A Fair Share: Doing the Math on Individual Consumption and Global Warming

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May, 2018

Contents

Chapter 1

Introduction, or, the banality of conservation

> Unprovided with original learning,
> unformed in the habits of thinking,
> unskilled in the arts of composition, I
> resolved to write a book
>
> *Edward Gibbon, Memoirs of My Life and Writings*

Global warming, and widespread environmental damage have weighed heavily on my mind, but typically in the abstract. As a member of the Western consumer class, one is faced daily with decisions that one vaguely believes have a broader impact on the environment, and a confusing array of news reports send mixed messages daily. Is it worthwhile to even try consuming ethically? Does it have even a marginal impact, or is it mere vanity or worse: are hybrid cars and green-labeled products merely indulgences for the rich that fail to address or even exacerbate the underlying drivers of environmental degradation? The notion that consumer choices are meaningful often faces derision from both the political right and left. Could it be that such banal acts as turning down the heater/AC or driving less actually have global significance? Doesn't the answer, "drive less," make a mockery of the enormity of global warming? Hence this book.

This book is one I wrote for myself. I wished to answer the question, to my own satisfaction, of whether one can consume, in the broad sense of the word, in a manner that is environmentally responsible, or whether any such effort is mere vanity. To answer this question, we must first answer a prerequisite inquiry: is consumption at the level of individual (Western) consumers a meaningful driver of environmental damage in general, and global warming in particular? The answer, as I will show, is decidedly yes. And, answering the natural follow-up question, yes, this consumption can be readily modified at the individual scale to dramatically reduce environmental impact.

To answer my previous inquires, it is indeed true that those acts most necessary are also most banal. Personal transportation (mainly in private vehicles), direct energy use within residential and commercial spaces, and food production collectively account for the greater share of America's environmental impact. Upstream energy and resource consumption for other goods and services account for most of the remainder. The Western consumer is the final common driver of the greater part of environmental degradation, and his day-to-day choices collectively drive the global carbon emissions and land use changes that chiefly underly global warming, mass extinction, and the emptying of the wilds.

It is my purpose to quantify the impact of Western, and in particular American consumption. It is my opinion that we are often distracted by red herrings, with stories in the popular environmental press expounding on the evils of everything from straws to toilet paper. While not all necessarily false, such reports can detract from the factors of major importance, and, I believe, induce defeatism. After all, if literally everything is killing the planet in equal measure, why even bother trying? Clearly then, one would be forced to the conclusion that there is simply no reasonable way to live in modern society without an enormous impact, short of renouncing the world? Hence the importance of quantifying the impact of our behaviors in a rigorous way, and determining those of true import.

Greenhouse gas (GHG) emissions, measured in carbon dioxide-equivalents (CO_2e), are ultimately generated, in large part, by acts of consumption, and so it is imperative to quantify them with respect to such acts. However, they are most typically inventoried at national, regional (e.g. North America, Europe, etc.), and global territorial scales, and are attributed to different *economic* sectors. At the coarsest scale, the EPA divides these sectors into (1) transportation, (2) industrial, (3) residential and commercial, and (4) agriculture; electricity generation, which supports all other economic sectors, may also be disaggregated as its own sector. This division is useful, but it masks how household level consumption acts across all sectors, and ultimately drives emissions across all sectors as well. Therefore, to truly understand individual emissions, it is far more instructive to make our unit analysis not *economic sector*, but *consumption category*, and many authors have undertaken just such an analysis, relying on a variety of data sources. In general, these authors (e.g. [1, 2]), and my own analysis (presented at length in the book before you), find that each American household generates on the order of 48–57 metric tons (or "tonne") of CO_2e annually, and, since the average household consists of just over 2.5 persons, this equals about 19–23 tonnes CO_2e per person. The majority of this impact is attributable to those three basic things everyone does every day: get around (personal transportation), directly use energy (heating, cooling, other residential energy uses, etc.), and eating, all things one has direct control over day by day, and the principle focus of this text.

