through envelope, and convection from outer envelope surface to outside air at $T_{od}$.
- Some envelope components are more complicated, such as the ceiling/roof, which has a ceiling, attic air at a temperature different from outdoors, and a roof.
- Two other heat loss routes are *infiltration* and *duct losses*. 
Infiltration

- Infiltration is the term applied to the unwanted influx of outside air through various leakage areas in the envelope.
- Infiltration introduces cold, dry air in the winter and hot, humid air in the summer.
- Typical infiltration sites are gaps between floor, walls, and ceilings, window and door frames, switch and light fixture penetrations, pipe and duct penetrations, fireplaces, exhaust fans, etc.
Duct Losses

- Ducts that carry air to and from the furnace/air conditioner air handler are subject to both leakage losses and conduction losses.
- Ducts are often located in attics or crawlspaces where the air is colder than the indoor air.
- Duct loss can be greatly reduced through proper insulation and sealing (using mastic or top quality tape).
- Duct loss can be eliminated by locating ducts in the conditioned space.
Recall that heat transfer $q$ through a wall having several resistances is calculated as:

$$q = \frac{\Delta T}{\Sigma R_{th}}$$

- Conduction $R_{th} = \frac{\Delta x}{kA}$
- Convection $R_{th} = \frac{1}{hA}$
- For buildings, usually:
  $$R_{\text{conduc}} \gg R_{\text{convec}}$$
R-Value

- Building energy calculations are based on R-value rather than $R_{th}$.
- R-Value (called “R” from here on) is defined as:
  \[
  R\text{-value} = R = \frac{\Delta x}{k} = A \times R_{th}
  \]
- Conduction(257,488),(799,705) through a wall of area $A$ built of several layers of materials is:
  \[
  q = A \times \frac{\Delta T}{\sum R}
  \]
- R-value for a given envelope component (insulation, window, etc.) doesn’t depend on $A$.
- Units of $R$ are: hr-ft$^2$-F/Btu
Heat Transfer (Cont’d)

- Heat transfer $q$ is calculated for each conductive element by considering its $R$ and surface area $A$.
- $R$-values are summed for built-up series resistances (e.g., wall has sheet rock, $R = 0.5$, + fiberglass insulation, $R = 11$, + R-3 bead-board, + brick, $R = 1$, for a total $R = 15.5$ wall).
- Convection resistances (small) are usually ignored-causes slight overestimation of $q$.
- Roof/ceiling combo has a total effective $R$.
- Floor (slab, crawlspace, or basement) requires special treatment.
Heat Transfer (Cont’d)

- Duct losses include a conduction loss that requires a duct R-value plus an estimation of the duct surroundings temperature.
- Duct loss also includes an estimate of leakage loss (accurate calculation very difficult without duct blower test).
- Infiltration loss incorporates an estimation of infiltration area (total), which is used to estimate an infiltration cfm, then a total heat loss taking $T_{od}$ into account. A blower door test can be used to actually measure infiltration.
Example

**Given:** A wall consists of 200 ft² of wall with 4 inches of material with $k = 0.04 \text{ W/m°C}$ and 50 ft² of windows having an R-4 rating. $T_i = 70°\text{F}$ and $T_{od} = 35°\text{ F}$.

**Find:** the rate of heat loss through the wall.

**Sol’n:** First find R-value of material:

$$R = \frac{\Delta x}{k} = \frac{4 \text{ in} \times \frac{1 \text{ ft}}{12 \text{ in}}}{0.04 \frac{\text{W}}{\text{m}°\text{C}}} \times 0.578 \frac{\text{hr} \cdot \text{ft}^2 \cdot °\text{F}}{\text{Btu}}$$

$$= 14.4 \frac{\text{hr} \cdot \text{ft}^2 \cdot °\text{F}}{\text{Btu}} = R 14.4$$
Next, use \( q = A \times \Delta T/R \):

\[
q_{\text{wall}} = \frac{[200 \text{ ft}^2 \times (70 - 35) \, ^\circ\text{F}]}{14.4 \text{ hr-ft}^2{^\circ}\text{F/Btu}}
= 486 \text{ Btu/hr}
\]

