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

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Materials for class discussion

- David JC MacKay. Sustainable Energy - Without the Hot Air. UIT Cambridge Ltd., 1 edition, February 2009. Chapters 7,9,11, App E
- Deborah A. Sunter, Sergio Castellanos, and Daniel M. Kammen. Disparities in rooftop photovoltaics deployment in the United States by race and ethnicity. Nature Sustainability, 2(1):7176, January 2019. doi. URL.
- Maximilian Auffhammer. Consuming Energy While Black, June 2020. URL.
- Shuchen Cong, Destenie Nock, Yueming Lucy Qiu, and Bo Xing. Unveiling hidden energy poverty using the energy equity gap. Nature Communications, 13(1):2456, May 2022. doi. URL.

We shape buildings, and afterwards our buildings shape us.

– Winston Churchill

Buildings

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   - 35% of primary energy, 38% of GHG emissions worldwide (UN, 2020)

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   - COVID, ventilation, and real estate (SF Fed, 2022)
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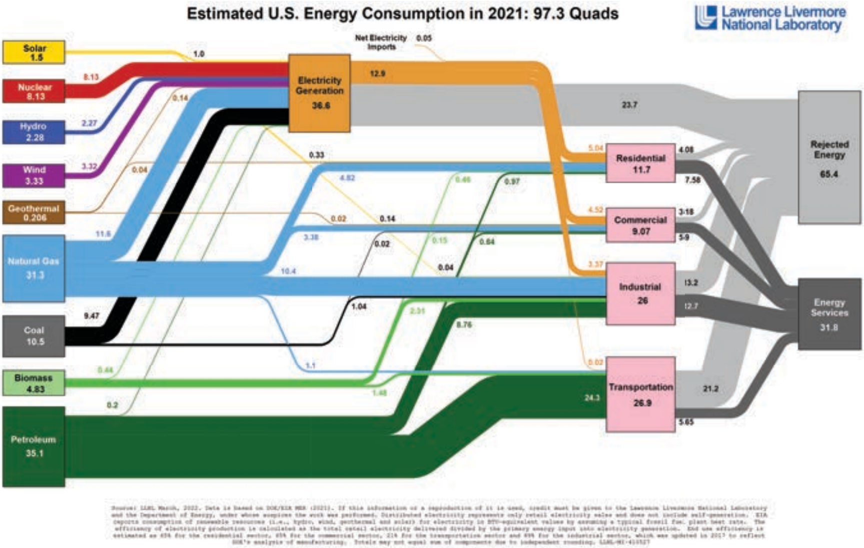
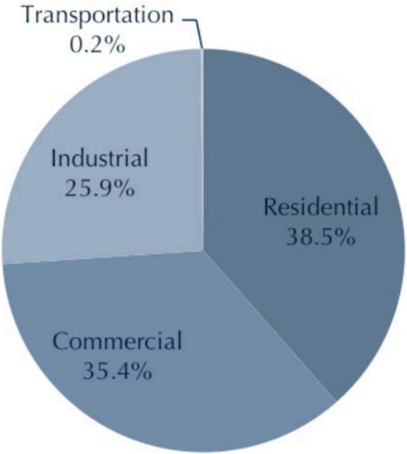
4. Mackay: how much it takes to heat, cool and use various appliances
   - how much energy is used in buildings?
   - how much more efficient can buildings be?
   - what specific activities in buildings lead to energy use (and waste)?
   - how can we motivate individual users to save energy in buildings?