American household consumption CO_2e emissions estimates equate, in the aggregate, to about 85% to *over* 100% of US territorial emissions. The latter possibility arises from the fact that emissions are widely "imported" and "exported" across national borders. To see this, consider some product manufactured in a Chinese factory powered by coal and shipped via international freight to the US for consumption. Under territorial accounting, the resulting CO_2 is assigned to China (and international freight CO_2 is assigned not at all), despite the fact that the US consumer is more ultimately responsible for its generation, and consumption-based accounting allocates this CO_2 to the American consumer. Perhaps 10–30% of US emissions are similarly imported: Weber and Matthews [1], at the high end, calculated that about 30% of US household emissions are imported from outside the country; other estimates are somewhat lower, with Hertwich and Peters [4] giving 18% of all US consumption emissions imported, while Davis and Caldeira [5] estimated a net 10.8% of total US consumption emissions were imported from outside the country. Many other developed, mainly European countries, import even larger fractions of their consumption footprint [5], and it is especially noteworthy that while territorial emissions have fallen in many such countries over the last couple decades, this is likely at least partially due to "outsourcing" emissions generation to developing countries, with net consumption emissions actually increasing for some of these nations [6].

Now, at least 70% of household CO_2e emissions can be attributed to, in descending order of importance, (1) personal transportation (25–40%), (2) household energy use and operations (25–30%), and (3) food consumption (15–20%), with the remaining 15–30% due to the emissions involved in conveying various goods and services. Thus, even at this coarse scale, it should be obvious that how much, and in what vehicles, Americans drive matters quite a bit. So do all the other banal and half-invisible everyday behaviors, from the choice of thermostat setting to one's daily bread. In the subsequent sections, I try to put these emissions numbers in a larger context, and look closer at the consumption that drives them. The overarching goal of the chapters that follow is to develop a comprehensive understanding of the major greenhouse gases, technologies, and industrial processes that all converge at the consumer level.

1.1 A fair share

In this section I perform some basic calculations to demonstrate that each US citizen is responsible for annual emissions of roughly 20 metric tons of CO_2e, and that, to meet near-term climate stabilization targets, one is entitled to, at *most* only 15 tonnes of CO_2e/year, while 10 MgCO_2e/year is a more reasonable short-term "fair share." In the longer-term, fair share per capita emissions are <4 MgCO2e/year.

It has been generally accepted that global atmospheric warming must be capped at a 2 °C (3.6 °F) rise to avoid the most dangerous consequences of global warming, and to achieve this, atmospheric CO_2 concentrations must be stabilized at the 450 ppm level. In its fourth assessment report, the International Panel on Climate Change (IPCC) estimated that this stabilization target would require developed countries (i.e. "Annex I" countries) to reduce their emissions by 25–40% by 2020, and by 80–95% by 2050 relative to a 1990 baseline [9]. In 2015, the US EPA inventory [10] estimated 1990 US territorial emissions at 6.301 billion metric tons of CO_2-equivalents (CO_2e). Using the January 1, 2016 Census estimate of the US population, 322.3 million persons, this amounts to about 19.5 metric tons of CO_2e (MgCO_2e) per capita, as the baseline from which reductions must be made. Note that I am using 1990 baseline emissions data, but the current population estimate. Therefore, if we assume all US citizens are equally responsible for meeting IPCC reduction targets, we may consider the maximum per capita CO_2e "fair share" for the year 2020 to be 14.6 MgCO_2e, a 25% reduction from the 1990 baseline. We get a more conservative 11.7 MgCO_2e using a 40% decrease from the baseline. However, the maximum longer-term fair share is just 3.9 MgCO_2e per capita (80% decrease from 1990 baseline).

Consider now that current per-capita emissions in the US now amount to about 21 MgCO_2e/ person/year, based upon territorial accounting, and using 2013 population and emissions figures. Each US household, via direct consumption, likely generates a very similar amount of CO_2e on average (see below). Therefore, a 25% reduction from the 1990 baseline is actually a slightly larger 30% reduction from current emissions rates. Nevertheless, the difference in figures is small, and the essential fact to remember is that the average US citizen is directly responsible for just over 20 metric tons of CO_2e per year, and this is the baseline that all other emissions numbers are (at least implicitly) always being compared to.

Now, these initial calculations ignore projected population growth, nor do they take into account the marked heterogeneity in per capita emissions both between developed and developing nations, and among developed nations. A better approach might be to assume all citizens of Annex I countries (essentially all developed countries) are entitled to the same carbon budget. United Nations Framework Convention on Climate Change (UNFCCC) estimates for total Annex I emissions in 1990 are 19.9 and 18.9 billion MgCO_2e, with and without CO_2e from land use changes, respectively. Using 2013 World Bank population estimates, the sum population of Annex I countries is just shy of 1.3 billion persons (excluding Liechtenstein and Monaco), and thus we arrive at about 15 MgCO_2e per capita, as our baseline for emissions reductions, across most developed countries. Twenty-five, 40, and 80% reductions from this baseline are 11.25, 9, and 3 MgCO_2e per capita, respectively.