\[
q_{\text{window}} = \frac{[50 \times (70 - 35)]}{4} = 438 \text{ Btu/hr}
\]

\[ q = 486 + 438 = 924 \text{ Btu/hr} \]
Sizing of Heating and Cooling Equipment

- To size heating equipment, use heat loss for near worst case weather conditions.
- Usually use the **97.5% design condition** - for heating, the actual outside temperature is lower than the design temperature only 2.5% of the hours during December, January and February.
- The thermal mass of a house will "flywheel" it through temporarily worse conditions.
- If building is very light, e.g. a mobile home, use 99% design condition.
## Design Temperatures and Summer Daily Range (°F)

<table>
<thead>
<tr>
<th>City</th>
<th>Winter 99%</th>
<th>Winter 97.5%</th>
<th>Summer DB</th>
<th>Summer WB</th>
<th>Summer DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston</td>
<td>6</td>
<td>9</td>
<td>88</td>
<td>71</td>
<td>16</td>
</tr>
<tr>
<td>Denver</td>
<td>-5</td>
<td>1</td>
<td>91</td>
<td>59</td>
<td>30</td>
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<tr>
<td>Houston</td>
<td>28</td>
<td>33</td>
<td>95</td>
<td>77</td>
<td>18</td>
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<tr>
<td>San Fran.</td>
<td>35</td>
<td>38</td>
<td>77</td>
<td>63</td>
<td>20</td>
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<td>St. Paul, MN</td>
<td>-16</td>
<td>-12</td>
<td>89</td>
<td>73</td>
<td>22</td>
</tr>
<tr>
<td>Tucson, AZ</td>
<td>28</td>
<td>32</td>
<td>10</td>
<td>66</td>
<td>26</td>
</tr>
<tr>
<td>Tuscaloosa</td>
<td>20</td>
<td>23</td>
<td>96</td>
<td>76</td>
<td>22</td>
</tr>
</tbody>
</table>
Summer Heat Gain

- Heating uses more energy except sub-tropical or warmer climates (So. Fla., So. Texas, So. Cal., Hawaii), but use of energy for air conditioning is certainly very significant.
- Much of cooling load comes from solar thermal radiation, so orientation, color or absorptivity, and shading of house becomes important.
- The summer heat gain, or cooling load, has two components: latent load and sensible load.
Sensible Cooling Load

- Sensible load refers to cooling air over some $\Delta T$, so $q$ is proportional to $m \times cp \times \Delta T$.
- Sensible load arises from heat gain through envelope, solar gain, lights, cooking, TV's, people, etc.
Latent Cooling Load

- Latent load refers to the need to dehumidify moist air for comfort by condensation and removal of water vapor
- Latent $q$ is proportional to $m_{\text{cond}} \times h_{f_g}$
- Latent load arises from occupant breathing and perspiring, intake of humid outside air, bathing, dish and clothes washing, cooking, etc.
To size cooling equipment, need to find both latent and sensible loads.

The latent load has a strong geographic dependence on summer wet bulb temperature (review table).

We can simplify calculation of total cooling load by calculating sensible load then using a rule of thumb with regional climate to get latent and total load.
Sensible Heat Factor

- The ratio of the sensible load to the total cooling load is the sensible heat factor (SHF).
- The approximate SHF as a function of climate is:

<table>
<thead>
<tr>
<th>Climate</th>
<th>Range</th>
<th>SHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humid</td>
<td>$T_{wb} &gt; 73$</td>
<td>0.7</td>
</tr>
<tr>
<td>Moderate</td>
<td>$67 &lt; T_{wb} &lt; 73$</td>
<td>0.75</td>
</tr>
<tr>
<td>Dry</td>
<td>$T_{wb} &lt; 67$</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Transmission Gains

- Gains of sensible heat through building envelope are called *transmission gains*, which differ from latent gains and internal sensible gains.