Sankey diagrams for the US and every state at flowcharts.LLNL.gov

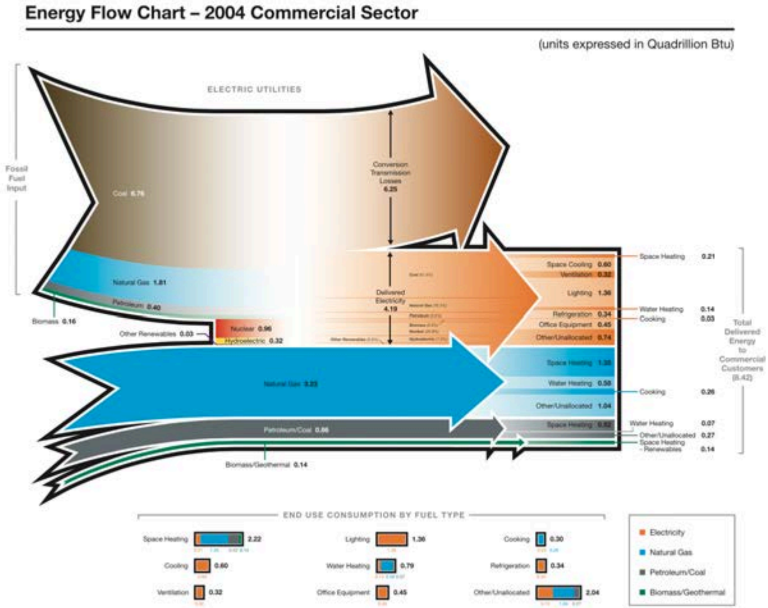
Public domain figure courtesy of LLNL / US Department of Energy.

Figure 3: Retail Sales of Electricity to Ultimate Customers, Total by End-Use Sector(2010)



Source: U.S. Energy Information Administration (EIA), *Electric Power Monthly*, Table 5.1, September 2012.
http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_01

Public domain image courtesy of the US Department of Energy.



Pacific Northwest National Lab, 2006

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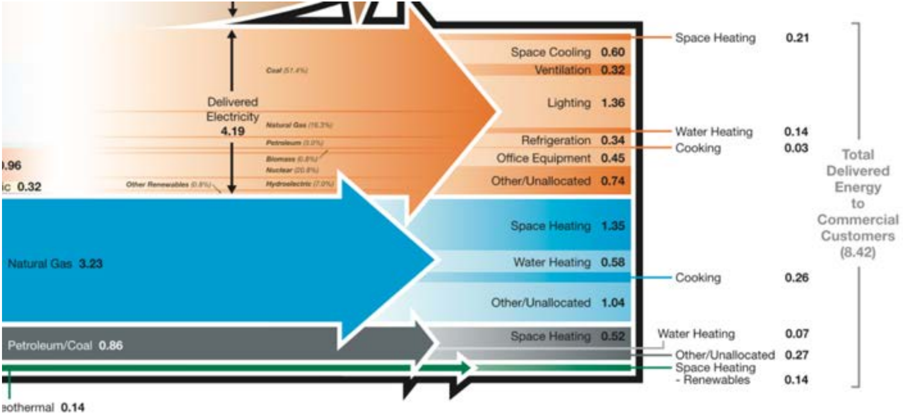

Pacific Northwest National Lab, 2006

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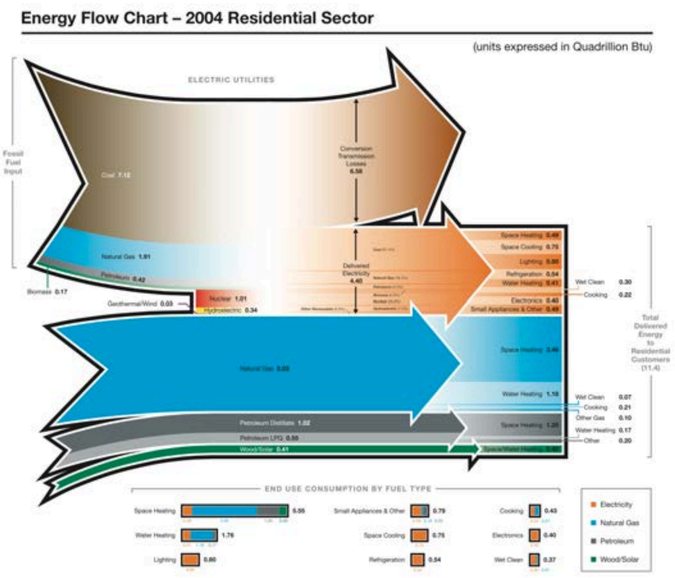