Thus, "reasonable" upper limits to what can be considered fair levels of carbon consumption are about 10–15 $MgCO_2e$ per capita in 2020, just three years from the time of this writing, and just 3–4 $MgCO_2e$ per capita in 2050, 33 years from the time of writing. These are still somewhat inflated, for if we believe that emissions should be shared equally among all citizens of the globe, and therefore our 25, 40, and 80% reduction targets should apply equally, dividing 38 $GtCO_2e$ (approximate 1990 global emissions) among 7.12 billion people (2013 World Bank estimate), baseline global per capita emissions are a mere 5.3 $MgCO_2e$, with corresponding reduction targets of 4.00, 3.20, and 1.07 $MgCO_2e$/capita. Therefore, *truly* fair per capita carbon emissions can only be considered to amount to 3–4 $MgCO_2e$ in the short-term, with a medium- to long-term share of only 1 $MgCO_2e$.

These calculations have worked out rather conveniently because, as already mentioned, current US per capita emissions are roughly 21 $MgCO_2e$, on both territorial and consumption bases. We may round down to 20 $MgCO_2e$ per capita as a rule of thumb and for numerical convenience, and then depending on how we do our calculations, 25% (to 15 $MgCO_2e$), 40–50% (to 10–12 $MtCO_2e$), 80% (to 4 $MgCO_2e$), and 95% (to 1 $MgCO_2e$) reductions from this baseline all represent a different "level of fairness." Is it possible to achieve such emissions levels as a US citizen without retiring to a cave? I will argue that the first two are, in fact, eminently achievable for the majority of households and individuals, while one may even approach the 80% reduction target through ambitious changes in one's own lifestyle. The final goal requires deeper society-wide decarbonization, but such an achievement would be greatly abetted by, and likely mandates as a component, lower carbon lifestyles across the consumer class.

1.1.1 Fair share based on cumulative emissions

The fifth assessment report of the IPCC has estimated that cumulative anthropogenic (Greek "born of man") carbon dioxide emissions must be limited to 3,670 $GtCO_2$ (1,000 GtC) for a 66% chance of limiting global warming to <2 °C. More than 50% of this global carbon budget had already been spent by 2011, at an estimated 1,890 $GtCO_2$ (1,630 to 2,150) (515 GtC [445 to 585]). Moreover, when including non-CO_2 forcers (e.g. methane), the cumulative CO_2 limit falls to just 3,300 $GtCO_2$ (900 GtC), and at current emissions rates (about 50 $GtCO_2e$/year globally), it will likely be less than 30 years before the carbon budget is exhausted [8].

Supposing about 135 million people are born per year until 2050[1] we have, from the year 2015, about 4.75 billion births added to the existing population of 7.2 billion; this amounts to roughly 12 billion lives. Extending to 2100 with the same annual birth number adds another 6.75 billion lives for a total of 18.75 billion individual human lives until 2100. Dividing the global carbon budget of about 1,778 billion $MgCO_2$ (485 billion MgC) among 12 billion humans yields a scant 148 $MgCO_2$ per person born up to 2050, or 95 $MgCO_2$ per person if we assume everyone born up to the year 2100 has an equal right to emissions.

Assuming everyone born up to 2050 has an equal claim on the global carbon budget, then we each are entitled to 148 $MgCO_2e$, and this yields about 1.9 $MtCO_2e$/year over a life expectancy of 78.74 years (US, 2012), or 2.5 $MgCO_2e$/year if the counter starts at age 18. Similarly, about 1.2–1.6 $MtCO_2e$/year is the fair allocation out to the 2100 window.

Put more simply, on the basis of a cumulative emissions cap, everyone has a roughly 150 $MgCO_2e$ lifetime allocation, or about 2 $MgCO_2e$/year, and under the assumption that human activity is largely de-carbonized by the latter half of this century. The allocation falls to closer to 1 $MgCO_2e$/year if overall decarbonization takes longer, similar to the long-term, global-average fair share I derived above.

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[1] Birth rate based upon CIA World Factbook fertility figures and, based upon UN projected fertility rates, population growth, and life expectancy through 2050 [11], the total *number* of annual global births is likely to remain roughly constant for the next few decades.

