Cities & the idea of energy efficiency
MIT 11.165/477, 11.286J

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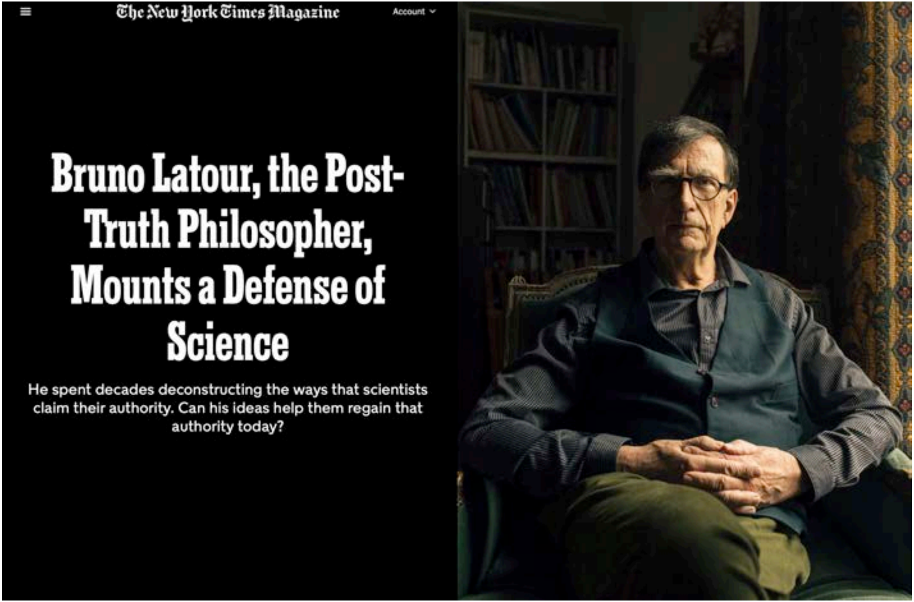
October 13, 2022

Materials for today

- Elizabeth Shove. What is wrong with energy efficiency? Building Research & Information, 46(7):779789, October 2018. doi. URL.
- Jonathan M. Cullen and Julian M. Allwood. The efficient use of energy: Tracing the global flow of energy from fuel to service. Energy Policy, 38(1):7581, January 2010. URL.
- Jonathan M. Cullen and Julian M. Allwood. Theoretical efficiency limits for energy conversion devices. Energy, 35(5):20592069, May 2010. URL.
- OPTIONAL: Saul Griffith, Sam Calisch, and Laura Fraser. Rewiring America. Technical report, 2020.



Bruno LaTour in the NYT, 2018

Philosophy

Bruno Latour obituary

French philosopher whose work spanned many disciplines and who believed we must take greater care of the Earth's resources

Stuart Jeffries

Mon 10 Oct 2022 06.10 EDT

1

Bruno Latour's ideas were profoundly influenced by the Gaia theory of the British scientist James Lovelock. Photograph: Joel Saget/AFP/Getty Images

In his penultimate book, After Lockdown: A Metamorphosis (2021), the philosopher and ecological thinker Bruno Latour, who has died aged 75, argued that humans should emulate termites - even though they live in mounds made from masticated earth and faecal matter.

Termites should be our role models, Latour argued, because they do not lay waste to the Earth, nor are any of them insect Elon Musks who seek to relocate to another planet. "That is escapist," Latour said. "But when you think in terms of a critical zone, you are locked in, you cannot escape." By

Bruno LaTour obituary in the Guardian, 2022

What is energy efficiency?

Abstract definition: "efficient provision of energy services"

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So, how do we define efficiency?

Shove, 2018, "What is wrong with energy efficiency?"

Critiques of energy efficiency:

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Critiques of energy efficiency:

1. unable to meet climate change on its own
2. rebound effects (Jevons paradox)
3. improving rather than overhauling or rethinking
4. counts some things rather than others ('purification')
5. status quo (framing, bounding)

Mackay, chapter 19

19 *Every BIG helps*

We've established that the UK's present lifestyle can't be sustained on the UK's own renewables (except with the industrialization of country-sized areas of land and sea). So, what are our options, if we wish to get off fossil fuels and live sustainably? We can balance the energy budget either by reducing demand, or by increasing supply, or, of course, by doing both.