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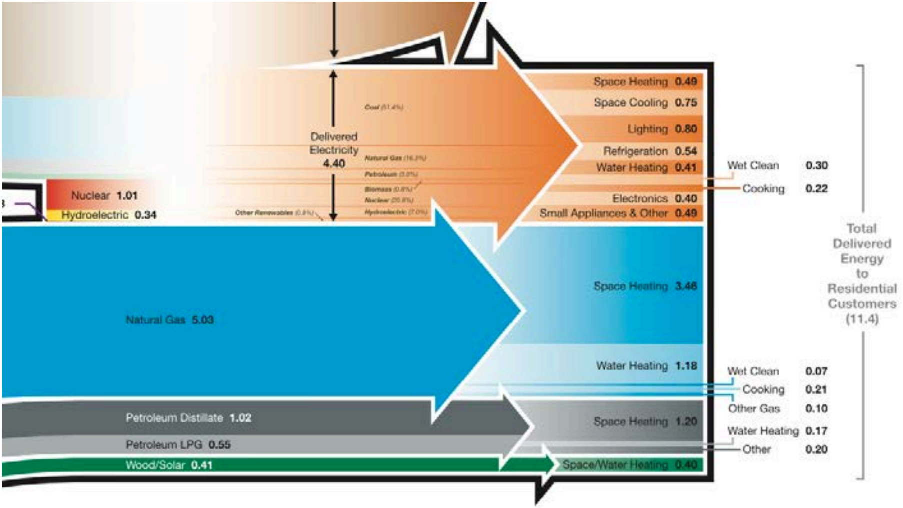
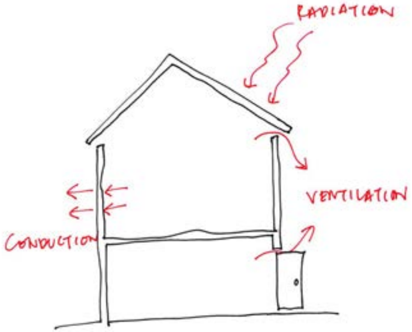


Pacific Northwest National Lab, 2006

All numbers in quads (.9478 quad = EJ)
Total US economy in 2020 uses 100.8 quads;
100% RE economy in 2050 uses 72.8 quads

	WILLIAMS ET AL 2020 **2020 Reference**	**2050 100% Renewable**	**Total % growth, 2020-2050**	**Notes**
Buildings (residential + commercial)				
Primary energy supply				
Electricity	20.2	12.9	-36%	Decline in total use
Pipeline natural gas	9.5	-	-100%	Eliminate completely
Biomass conversion	1.6	3.6	130%	(Via electricity)
TOTAL PRIMARY ENERGY	31.3	16.6	-47%	Reduce by half
Final demand (use)	19.9	13.1	-34%	
Implied losses	-36%	-21%		
Gain in efficiency		15%		

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)

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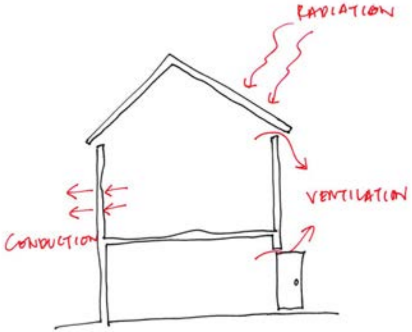