1.2 Typical household emissions patterns and reductions potential

In subsequent chapters, I examine and quantify the major consumer drivers of carbon emissions in detail, and the results of these investigations are summarized here. I conclude that consumptive household emissions are driven by four major classes of activity, with approximate overall annual per capita emissions in parentheses: (1) personal transportation (6 $MgCO_2e$) (2) residential shelter (5 $MgCO_2e$), (3) food consumption (3–5 $MgCO_2e$), (4) and all other consumer goods and services (5–6 $MgCO_2e$), for a grand total of about 21 $MgCO_2e$/capita (or 53 $MgCO_2e$ per average household), and within the range reported by existing analyses, e.g. [1, 2, 3]. Note again, that this individual carbon impact, when aggregated across the entire US population, roughly matches 100% of *all* US territorial CO_2e. However, these averages mask marked variations about the mean, and in any given category of consumption, the top and bottom 20% of consumers (whether our unit of consumption be household or individual) vary by at least a factor of two in terms of their carbon impact, and generally much more: transportation emissions likely vary by more than a factor of *ten* between the top and bottom quintiles, residential energy emissions vary over threefold, and food and goods/services emissions also both vary by at least a factor of two or three.

Given this, it is clear that marked reductions in one's carbon footprint relative to the mean are readily achievable, and that the greatest absolute benefits are realized when the heaviest consumers alter their habits. For example, an individual in the top 20% across consumption categories might easily generate 40–45 $MgCO_2e$ in total, and thus, just bringing this person's consumption down to the mean would yield carbon savings as great as those to be had if a more typical individual's footprint went completely to zero. For comparison, a bottom 20% individual might be responsible for just 8–12 $MgCO_2e$ yearly, and such a person has already met a reasonable short-term emissions reductions target.

Carbon emissions for the first two consumption categories above (transportation and residential shelter) are primarily direct (including electricity generation), and under an individual's immediate control. Direct consumption of gasoline via passenger automobile transport dominates the personal transportation category, with emissions due to both the direct combustion of fuel (about 75–80%), and to the energy-intensive processes of petroleum extraction and refining. Jet fuel for air travel and the amortized costs of automobile manufacture are the two other major contributors, while public transportation amounts to a rounding error. Direct consumption of electricity and heating fuels dominate emissions attributable to the residence, along with the amortized carbon cost of home construction. Space and water heating are the two single largest users of residential energy, while a variety of miscellaneous electric loads are also of major importance. These two categories, personal transportation, and residential shelter, account for over half of household-level emissions, and are, again, essentially under the direct control of the consumer.

Food consumption is the largest indirect driver of emissions, with the majority occurring at the production stage, and with methane produced via enteric fermentation in beef (primarily) and dairy (secondarily) cattle the single greatest CO_2e source in US agriculture. A variety of post-farm processing and packaging activities downstream of the farm gate account for around 20–33% of emissions, while transport *per se* is a relatively minor component of the carbon footprint, despite the prominent billing of "food miles" in public discourse; landfilling of food waste also results in warming methane emissions. In terms of actual food products, beef alone likely accounts for almost one-third of all dietary emissions, despite making up only about 4% of the American diet. Meat consumption overall accounts for as much as half of diet-related emissions (and even more for heavier meat eaters), while dairy also has a substantial impact, and

