Cities & buildings & energy efficiency
MIT 11.165/477, 11.286J

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Urban Studies & Planning
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Materials for class discussion

- Maximilian Auffhammer. Consuming Energy While Black, June 2020. URL.
We shape buildings, and afterwards our buildings shape us.

– Winston Churchill
Buildings

1. operational energy:
   - 35% of primary energy, 38% of GHG emissions worldwide (UN, 2020)
Buildings

operational energy:

- 35% of primary energy, 38% of GHG emissions worldwide (UN, 2020)
  - far higher percentage of city building emissions
  - (NY 70%, in contrast to Singapore 20%)
Buildings

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   - people spend 87% of their lives indoors and 6% in enclosed vehicles (LBNL, 2001)
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4. Mackay: how much it takes to heat, cool and use various appliances
   - how much energy is used in buildings?
   - how much more efficient can buildings be?
   - what specific activities in buildings lead to energy use (and waste)?
   - how can we motivate individual users to save energy in buildings?
Sankey diagrams for the US and every state at [flowcharts.LLNL.gov](http://flowcharts.LLNL.gov)

Public domain figure courtesy of LLNL / US Department of Energy.
Figure 3: Retail Sales of Electricity to Ultimate Customers, Total by End-Use Sector (2010)

- **Transportation**: 0.2%
- **Industrial**: 25.9%
- **Residential**: 38.5%
- **Commercial**: 35.4%


http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_01

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Public domain image courtesy of the US Department of Energy.
Public domain image courtesy of the US Department of Energy.

Pacific Northwest National Lab, 2006
Public domain image courtesy of the US Department of Energy.
All numbers in quads (0.9478 quad = EJ)
Total US economy in 2020 uses 100.8 quads;
100% RE economy in 2050 uses 72.8 quads

<table>
<thead>
<tr>
<th>Buildings (residential + commercial)</th>
<th>WILLIAMS ET AL 2020</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2020</td>
</tr>
<tr>
<td>Reference</td>
<td>2020</td>
</tr>
<tr>
<td>Renewable</td>
<td>2020</td>
</tr>
<tr>
<td>Primary energy supply</td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>20.2</td>
</tr>
<tr>
<td>Pipeline natural gas</td>
<td>9.5</td>
</tr>
<tr>
<td>Biomass conversion</td>
<td>1.6</td>
</tr>
<tr>
<td>TOTAL PRIMARY ENERGY</td>
<td>31.3</td>
</tr>
<tr>
<td>Final demand (use)</td>
<td></td>
</tr>
<tr>
<td>Implied losses</td>
<td>-36%</td>
</tr>
<tr>
<td>Gain in efficiency</td>
<td></td>
</tr>
</tbody>
</table>
Heat transfer → heating loss and load

Three ways to gain and lose heat from house to the environment:

- ventilation (conduction, infiltration): air moving in and out (drafts)
Heat transfer → heating loss and load

Three ways to gain and lose heat from house to the environment:

- ventilation (conduction, infiltration): air moving in and out (drafts)
- conduction: heat transfers out, i.e. molecules excite neighbors, etc. (through external walls, ground slab)
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Three ways to gain and lose heat from house to the environment:

- ventilation (conduction, infiltration): air moving in and out (drafts)
- conduction: heat transfers out, i.e. molecules excite neighbors, etc. (through external walls, ground slab)
- radiation: generated and absorbed photons (transmission through windows; absorption to roofs)

Check out NIST paper for a detailed breakdown.
Heat transfer → heating loss and load

Conduction and ventilation depend on temperature difference between inside and outside $\Delta T$, while radiation depends on area:

Energy loss:

\[
\text{conduction} = \text{area} \times U \times (\Delta T \times \text{time})
\]  \hspace{1cm} (1)

\[
\text{ventilation} = \text{volume} \times N \times (\Delta T \times \text{time})
\]  \hspace{1cm} (2)

\[
\text{radiation} = \text{area} \times \text{solar intensity}
\]  \hspace{1cm} (3)
Table E.8. Breakdown of my house’s conductive leakiness, and its ventilation leakiness, pre-2006. I’ve treated the central wall of the semi-detached house as a perfect insulating wall, but this may be wrong if the gap between the adjacent houses is actually well-ventilated.

I’ve highlighted the parameters that I altered after 2006, in modifications to be described shortly.