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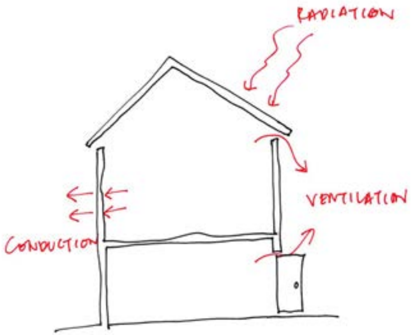

Three ways to gain and lose heat from house to the environment:

- 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 ΔT, while radiation depends on area:

Energy loss:

$$\begin{aligned} \texttt{conduction} &= \texttt{area} \times U \times (\Delta T \times \texttt{time}) \quad (1) \\ \texttt{ventilation} &= \texttt{volume} \times N \times (\Delta T \times \texttt{time}) \quad (2) \\ \texttt{radiation} &= \texttt{area} \times \texttt{solar intensity} \quad (3) \end{aligned}$$

What happened to Mackay's house in 2007? p. 295

CONDUCTIVE LEAKINESS	area (m^2)	U-value ($W/m^2/°C$)	leakiness (W/°C)
Horizontal surfaces			
Pitched roof	48	0.6	28.8
Flat roof	1.6	3	4.8
Floor	50	0.8	40
Vertical surfaces			
Extension walls	24.1	0.6	14.5
Main walls	50	1	50
Thin wall (5in)	2	3	6
Single-glazed doors and windows	7.35	5	36.7
Double-glazed windows	17.8	2.9	51.6
Total conductive leakiness			232.4

VENTILATION LEAKINESS	volume (m^3)	N (air-changes per hour)	leakiness (W/°C)
Bedrooms	80	0.5	13.3
Kitchen	36	2	24
Hall	27	3	27
Other rooms	77	1	25.7
Total ventilation leakiness			90

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 courtesy of David MacKay.

David Mackay's house in Cambridge (UK)

"Main ways to lose heat energy are conduction and ventilation":

$$\texttt{conduction} = 232 W/^{\circ}C \quad = \quad 78\%$$
$$\texttt{ventilation} = 90 W/^{\circ}C \quad = \quad 22\%$$

David Mackay's house in Cambridge (UK)

"Main ways to lose heat energy are conduction and ventilation":

$$\texttt{conduction} = 232 W/^{\circ}C \quad = \quad 78\%$$
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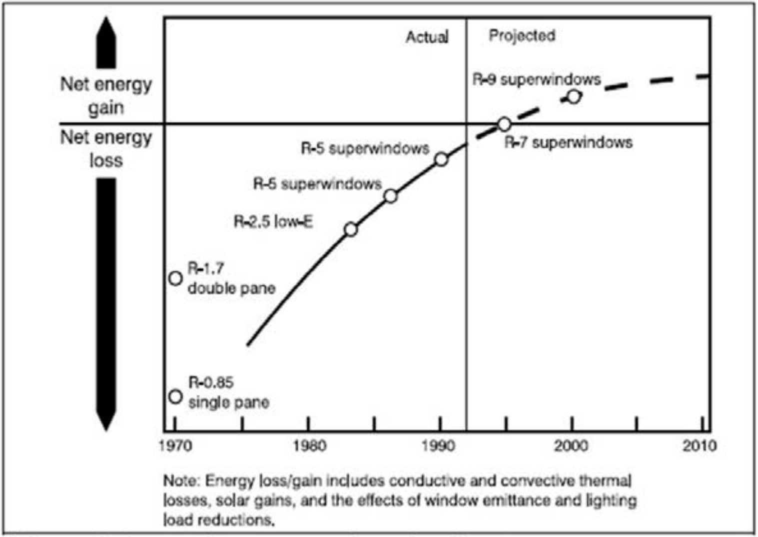
- added cavity wall insulation
- increased roof insulation
- added new storm door
- replaced back door and window with double-glazed

Windows

Public domain image courtesy of the US Department of Energy.