- Transmission gains are affected by solar insolation (flux), which have the effect of heating the outer surface of the envelope to a higher $T$ than outside air temperature, $T_{od}$. 
Gains Through Non-Transmitting Envelope

- For all but windows, the design equivalent temperature difference (DETD) method uses a higher $\Delta T$ than $T_{od} - T_i$ to account for solar gain.
- The design equivalent temperature is calculated for various non-window portions of the envelope.
- Then heat gain $q$ is calculated as:
  $$q = A \times \text{DETD}/R$$
Gains Through Windows

- Heat gain by both conduction and radiation.
- An effective heat flux \( q/A \), called cooling load factor (CLF), is found for each window, then:
  \[
  q = A_w \times CLF
  \]
- CLF depends on design \( T_{od} \), window shades, blinds, etc., direction which the window faces, and shading.
- Shading depends on tinting or actual shading (trees, etc.) of window.
Heat Gains in Ductwork

- Method is similar to finding heat loss in winter, except must account for attics being hotter and crawl spaces being cooler than outdoors.
- Use modified equations to calculate attic and crawlspace temperatures.
- Use empirical relationships to get DETD, then:
  \[ q = A \times \frac{DETD}{R} \]
- \( R \) is the equivalent R-value for the roof/ceiling combination or the crawlspace.
Infiltration Gains

- Sensible heat gain by infiltration is calculated for summer just as for winter.
- Infiltration losses are usually smaller in summer than winter because average wind speeds and average $\Delta T$s are smaller in summer.
Internal Sensible Gains

- Internal sensible gains result from sensible heat sources, e.g., people, appliances and lighting.
- Some typical values (averaged over a 24-hour period), in Btu/hr are (multiply by 0.293 for W):
  - People (avg. activity)……. 225 Btu/hr/person
  - Refrigerator (w/ freezer)……. 650 Btu/hr
  - Range (electric/gas)…….. 270 - 470/500 - 1100
  - Television…………………………..150 - 180
  - Dryer (electric/gas)…….. 370 - 500/500 - 800
  - Lighting- 3.4 × avg watts or... 400 - 800
Total Heat Gain (Cooling Load)

- Sum all sensible gains (transmission, window, duct, infiltration and internal sensible gains) to get total sensible heat gain, $q_s$. Heat gain is determined for the summer design condition.
- Total heat gain (cooling load) is $q_c = q_s / \text{SHF}$.
- The winter heat loss and summer cooling load (both for the design condition) can be tabulated by category to identify major energy use areas.
- Unusually large components should be the first target for energy conservation improvements.
Annual Heating and Cooling Costs

- The design heating load (an instantaneous rate) is used with the *heating degree days* to find the annual heating energy requirement.
- The annual heating energy requirement, along with heating system efficiency, fuel type, and fuel cost, determines the annual heating bill.
- The cooling costs are computed the same way using the design cooling load and the *cooling degree days*. 
Degree Days

- Degree Days (DD) represent the area between the $T_i$ and $T_{od}$ curves in units of degrees × days.
- DD × 24 hr/day × Btu/hr·°F for the house gives the total Btu of heating or cooling energy required.

Area represents Heating Degree Days

°F

65

$T_{od}$
## Typical Degree Days

<table>
<thead>
<tr>
<th>City</th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wind DDC</td>
<td>70</td>
</tr>
<tr>
<td>Boston</td>
<td>11.8</td>
<td>5593</td>
</tr>
<tr>
<td>Denver</td>
<td>7.5</td>
<td>6014</td>
</tr>
<tr>
<td>Houston</td>
<td>10.0</td>
<td>1549</td>
</tr>
<tr>
<td>San Fran.</td>
<td>10.5</td>
<td>3161</td>
</tr>
<tr>
<td>St. Paul, MN</td>
<td>11.2</td>
<td>8007</td>
</tr>
<tr>
<td>Tucson, AZ</td>
<td>---</td>
<td>1960</td>
</tr>
<tr>
<td>Tuscaloosa</td>
<td>9.8</td>
<td>2685</td>
</tr>
</tbody>
</table>
Estimating Heating Energy Use with Degree Days

The quantity of heating “fuel” required is about:

\[ F = \frac{24 \cdot DD \cdot q_h \cdot C_D}{\eta \cdot (T_i - T_{od}) \cdot HV} \]

where:

- DD is the number of heating Degree Days
- \( q_h \) is the design heating load in Btu/hr
- \( C_D \) is an adjustment constant (see next slide)
- \( \eta \) is heating unit efficiency; use AFUE for gas, HSPF for a heat pump and \( \eta = 1 \) for strip electric
- HV is fuel heating value in Btu per unit of fuel
Calculating Correction Factor

- The value of $C_D$ for the annual heating energy equation is taken from the plot below:
Annual Cooling Energy

The annual air conditioner energy requirement is:

\[ kWh = \frac{24 \cdot DD \cdot q_c}{SEER \cdot (T_{od} - T_i) \cdot 1000} \]

where:

- **DD** is degree days of cooling
- **Q_c** is design cooling load in Btu/hr
- **SEER** is corrected ARI rating of appliance

To use the above equation, the correct DD value should be used, as explained on the next slide.
Cooling Degree Day Correction

- Select DD from the previous table by interpolating based on $T_b$, obtained as:
  - $T_b = T_i - \frac{q_{ig}}{UA}$, where $UA = \frac{q_s}{(T_{od} - T_i)}$
  - $q_{ig}$ is the sum of the internal gains in Btu/hr
  - Interpolate for DD using $T_b$ in the previous DD table
Climate Affects Efficiency

- The climate in which air conditioners and heat pumps operate affects their efficiency.
- Heat pumps and air conditioners are rated by the American Refrigeration Institute (ARI).
- ARI divides country into 6 regions. Standard ratings are based on Region IV, including NYC, Indianapolis and Salt Lake City.
- Hotter climates have higher heating ratings and lower cooling ratings.
- Tuscaloosa (on Region II/III border):
  \[ \text{HSPF} \approx \text{ARI} + 0.6 \quad \text{SEER} \approx \text{ARI} - 0.6 \]
Residential HVAC Equipment

- We will look at typical heating and cooling equipment used in U.S. homes, concentrating on equipment typical of the Southeast.
Cooling/Dehumidification

- Evaporative cooler- "desert or swamp cooler."
- Works on adiabatic saturation principal-water/air can be cooled to near the wet bulb temperature.
- Effective in very dry climates, certainly ineffective as primary A/C in Southeast.
Evaporative Cooler

1. Control for air volume
2. Switches
3. Blower pulley (quiet action)
4. Motor
5. Weather resistant exterior finish
6. Supports
7. Water pump, plastic impeller
8. Bolts
9. Snap-shut type pad frames
10. Blower mount support
11. Blower wheel
12. Even-drip water trough
13. Bronze bearings
14. Blower shaft
Air Conditioner

- Operates on thermodynamic refrigeration cycle between cool inside and warm outside. All air conditioners both cool and dehumidify. Types:
  - "Window" unit- Typically 1 Ton or lower, window mounted so inside air circulates over evaporator and outside air circulates over condenser.
  - **Advantages**: Inexpensive, no ductwork, provides A/C for short cooling seasons w/ low first cost.
  - **Disadvantages**: Low SEER, single point air distribution only cool one room well, UGLY, NOISY.
Central Air Conditioning

- Evaporator is inside air handler, air-cooled condenser and compressor located in outdoor unit.

- **Advantages** - Has better efficiency (SEER) and improved comfort compared to window units. Integrates well with forced-air gas or oil-fired furnace (same air handler and ductwork used).

- **Disadvantages** - High first cost, needs ductwork.

- Various efficiencies available (at a price). Note that some “high efficiency” units have low latent capacity. Multiple speed units now appearing.
Central A/C (This is really a commercial unit)
Heat Pump

- Air-to-air heat pump- essentially identical to central A/C in the cooling mode.
- Evaporator becomes condenser and vice versa when reversing valve switches.
Water-Source Heat Pump

- Condenser is cooled by water from a well or lake.

**Advantages** - Groundwater is nearly at a constant year-round temperature (65°F in Tuscaloosa) and is typically cooler than outside air in summer and warmer in winter. SEER can be significantly higher than air-to-air. No need for condenser to be outside (but not in your attic!).