<table>
<thead>
<tr>
<th>Conductive Leakiness</th>
<th>area (m²)</th>
<th>U-value (W/m²/°C)</th>
<th>leakiness (W/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal surfaces</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pitched roof</td>
<td>48</td>
<td>0.6</td>
<td>28.8</td>
</tr>
<tr>
<td>Flat roof</td>
<td>1.6</td>
<td>3</td>
<td>4.8</td>
</tr>
<tr>
<td>Floor</td>
<td>50</td>
<td>0.8</td>
<td>40</td>
</tr>
<tr>
<td>Vertical surfaces</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extension walls</td>
<td>24.1</td>
<td>0.6</td>
<td>14.5</td>
</tr>
<tr>
<td>Main walls</td>
<td>50</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>Thin wall (5in)</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Single-glazed doors and windows</td>
<td>7.35</td>
<td>5</td>
<td>36.7</td>
</tr>
<tr>
<td>Double-glazed windows</td>
<td>17.8</td>
<td>2.9</td>
<td>51.6</td>
</tr>
<tr>
<td>Total conductive leakiness</td>
<td></td>
<td></td>
<td>232.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ventilation Leakiness</th>
<th>volume (m³)</th>
<th>N (air-changes per hour)</th>
<th>leakiness (W/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedrooms</td>
<td>80</td>
<td>0.5</td>
<td>13.3</td>
</tr>
<tr>
<td>Kitchen</td>
<td>36</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>Hall</td>
<td>27</td>
<td>3</td>
<td>27</td>
</tr>
<tr>
<td>Other rooms</td>
<td>77</td>
<td>1</td>
<td>25.7</td>
</tr>
<tr>
<td>Total ventilation leakiness</td>
<td></td>
<td></td>
<td>90</td>
</tr>
</tbody>
</table>

Table courtesy of David MacKay.
David Mackay’s house in Cambridge (UK)

“Main ways to lose heat energy are conduction and ventilation”:

\[
\text{conduction} = 232 \text{W/°C} = 78% \\
\text{ventilation} = 90 \text{W/°C} = 22% 
\]
David Mackay’s house in Cambridge (UK)

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\[
\text{conduction} = 232 \text{W/}^\circ \text{C} = 78\%
\]
\[
\text{ventilation} = 90 \text{W/}^\circ \text{C} = 22\%
\]

- added cavity wall insulation
- increased roof insulation
- added new storm door
- replaced back door and window with double-glazed
Public domain image courtesy of the US Department of Energy.

Advanced glazings have increased windows’ resistance to heat flow, or R-value.

Note: Energy loss/gain includes conductive and convective thermal losses, solar gains, and the effects of window emittance and lighting load reductions.
Table 2. Summary of R-values utilized in the model building based on what the two IECC codes require as well as what has been modeled using aerogel insulation on the above ground exterior walls of the model home.

<table>
<thead>
<tr>
<th>Material</th>
<th>IECC 2000, m²K/W (F-ft²-hr/Btu)</th>
<th>IECC 2012, m²K/W (F-ft²-hr/Btu)</th>
<th>Proposed, m²K/W (F-ft²-hr/Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling</td>
<td>6.7 (38)</td>
<td>8.6 (49)</td>
<td>12.8 (73)</td>
</tr>
<tr>
<td>Above ground walls</td>
<td>3.2 (18)</td>
<td>3.5 (20)</td>
<td>12.8 (73)</td>
</tr>
<tr>
<td>Basement walls</td>
<td>1.8 (10)</td>
<td>2.6 (15)</td>
<td>2.6 (15)</td>
</tr>
<tr>
<td>Floors</td>
<td>3.7 (21)</td>
<td>5.3 (30)</td>
<td>5.3 (30)</td>
</tr>
<tr>
<td>Roofs</td>
<td>6.7 (38)</td>
<td>8.6 (49)</td>
<td>12.8 (73)</td>
</tr>
<tr>
<td>Mass walls</td>
<td>NA</td>
<td>2.6 (15)</td>
<td>2.6 (15)</td>
</tr>
</tbody>
</table>

Heating degree days (Mackay, appendix E)

(a) 3188 degree-days of heating

(b) 2265 degree-days of heating

Courtesy of David MacKay.
Heat pumps (Randolph and Masters)

You could remove your refrigerator door, back the refrigerator up to an outside doorway, and then use it as a heat pump to heat or cool your house.

Refrigerator as an air conditioner ... and heat the world.
Refrigerator as heater ... and cool the world.