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

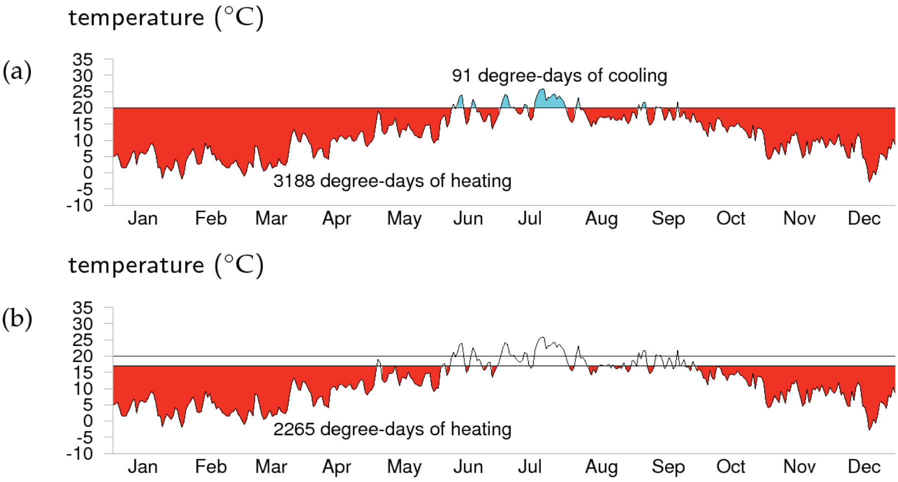
vc-cd16-a1515-06

Materials (Golbazi and Aktas)

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.

	IECC 2000, m^2K/W (F-ft^2-hr/Btu)	IECC 2012, m^2K/W (F-ft^2-hr/Btu)	Proposed, m^2K/W (F-ft^2-hr/Btu)
Ceiling	6.7 (38)	8.6 (49)	12.8 (73)
Above ground walls	3.2 (18)	3.5 (20)	12.8 (73)
Basement walls	1.8 (10)	2.6 (15)	2.6 (15)
Floors	3.7 (21)	5.3 (30)	5.3 (30)
Roofs	6.7 (38)	8.6 (49)	12.8 (73)
Mass walls	NA	2.6 (15)	2.6 (15)

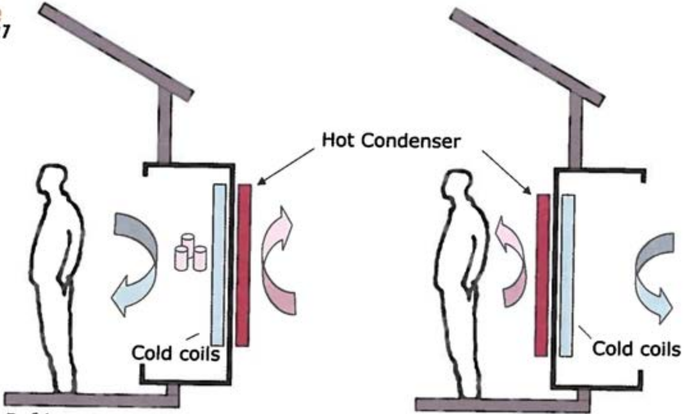
Heating degree days (Mackay, appendix E)



Courtesy of David MacKay.

Heat pumps (Randolph and Masters)