Have no illusions. To achieve our goal of getting off fossil fuels, these reductions in demand and increases in supply must be *big*. Don't be distracted by the myth that "every little helps." *If everyone does a little, we'll achieve only a little*. We must do a lot. What's required are *big* changes in demand and in supply.

Text courtesy of David MacKay.

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What matters? Total impact on the problem of energy use & climate:

$$\text{impact} = \text{volume} \times \text{change}$$

Text courtesy of David MacKay.

Cullen & Allwood, both 2010 papers

$$\begin{matrix}\text{Potential for}\\ \text{saving energy}\end{matrix} = \begin{matrix}\text{Scale of}\\ \text{energy flow}\end{matrix} \times \left[\begin{matrix}\text{Target}\\ \text{efficiency}\end{matrix} - \begin{matrix}\text{Current}\\ \text{efficiency}\end{matrix}\right]$$

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What matters? Potential for energy savings measured vs. current efficiency

$$\Delta \propto [\text{target efficiency} - \text{current efficiency}]$$

Cullen & Allwood, Energy 35 (2010) 2059-2069

1. Introduction: the efficient use of energy

The reasons for using energy more efficiently are clear: to relieve pressure on scarce energy resources, to reduce energy costs by avoiding wastefulness, and perhaps most pressing, to reduce energy related carbon dioxide (CO_2) emissions which contribute to climate change. The well-known Kaya identity [1] expresses the generation of energy-based CO_2 emissions as the product of four drivers: population, per capita wealth, energy intensity (energy per unit wealth) and carbon intensity (CO_2 per unit energy). The first two drivers are socio-economic and are difficult to limit in practice. The third and fourth drivers are technical options which require energy to be used more efficiently (which lowers energy intensity) and the decarbonisation of energy supplies (which reduces carbon intensity).

Cullen & Allwood, Energy 35 (2010) 2059-2069

Significant socio-economic barriers also limit the uptake of new efficient designs. These include market imperfections (such as a lack of adequate information and financing, higher perceived costs, and differential benefits to the owner and user) and behavioural barriers (for example, consumer trends and habits, and the rebound effect). It is important that theoretical measures of efficiency gain, such as the work presented in this article, are in turn evaluated against such socio-economic considerations. Neverthe-

Cullen & Allwood, Energy 35 (2010) 2059-2069

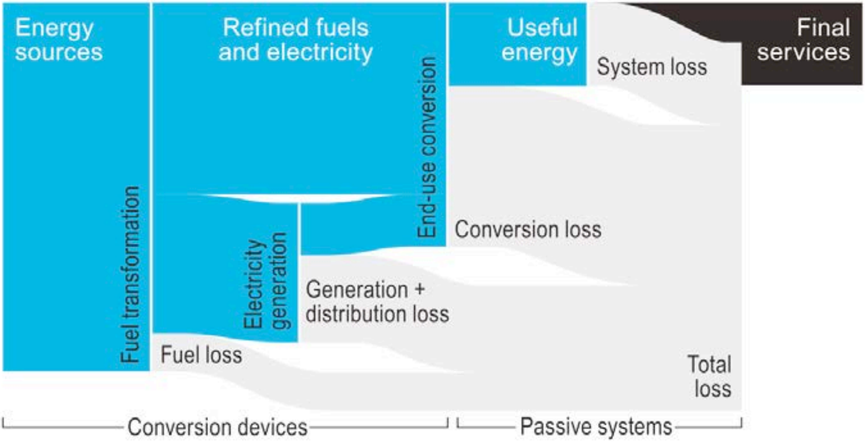


Fig. 1. The flow-path of energy.