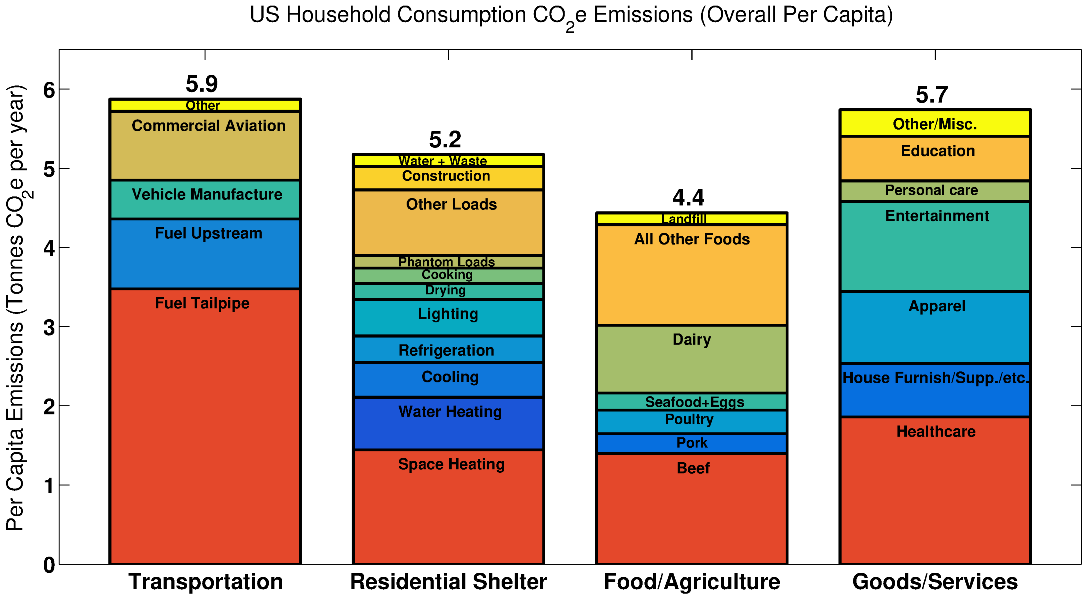

Figure 1.1: Approximate overall mean per capita consumption-based CO_2e emissions attributable to US households, disaggregated primarily by end-use or final product (e.g. space heating, beef), although note that gasoline for passenger vehicles is divided into the tailpipe emissions and those emissions due to upstream gasoline extraction and refining.

animal products all together may sum to almost 70% of the dietary carbon footprint. Finally, consumer-level food wastage (across all food types) amounts to up to one-third of the total impact of diet.

Overall per capita emissions attributable to household consumption, as calculated in the remainder of this book, are summarized in Figures 1.1 and 1.2 (following roughly the format introduced in [2]), with the two figures giving different disaggregations of residential and food emissions (note that food-related emissions differ slightly between the figures due to different methodologies for calculations).

Now, the above sums give household level consumption averaged across the entire US population, a population that includes many household types (single adults, large families with many children, poor and rich, etc.) spanning disparate geographic regions. Furthermore, nearly a quarter of US persons are under age 18, and they clearly have much less direct control over household consumption patterns in general. Therefore, a typical adult American will have an even larger carbon footprint than these numbers suggest; single adults especially, tend to have a relatively large impact, as there is little "sharing" of emissions across other household members. Tabulating the numbers for an average single-person household (and assuming such a person is also a typical driver), I arrive at a carbon footprint of around 31 $MgCO_2e$/year, roughly 50% higher than the overall per capita average. This sum disaggregates into about 8 $MgCO_2e$ for transportation, 10 $MgCO_2e$ from the residence, 4.5 $MgCO_2e$ for food, and 8.5 $MgCO_2e$ due to spending on general goods/services. Thus, both the potential for, and importance of, emissions reductions for single adults are appreciably greater than for the general US populace.

The above discussion gives us our baseline averages, but the next essential tasks are to examine (1) *existing* variation in consumption emissions, and (2) how basic conservation strategies might feasibly affect the consumption footprint, relative to baseline. Concerning the first point, I have already mentioned that the data presented in this book indicates dramatic variation, but it is instructive to consider transportation as an example, where differences in consumption emissions are especially profound, and indeed, in terms of gasoline use, the bottom and top 20%