figure 6.27

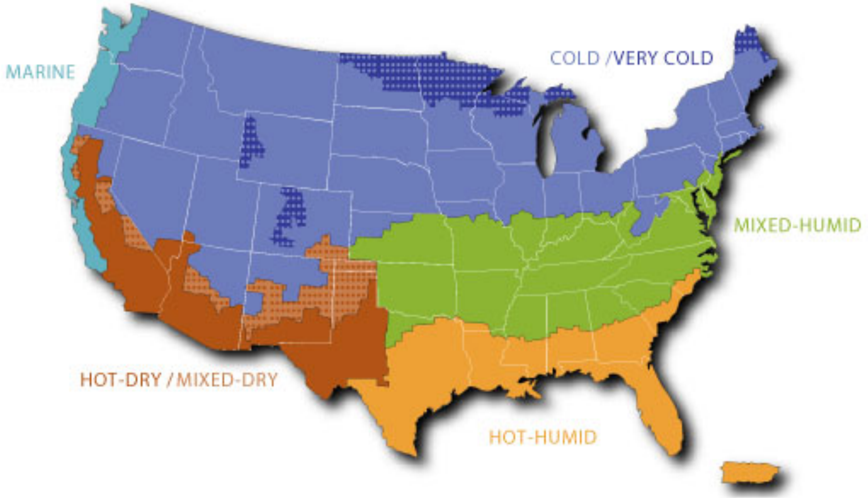


Refrigerator as an air conditioner ... and heat the world.

Refrigerator as heater ... and cool the world.

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.

U.S. climate zones



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

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

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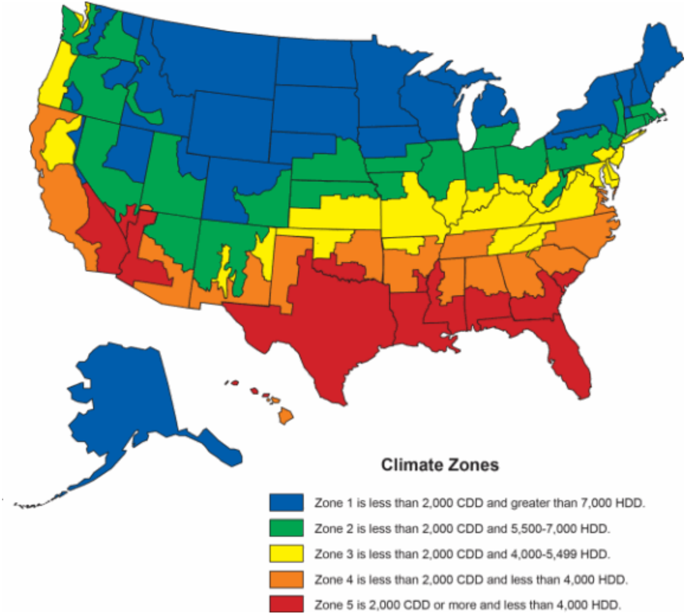


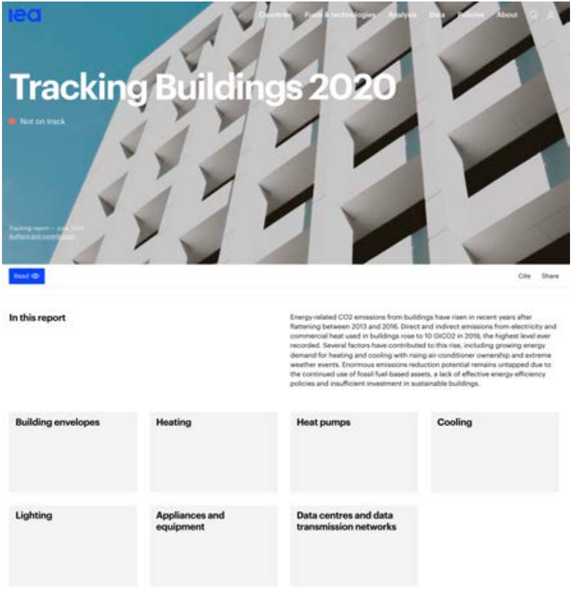
ESTIMATING LOAD FROM SELECTED APPLIANCES