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U.S. climate zones

http://www.eia.gov/consumption/commercial/maps.cfm

Public domain image courtesy of the U.S. Energy Information Administration.
U.S. climate zones

Climate Zones

- Zone 1 is less than 2,000 CDD and greater than 7,000 HDD.
- Zone 2 is less than 2,000 CDD and 5,500-7,000 HDD.
- Zone 3 is less than 2,000 CDD and 4,000-5,499 HDD.
- Zone 4 is less than 2,000 CDD and less than 4,000 HDD.
- Zone 5 is 2,000 CDD or more and less than 4,000 HDD.

Public domain image courtesy of the U.S. Energy Information Administration.
## ESTIMATING LOAD FROM SELECTED APPLIANCES

Mackay, page 51:

2 people per household in England

<table>
<thead>
<tr>
<th></th>
<th>power (kW)</th>
<th>time p. d. (hours)</th>
<th>energy p. d. (kWh)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cooking</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kettle</td>
<td>3.00</td>
<td>0.33</td>
<td>0.99</td>
<td>8%</td>
</tr>
<tr>
<td>microwave</td>
<td>1.40</td>
<td>0.33</td>
<td>0.46</td>
<td>4%</td>
</tr>
<tr>
<td>electric cooker (rings)</td>
<td>3.30</td>
<td>0.50</td>
<td>1.65</td>
<td>13%</td>
</tr>
<tr>
<td>electric oven</td>
<td>3.00</td>
<td>0.50</td>
<td>1.50</td>
<td>12%</td>
</tr>
<tr>
<td><strong>Cleaning</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>washing machine</td>
<td>2.50</td>
<td>0.40</td>
<td>1.00</td>
<td>8%</td>
</tr>
<tr>
<td>tumble dryer</td>
<td>2.50</td>
<td>0.80</td>
<td>2.00</td>
<td>16%</td>
</tr>
<tr>
<td>airing cupboard</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>washing line drying</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0%</td>
</tr>
<tr>
<td>dishwasher</td>
<td>2.50</td>
<td>0.60</td>
<td>1.50</td>
<td>12%</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>refrigerator</td>
<td>0.02</td>
<td>24.00</td>
<td>0.48</td>
<td>4%</td>
</tr>
<tr>
<td>freezer</td>
<td>0.09</td>
<td>24.00</td>
<td>2.16</td>
<td>18%</td>
</tr>
<tr>
<td>air conditioning</td>
<td>0.60</td>
<td>1.00</td>
<td>0.60</td>
<td>5%</td>
</tr>
</tbody>
</table>

TOTAL DAILY PER 2 PEOPLE

TOTAL ANNUAL PER 2 PEOPLE: 12.34 kWh p. d. 4,505 kWh p. y

Average household electricity consumption in United Kingdom: 3,941 kWh / year

Average household electricity consumption in Tanzania (per electrified household in 2014!): 1,432 kWh / year
Home Sense monitor
Home Nest monitor
Home SolarEdge monitor
Home electricity monitor
IEA, Tracking Buildings, 2020

Image courtesy of IEA. License: CC BY.
In 2019, LED sales reached a critical milestone, achieving a record number of sales of more than 10 billion units, including both light sources (bulbs, tubes, modules) and luminaires. Both residential and commercial LED deployment is advancing, and LED sales now exceed fluorescent lamps. As LED costs continue to fall, sales are on track with the SDS, although continued robust growth is needed for LEDs to make up over 90% of sales by 2030.

Lighting: Tracking progress 2020

Content courtesy of IEA. License: CC BY.
Almost two-thirds of countries lacked mandatory building energy codes in 2019, meaning more than 5 billion m² were built last year without mandatory performance requirements. To be in line with the SDS by 2030: all countries need to establish mandatory building energy codes; new high-performance construction needs to increase from around 275 million m² to cover almost 5 billion m²; and energy intensity reductions currently effectuated by energy-efficiency renovations of existing building stock must double from 15% to at least 30%.  

Building Envelopes: Tracking progress 2020

**Tracking progress 2020**

Global building construction area by type of building code in the Sustainable Development Scenario, 2019-2030
The heating equipment market continues to be dominated by fossil fuel-based equipment and less-efficient conventional electric heating technologies, which make up almost 80% of new sales. However, sales of heat pumps and renewable heating equipment such as solar hot water systems have increased, representing more than 10% of overall sales in 2019. To be in line with the SDS, the share of clean heating technologies – heat pumps, district heating, renewable and hydrogen-based heating – needs to more than double to 50% of sales by 2030.