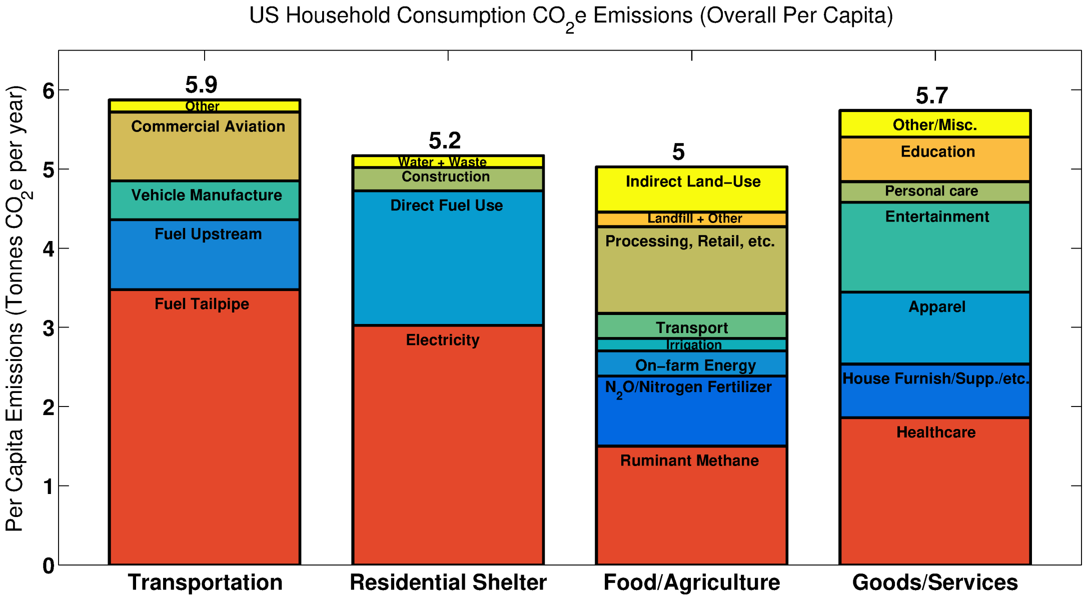

Figure 1.2: Approximate overall mean per capita consumption-based CO_2e emissions attributable to US households, but differing from Figure 1.1 in that residential emissions are given mainly in terms of energy source, and food emissions are divided by broad mechanism.

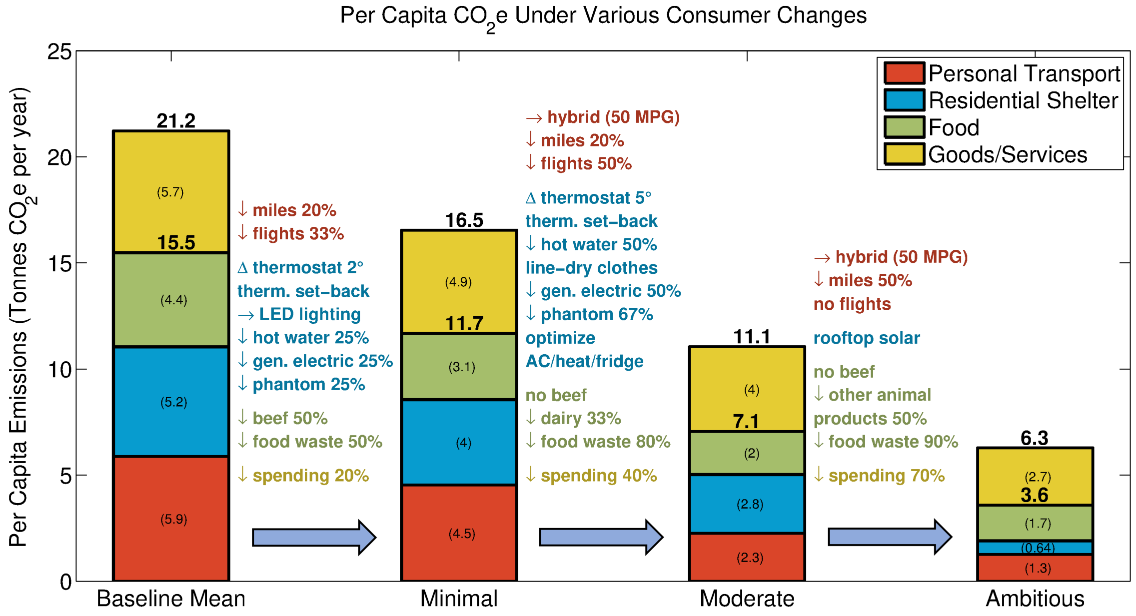

Figure 1.3: Carbon-equivalent emissions reductions from the mean US baseline under various collections of "minimal," "moderate," and "ambitious" changes in consumption patterns. Note that I consider healthcare spending relatively inflexible, and spending reductions in this category are only a fourth of the others (e.g. a 20% reduction in general spending gives just a 5% reduction in healthcare spending).

households vary over 11-fold, with mean gasoline-related emissions of 2.5 and 28 $MgCO_2e$ per household, for the bottom and top quintiles, respectively. In terms of vehicle ownership, the top 20% owned 3.5 cars to every one in the bottom 20% (See Chapter 6). Concerning aviation, I calculate that the top 20% of fliers travel roughly four times the air miles as the American average, while over 50% of US adults actually take *no* airplane trips in any given year. Thus, a "top-20% individual" might generate over 20 $MgCO_2e$ per year from personal transportation (15.4 $MgCO_2e$ from gasoline, 1.6 $MgCO_2e$ from vehicle manufacture, and about 3.5 $MgCO_2e$ from aviation), while a "bottom-20%" individual would be responsible for <2 $MgCO_2e$ (just 1.33 $MgCO_2e$ from gasoline and <0.5 $MgCO_2e$ from the vehicle itself).