Mackay, page 51:
2 people per household in England

	power (kW)	time p. d. (hours)	energy p. d. (kwH)		
Cooking					
kettle	3.00	0.33	0.99		8%
microwave	1.40	0.33	0.46		4%
electric cooker (rings)	3.30	0.50	1.65		13%
electric oven	3.00	0.50	1.50		12%
Cleaning					
washing machine	2.50	0.40	1.00		8%
tumble dryer	2.50	0.80	2.00		16%
airing cupboard	-	-	-		0%
washing line drying	-	-	-		0%
dishwasher	2.50	0.60	1.50		12%
Cooling					
refrigerator	0.02	24.00	0.48		4%
freezer	0.09	24.00	2.16		18%
air conditioning	0.60	1.00	0.60		5%
TOTAL DAILY PER 2 PEOPLE			12.34	kWH p. d.	100%
TOTAL ANNUAL PER 2 PEOPLE			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

Tracking Buildings 2020

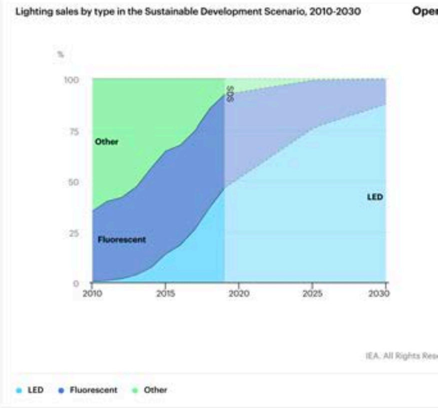
Lighting

On track

Tracking progress 2020

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



IEA, Tracking Buildings, 2020

Tracking Buildings 2020

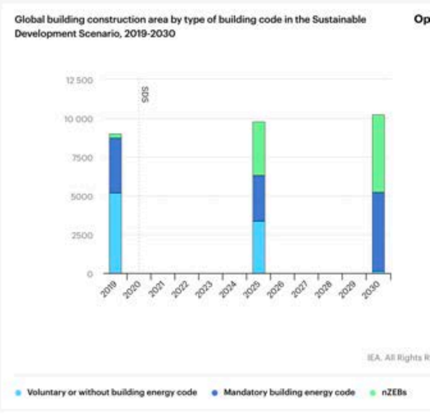
Building envelopes

Not on track

Tracking progress 2020

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 50%.

Building Envelopes: Tracking progress 2020



IEA, Tracking Buildings, 2020

Tracking Buildings 2020

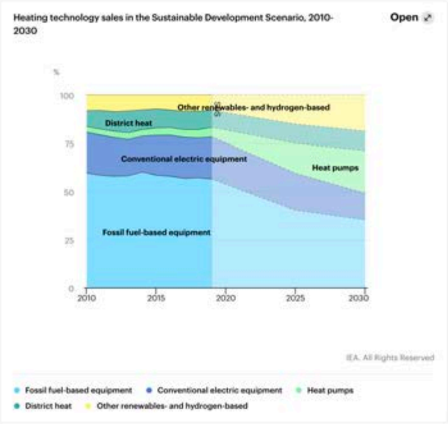
Heating

Not on track

Tracking progress 2020

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



IEA, Tracking Buildings, 2020

Tracking Buildings 2020

Heat pumps

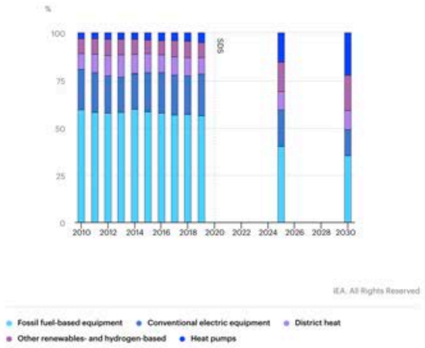
More efforts needed

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

Share of households purchasing heat pumps for heating and hot water production in selected regions the Sustainable Development Scenario, 2010-2030 Open



IEA, Tracking Buildings, 2020

Tracking Buildings 2020

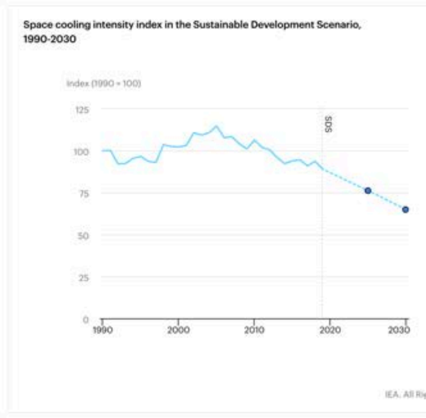
Cooling

More efforts needed

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.