**Disadvantages** - Need water source, possible fouling, difficult to find information, few qualified installers in many areas, higher first cost.
Water-Source Heat Pump

- Blower
- Air/Refrigerant Coil
- Refrigerant Reversing Valve
- Expansion Valve
- Heat Exchanger Coil
- Air/Water HX
- Discharge Well or Sprinkler
- Compressor
- Supply Well
- Expansion Valve
Ground Source Heat Pump

- Condenser is cooled by water that circulates through ground in plastic piping.

  **Advantages**- Uses ground (warmer in winter, cooler in summer) as heat sink/source, no water quality problems, high SEER (though SEER of water source is potentially higher), condenser is indoors (more attractive).

  **Disadvantages**- Few qualified installers, must have driller install ground couplings (in the more efficient vertical installations), higher first cost, burdensome regulations in some states.
Heating Equipment

- **Wood-burning equipment** - Certainly the oldest technology. A variety of relatively efficient stoves and fireplace inserts are available.

- **Advantages** - Cheap if wood available at very low cost (like free). Aesthetically pleasing.

- **Disadvantages** - Normally must hand load fuel, wood burning generates significant pollution-banned in some areas. Open market firewood is an expensive source of energy compared to fossil fuels, etc.
Large, Open Fireplace

Efficiency: Poor - about 10%
Wood Stove

In best wood stoves, combustion air is taken from outside through a controlled damper, stove is sealed with gaskets, and a catalytic converter is used.

**Efficiency**: Moderate- from 20% to 50%
Boilers/Hydronic Heating

- Popular in colder climates.
- Typically gas or oil fired (occasionally coal-stoker).
- Heating is done by a boiler.
- Hot water is circulated through radiators, baseboard convectors or through floor piping.
- Good AFUE but high first cost—does not pay in Southeast.
Floor Hydronic Heating
Combined Systems

- Oversized hot water heater supplies domestic hot water, plus supplies coil in air handler for central heating. Applicable to SE conditions used in combination with central A/C.

- Advantages - Need not purchase natural gas furnace - hot water heater serves double duty, yielding low first cost and AFUE similar to gas furnace. Hot water heater lasts longer because of more circulation (reduces bottom sediment).

- Disadvantage - Possible water leaks in attic.
Gas- or Oil-Fired Furnace

- Air passed through air handler’s heat exchanger is heated by oil or gas flame and sent to ducts.
- Along with heat pump, most common heating method in SE. Combines well with central A/C.
- AFUE varies from 65 to 95%.
- High AFUE units capture heat by condensing exhaust H₂O. They are presently expensive and probably not justified in the SE, but do have advantage of being able to vent low temperature exhaust laterally through wall in plastic pipe.
Gas-Fired Furnace in Air Handler
Heat Pumps

- Same types as discussed in cooling section.
- Air-to-air heat pumps have relatively cool supply air temperature compared to gas furnace or water/ground source heat pump.
Baseboard Electric

- Uses electric resistance heating units mounted on wall near floor.

- **Advantages**- Very low first cost, clean, dependable operation, very low maintenance, controls temperature of individual rooms independently, is good option for heating in very mild climates (in conjunction with central A/C)

- **Disadvantages**- COP = 1 (SEER = 3.4), very low energy efficiency. Slight safety hazard with exposed warm surfaces.
Residential Calculator Example

Ceilings are 8-ft high. Brick veneer walls, 1-in Styrofoam sheathing, $2 \times 4$ stud wall with R-13 fiberglass insulation, $\frac{1}{2}$-in gypsum board walls. Slab foundation. Two 20 sq ft insulated metal doors N and S sides. Double pane vinyl windows with Venetian blinds. Five 250 Btuh occupants, 1500 Btuh kitchen load, and 350 W other internal load. Ducts are R-4 and located in the attic with >120 F supply temperature.

Window areas:
- N – 80 sq ft
- E – 40 sq ft
- S – 50 sq ft
- W – 20 sq ft

Age: 10 yr old
Elev: 180 ft
Location: Tuscaloosa