Cullen & Allwood, Energy 35 (2010) 2059-2069

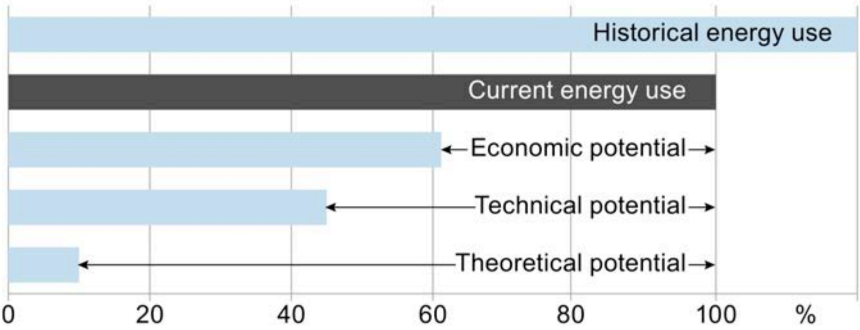
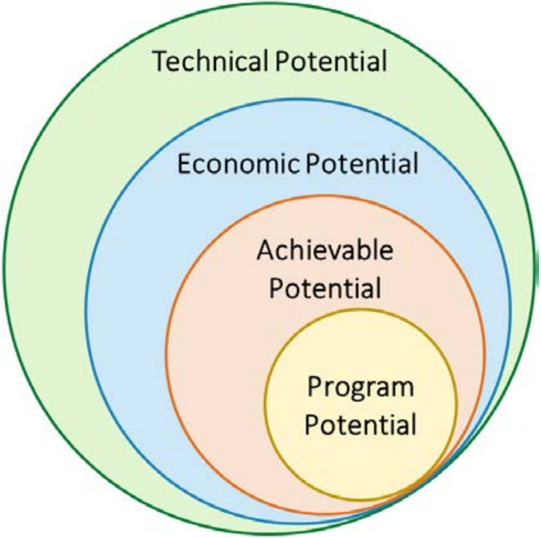


Fig. 2. Diagram of the potential gains from energy efficiency.

DOE Energy Efficiency Potential Studies Catalog



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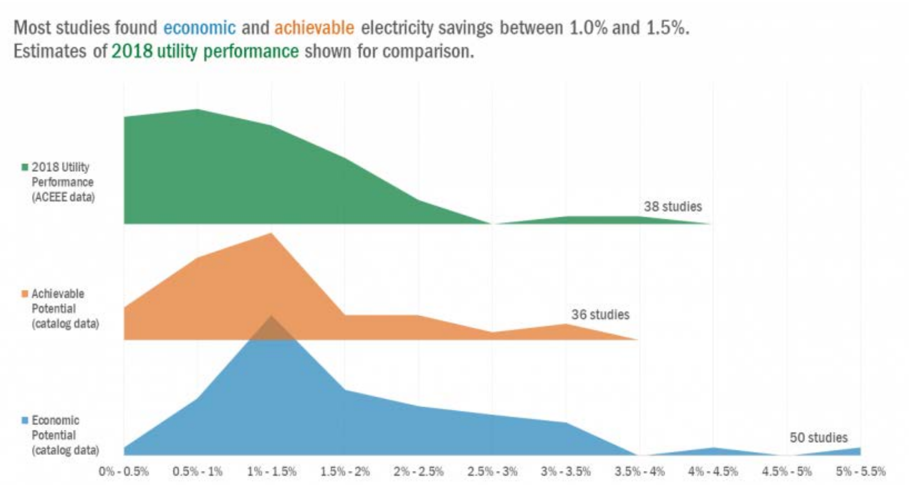

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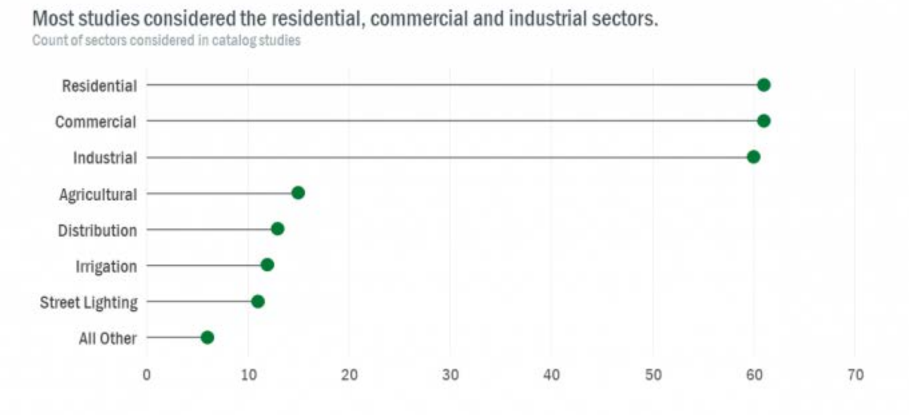