Cooling: Tracking progress 2020



IEA, Tracking Buildings, 2020

Tracking Buildings 2020

Appliances and equipment

More efforts needed

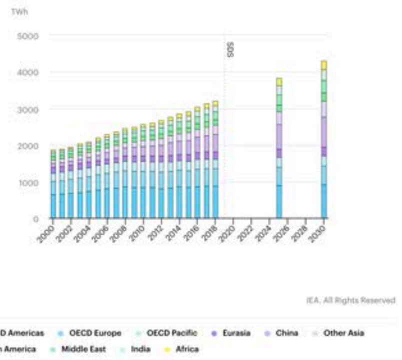
Tracking progress 2020

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

Consumption by household appliances and plug loads by region in the Sustainable Development Scenario, 2000-2030

Open



IEA, Tracking Buildings, 2020

nature energy

ARTICLES

https://doi.org/10.1038/s41560-019-0467-2

Simple interventions can correct misperceptions of home energy use

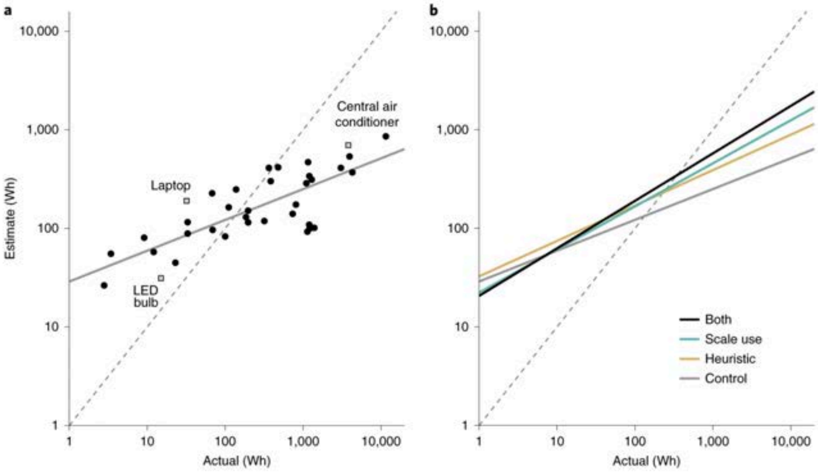
Tyler Marghetis[1,2,4]*, Shahzeen Z. Attari[1] and David Landy[2,3]

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 benefitted 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

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

From: Simple interventions can correct misperceptions of home energy use



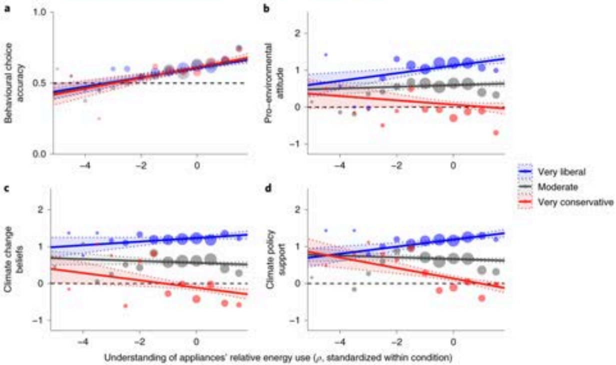
Marghetis et al, 2019, Nature Energy

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[24]. People underestimate the energy used by appliances that change the temperature[3], 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.

Marghetis 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