While the existence of variation alone indicates the strong potential for conservation, a more bottom-up look at the major emissions sources may ultimately be more instructive. Relative to the baseline for a typical adult driver, who puts in about 12,500 miles per year in a vehicle getting just 22 MPG, upgrading to a hybrid or smaller electric vehicle getting 50 MPG-equivalent, while reducing miles driven by 20%, and changing driving style to be just 5% more efficient, would reduce fuel use by two-thirds and associated fuel-cycle emissions from almost 6.5 $MgCO_2e$ to just over 2 $MgCO_2e$, a net savings of almost 4.5 $MgCO_2e$. Most of these savings are attributable to the vehicle upgrade, and I discuss the comparative benefits of gasoline hybrid and pure electric vehicles extensively in Section 6.6.

Moving to residential energy, a variety of simple strategies that, while requiring conscientiousness, ultimately represent a minimal burden (in my view) and no true change in quality of life, can collectively reduce the emissions associated with household energy use by at least 33%, relative to baseline. The two most important are adjusting one's baseline thermostat (by, say 3–5 ^{o}F from baseline, e.g. 78^{o} instead of 73^{o} in the summer, and 66^{o} instead of 70^{o} in the winter) and setting the thermostat back when the dwelling is unoccupied (especially during the day in summer) or at night (in the winter), and avoiding excessive general electric loads (leaving TVs on, phantom loads, etc.). Minimizing hot water use by limiting shower water and general faucet use, turning over any incandescent lighting to LEDs or CFLs, and dry-lining clothes are also of potential. Investing in rooftop solar has the potential to reduce net residential energy emissions to effectively zero, although this is best pursued in *conjunction*, not competition, with other conservation measures.

A diet that avoids nearly all beef (*including* 100% grass-fed beef) and minimizes food waste (up to one-third of all food in the US is wasted at the consumer level, a vast and inexcusable waste of land and other resources) may, via these factors alone, have associated dietary emissions only 50% of the average. By further minimizing other animal products, including dairy, one may reduce the carbon footprint of their diet by closer to 60 or even 70% (with the latter possible under a near-vegan, near-waste-free diet). Avoiding highly processed and packaged foods, and preferentially eating at home yields modest benefits as well. Note that eating locally is, in my analysis, relatively unimportant, and there is no clear systematic advantage to organic products over conventional (with pesticide avoidance the main benefit of organic, but at the cost of increased land requirements due to lowered agricultural efficiency), and these statements are defended further in Part IV. Again, it must be emphasized that minimizing beef and waste are the two most effective strategies for reducing the carbon (and broader environmental) impact of diet, by far, and one need not be either strictly vegetarian or vegan to realize appreciable benefits in diet (and indeed, dairy is roughly comparable to poultry or pork, in its per-unit environmental impact).

In terms of general goods and services, nearly all direct consumer spending has an associated carbon cost on the order of 0.5–1.5 $kgCO_2e$ per dollar, due to the fundamental and wholly inescapable dependence of the modern industrial and commercial infrastructure upon fossil fuels. Thus, minimizing spending, but especially upon clothing and apparel, household goods in general, and entertainment is the only real way to reduce one's impact in this area. Healthcare is likely the most impactful category of goods and services overall, but I consider use of this resource relatively inflexible and often beyond a typical individual's control.

Not fitting neatly into any other category, I also note that maximal household recycling of all commonly recycled materials may annually offset around 0.35 $MgCO_2e$ per person, relative to a counterfactual with no recycling, a nontrivial but still quite modest sum. About two-thirds of this potential benefit is related to *paper* recycling (with the benefit mainly manifested in preserved forest carbon), with plastic and aluminum recycling of secondary importance. Otherwise, direct waste collection and management has only a very minimal carbon impact, with the partial exception of landfill gas emissions from food waste, which I attribute to diet in my accounting.