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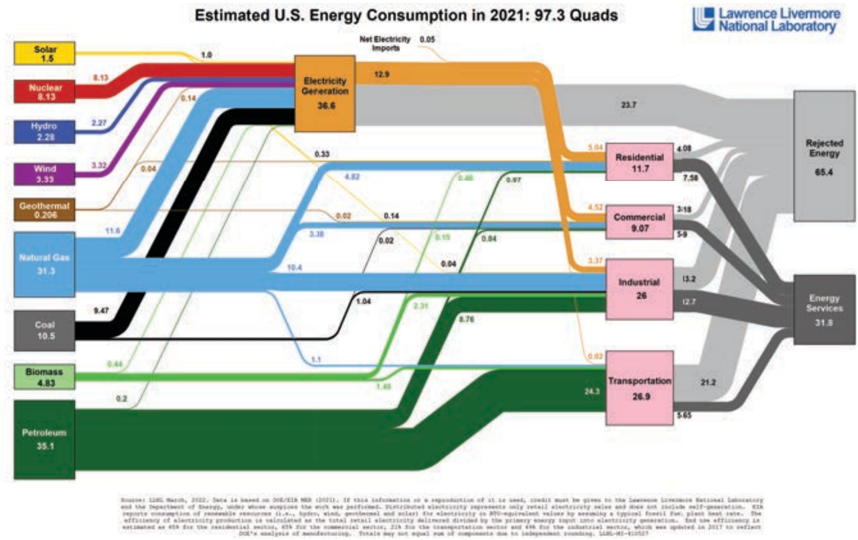

Public domain image courtesy of LLNL / US Department of Energy.

Cullen and Allwood, 2010, “The efficient use of energy”

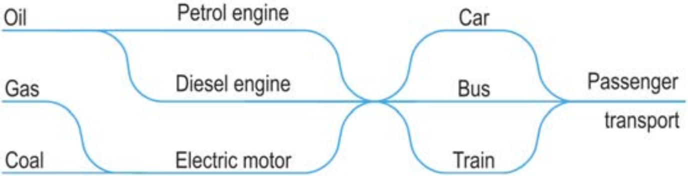

Fig. 3. Delivering passenger transport using alternative energy chains.

Cullen and Allwood, 2010, “The efficient use of energy”

80 J.M. Cullen, J.M. Allwood / Energy Policy 38 (2010) 75–81

Table 6
Vertical slices with technical components ranked by the scale of primary energy use.

Energy source	EJ	Conversion device	EJ	Passive system	EJ	Final service	EJ
Oil	152	Diesel engine	58	Appliances/goods	88	Thermal comfort	90
Coal	127	Electric heater	58	Heated/cooled space	86	Sustenance	84
Gas	97	Electric motor	55	Steam system	67	Structure	68
Biomass	54	Biomass burner	49	Driven system	56	Freight transport	64
Nuclear	30	Gas burner	47	Car	40	Passenger transport	64
Renewables	15	Petrol engine	41	Truck	38	Hygiene	56
		Cooler	33	Furnace	31	Communication	29
		Coal burner	31	Hot water system	23	Illumination	19
		Oil burner	28	Illuminated space	18		
		Heat exchanger	20	Plane	10		
		Light device	18	Ship	10		
		Electronic	16	Train	8		
		Aircraft engine	11				
		Other engine	10				
Direct fuel use	272	Heat	233	Buildings	215		
Electricity	183	Motion	175	Factory	154		
Heat	20	Other	67	Vehicle	106		
Total	475	Total	475	Total	475	Total	475

Cullen and Allwood, 2010, "The efficient use of energy"