Heating: Tracking progress 2020
Heat pumps

More efforts needed

Tracking progress 2020

Nearly 20 million households purchased heat pumps in 2019. Even if some are reversible units that only partially cover space and water heating needs, growth is evident across all primary heating markets – North America, Europe and Northern Asia. Although heat pumps have even become the most common technology in newly built houses in many countries, they meet only 5% of global building heating demand. As their share is required to triple by 2030 under the SDS, further policy support and innovation are needed to reduce upfront purchase and installation costs, remove market barriers for renovations, and improve energy performance and refrigerant alternatives.

Heat Pumps: Tracking progress 2020

IEA, Tracking Buildings, 2020
Tracking progress 2020

Energy demand for space cooling has more than tripled since 1990, making it the fastest-growing end use in buildings. Space cooling was responsible for emissions of about 1 GtCO2 and nearly 8.5% of total final electricity consumption in 2019. While highly efficient AC units are currently available, most consumers purchase ones that are two to three times less efficient. To put cooling on track with the SDS, energy efficiency standards need to be implemented to improve AC energy performance more than 50% by 2030. Together with improved building design, increased renewables integration and smart controls, this measure would cut space cooling energy use and emissions and limit the power capacity additions required to meet peak electricity demand.

IEA, Tracking Buildings, 2020
Appliances and equipment

More efforts needed

Tracking progress 2020

Electricity consumption by household appliances continues to increase. It reached over 3 000 TWh in 2019 and accounted for 15% of global final electricity demand, or one-quarter of electricity used in buildings. Demand is driven by rising ownership of connected plug-load devices, especially in developing countries that are becoming wealthier. Mandatory Energy Performance Standards (MEPS) cover one-third of the energy used, mainly for large household appliances, but smaller plug loads, including consumer electronics, are less well regulated. Greater policy coverage and stringency will be needed to realise the SDS.

Appliances and Equipment: Tracking progress 2020
Simple interventions can correct misperceptions of home energy use

Tyler Marghetis, Shahzeen Z. Attari and David Landy

Public estimates of energy use suffer from severe biases. Failure to correct these may hinder efforts to conserve energy and undermine support for evidence-based policies. Here we present a randomized online experiment that showed that home energy perceptions can be improved. We tested two simple, potentially scalable interventions: providing numerical information (in watt-hours) about extremes of energy use and providing an explicit heuristic that addressed a common misperception. Both succeeded in improving numerical estimates of energy use, but in different ways. Numerical information about extremes primarily improved the use of the watt-hours response scale, while the heuristic improved underlying understanding of relative energy use. As a result, only the heuristic significantly benefited judgements about energy-conserving behaviours. Because understanding of energy use also predicted self-reported energy-conservation behaviour, belief in climate change, and support for climate policies, targeting energy misperceptions may have the potential to shape individual behaviour and national policy support.

Marghetis et al, 2019, Nature Energy

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Fig. 1: Relation between actual and estimated energy use.

From: Simple interventions can correct misperceptions of home energy use

Marghetis et al, 2019, Nature Energy
This account informed the development of two interventions for improving home energy estimation. First, we targeted the use of the response scale by supplying quantitative information about the extremes of electricity use (the typical energy use in 1 h by phone chargers, 5 Wh, and clothes dryers, 4,000 Wh). We predicted that this ‘scale-use’ intervention would help participants translate their beliefs about energy use into explicit estimates on the watt-hours scale without necessarily improving either their beliefs or their decisions that were based on those beliefs. Second, we targeted systematic misunderstandings by supplying a simple ‘explicit heuristic’ or guiding rule. People underestimate the energy used by appliances that change the temperature, perhaps because heat generation and heat removal may not be as noticeable as movement or lighting. This observation inspired the following explicit heuristic: large appliances that primarily heat or cool use a lot more energy than people think they use. Unlike the scale-use intervention, this explicit heuristic was intended to correct the underlying beliefs rather than just the way those beliefs are expressed in watt-hours.

Margheritis et al, 2019, Nature Energy
Fig. 3: Individual differences in understanding the appliances’ relative energy use.

From: Simple interventions can correct misperceptions of home energy use

a–d, Relations between understanding the appliances’ relative energy use and behavioural choice accuracy (a), pro-environmental attitudes (b), climate change beliefs (c) and climate policy support (d), illustrated with participants who reported being very liberal (n = 272), moderate (n = 313) and very conservative (n = 84) in their views. (Note that analyses in the main text use all participants.) Lines indicate the model-predicted relation, thus controlling for demographic variability, with error ribbons indicating 95% CIs. Circles indicate binned means, with the circle’s area indicating sample size.

Marghetis et al, 2019, Nature Energy
Project on indoor AQ in NYC