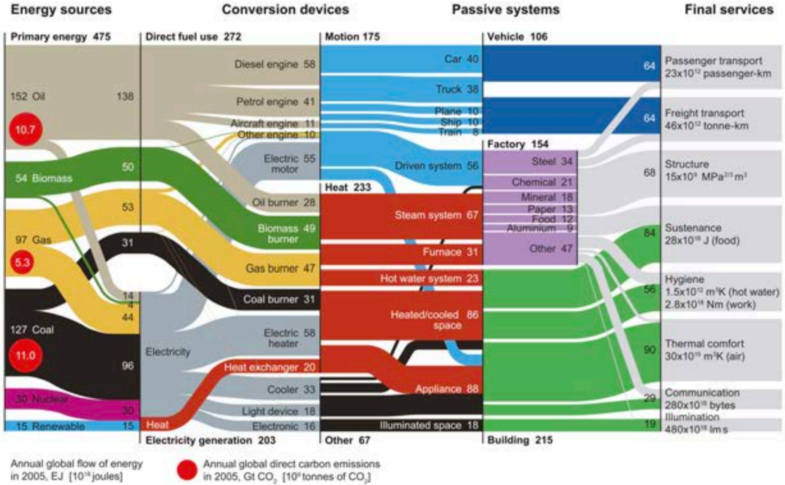

Fig. 2. From fuel to service: tracing the global flow of energy through society.

Exergy, energy & entropy

(Rosen and Dincer, 2008): “Exergy is a measure of the usefulness or value or quality of an energy form . . . defined using thermodynamics principles as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment.”

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In contrast, exergy efficiency (based on both the first and second laws of thermodynamics, and similar in concept to effectiveness or availability) provides a more equitable measure of conversion efficiency. It uses mechanical work rather than energy as the basis for comparing devices with each other and their thermodynamic ideal. Exergy efficiency is defined for a device as:

$$\epsilon = \frac{\text{exergy output}}{\text{exergy input}} = \frac{\text{work output}}{\text{maximum possible work output}} \tag{3}$$

By definition, the theoretical limit of exergy efficiency for an individual device or a chain of multiple conversion devices, is always unity.

Cullen and Allwood, 2010, "Theoretical efficiency limits"

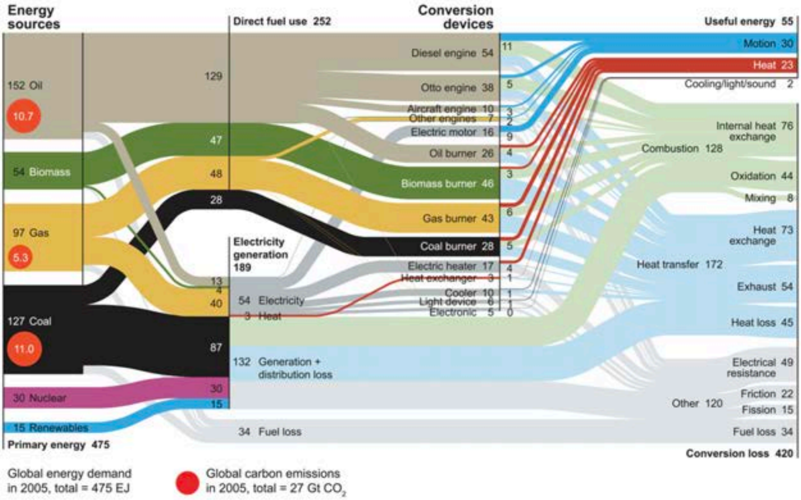

Fig. 3. The global map of energy conversion efficiency.

Cullen and Allwood, 2010, “Theoretical efficiency limits”

Table 1
Energy and exergy efficiencies for upstream conversion devices.

Device	Description	η %	ν %	ϵ %
Electricity generation from:				
Oil	Crude oil and petroleum products	37[a]	94	35
Biomass	Combustible plant/animal products and municipal/industrial waste	25[b]	90	23
Gas	Natural gas and gas works	40[a]	96	38
Coal	Hard coal, lignite and derived fuels (e.g. coke, blast furnace gas)	34[a]	94	32
Nuclear	Nuclear fission (heat equivalent of electricity)	33[c]	100	33
Renewable	Hydro, geothermal, solar, wind, tide, and wave energy	80[b]	100	80
Fuel transformation	In petroleum refineries, gas works, coal preparation, liquefaction, distribution and own-use	93[d]	100	93
CHP	Combined heat and power plants (all fuels)	56[d]	62	35
Heat	Utility heat plants (all fuels)	85[d]	24	20

Notes: η = energy efficiency, ν = quality factor, ϵ = exergy efficiency.
[a] IEA (p. 73) [25].
[b] Estimated.
[c] IEA (p. 138) [26].
[d] Calculated from IEA [24].

Cullen and Allwood, 2010, "Theoretical efficiency limits"

Table 3
Energy and exergy efficiencies of end-use conversion devices.

End-use device	Description	η %	ν %	ϵ %
Motion average		**26**	**90**	**24**
Diesel engine	Compression ignition diesel engine: truck, car, ship, train, generator	22	95	21
Petrol engine	Spark ignition otto engine: car, generator, garden machinery	13	99	12
Aircraft engine	Turbofan, turboprop engine	28	99	27
Other engine	Steam or natural gas powered engine	47	53	25
Electric motor	AC/DC induction motor (excl. refrigeration)	60	93	56
Heat average		**58**	**24**	**14**
Oil burner	Oil combustion device: boiler, petrochemical cracker, chemical reactor	61	25	15
Biomass burner	Wood/biomass combustion device: open fire/stove, boiler	34	20	7
Gas burner	Gas combustion device: open fire/stove, boiler, chemical reactor	64	21	13
Coal burner	Coal combustion device: open fire/stove, boiler, blast furnace, chemical reactor	59	31	19
Electric heater	Electric resistance heater, electric arc furnace	80	30	24
Heat exchanger	Direct heat application: district heat, heat from CHP	87	15	24
Other average		**60**	**14**	**8**
Cooler	Refrigeration, air con.: industry, commercial, residential	104	6	7
Light device	Lighting: tungsten, fluorescent, halogen	13	90	12
Electronic	Computers, televisions, portable devices	20	30	6
All devices		**51**	**50**	**25**

Notes: η = energy efficiency, ν = quality factor, ϵ = exergy efficiency.

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Cullen and Allwood, 2010, “Theoretical efficiency limits”

Table 5
Comparing the efficiency of conversion devices.

Energy chain	Conversion efficiencies			
	ϵ_f	ϵ_e	ϵ_d	ϵ_c
	%	%	%	**%**
Aircraft engine	93	100	27	**25**
Diesel engine	93	100	21	**20**
Other engine	92	78	25	**18**
Electric motor	93	32	56	**17**
Petrol engine	93	100	12	**12**
Motion average	**93**	**77**	**24**	**17**
Coal burner	90	100	19	**17**
Oil burner	93	100	15	**14**
Gas burner	91	100	13	**12**
Electric heater	93	32	24	**7**
Biomass burner	95	100	7	**6**
Heat exchanger	93	17	13	**2**
Heat average	**93**	**76**	**14**	**10**
Light device	93	34	12	**4**
Cooler	93	33	7	**2**
Electronic	93	32	6	**2**
Other average	**93**	**33**	**8**	**2**
Overall Average	**93**	**70**	**18**	**11**

Notes: ϵ = exergy efficiency, with subscripts, f = fuel transformation; e = electricity generation; d = end-use device conversion; c = compound efficiency.

Griffith et al, "Rewiring America"

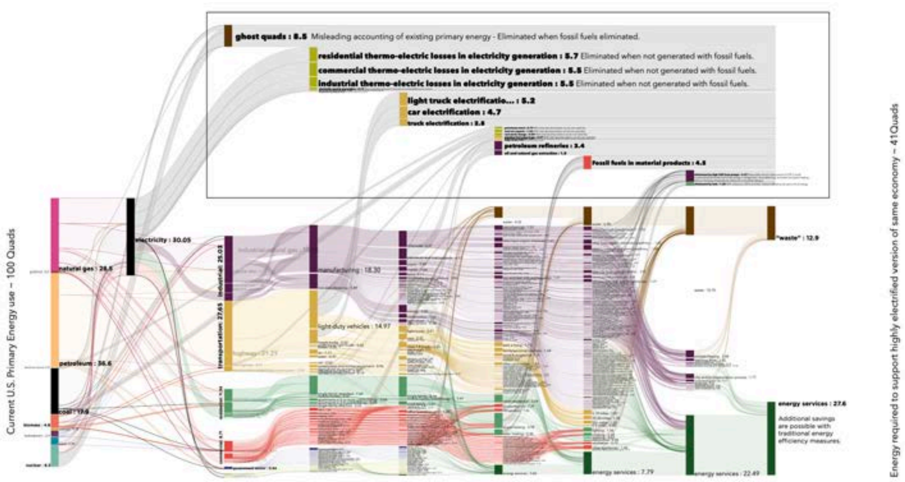
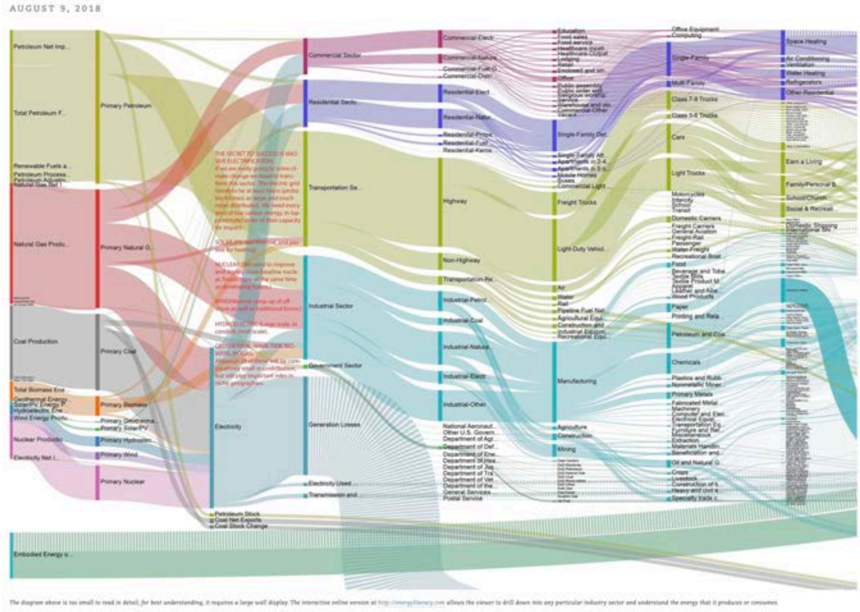


Figure 5.2: *A highly electrified, decarbonized U.S. energy sector roadmap showing where the massive efficiencies lie in electrification.*

Otherlab Super Sankey

Public domain image courtesy of Otherlab / US Department of Energy.



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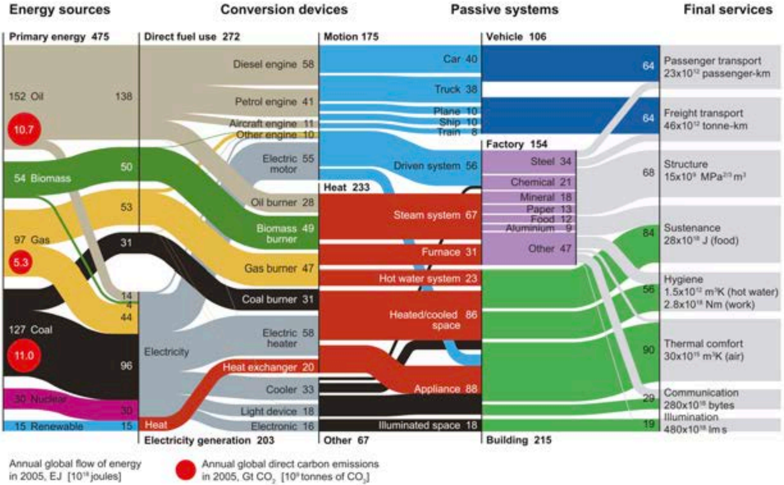

Fig. 2. From fuel to service: tracing the global flow of energy through society.

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Thinking through efficiency opportunities

As a member of Team Heat, Motion, or Other, consider from the articles:

1. How much energy and GHG emissions could *theoretically* be saved for your Team?
2. Which single technology improvement for your Team (fuel conversion or electricity generation, end-use conversion) would achieve the greatest reduction of energy and GHG emissions?
3. What reduction in primary energy could your Team achieve with a 20% reduction in final services?
4. How can you achieve a 50% reduction in primary energy?
5. Which technology would you not try to improve? Why?

Thank you!