Potential emissions savings, relative to the average baseline, using several combinations of the above strategies are summarized graphically in Figure 1.3, which I lump together as "minimal," "moderate," and "ambitious," defined as:

1. **Minimal (20–25% CO_2e decrease from baseline):** (1) Reduce miles driven by 20% and omit one-third of flights; (2) change the thermostat by 2 °F and set it back by 3–5 °F when absent or at night in winter, change lighting to all LED (or CFL), decrease hot water, general electric, and phantom electric loads by 25%; (3) cut out 50% of beef and food waste; and (4) decrease general consumer spending by 20%.
2. **Moderate (45–50% CO_2e decrease):** (1) Upgrade vehicle to a hybrid or electric vehicle getting 50 MPG-equivalent, reduce miles driven by 20%, and omit half of flights; (2) change thermostat by 5 °F and employ the set-back strategy, decrease hot water and generic electric loads by 50%, avoid two-thirds of phantom loads, line-dry clothes, and upgrade old HVAC equipment and refrigerators; (3) Cut out beef entirely, decrease dairy 33%, and avoid 80% of all food waste; and (4) cut general spending by 40%.
3. **Ambitious (70–75% CO_2e decrease):** (1) Upgrade vehicle to a 50 MPG-equivalent vehicle, reduce miles driven by 20%, and take no flights; (2) add rooftop solar sufficient to cover 100% of residential energy use; (3) avoid beef, decrease all other animal products by 50%, and avoid 90% of food waste; and (4) decrease general spending by 70%.

We see that, even if all individuals and households undertook a *minimal* emissions-reduction strategy, net US household emissions (which in aggregate equal roughly 100% of the US's territorial emissions) would fall by over 20%, enough to very nearly meet near-term climate stabilization targets. This would also have the additional benefit of reducing pressure on fossil energy supplies, and reduce the amount of energy infrastructure that must ultimately turnover to renewable, near-zero carbon sources. More significant ("moderate") changes from the baseline can nearly halve the household consumption footprint, and although these do represent much more overt changes in lifestyle, they are by no means beyond the capabilities (financial or otherwise) of the greater part of Americans.

For the extremely ambitious individual, it is possible to push the cumulative impact of the three most direct categories of consumption, transportation, the residence, and diet, to under 4 $MgCO_2e$, a rather remarkable feat. It is at this point (and only at this point), that those various goods and services conveyed by the fossil economy become the dominant impact category, with the impact dominated by largely involuntary participation in the carbon-intensive US healthcare system. For one who truly reaches this point, further decreases in one's environmental individual footprint mandate deeper decarbonization throughout the economy and energy systems.

We see then, that collective individual action (if this is not a contradiction in terms) can eliminate the greater part of the US's carbon emissions (as well as dramatically reduce fossil fuel, water, and agricultural land use), and the collective lifestyles of Americans are indeed the fundamental driving force underlying the majority of emissions. To fully decarbonize the economy requires a deeper, infrastructure-wide shift to other energy sources, but this can be aided greatly by conservation measures, and individual conservation can synergize with, for example, the deployment of renewable electricity for a much more rapid decarbonization than could otherwise occur.

1.2.1 A note on household vs. individual

Energy use is typically reported using energy per household as the basic unit, and several works have examined household-level carbon footprints; the mean US household size was 2.54 persons in 2015, per the US Census. As already noted, then, using per capita emissions numbers on the basis of household-level consumption includes a significant number of children in the calculation, and lumps a variety of households. Therefore, I have, when especially salient, examined household consumption stratified by household size, and I have made a special focus upon single-person households vs. the overall mean household. Since it is probably most correct to attribute consumption emissions primarily to adults, single-person household emissions may be more salient for most readers, and may better represent the impact of typical adults compared to an overall per capita average. My primary metric, throughout the book, is CO_2e per capita (or individual), and not CO_2e per household, although the latter features prominently as well.

1.2.2 A final summary

In the near-term, every American is "entitled" to emit, directly and indirectly, no more than 10–15 MgCO_2e at most, which is 25–50% less than current US per capita emissions. The 15 MgCO_2e/capita goal is likely *immediately* achievable for most households, and 10–12 MgCO_2e is a reasonable five- or ten-year goal for an individual to set, particularly if they live in a 2+ person household. It is achievable through a low-waste low-meat diet, a high mileage vehicle, or alternatively, cutting vehicle-miles by 30–50%, and reductions in household energy consumption that are readily achievable. Furthermore, limiting consumer spending is, like it or not, also important. None of these changes are qualitatively drastic, but do represent significant departures from business-as-usual.

An 8 MgCO_2e/capita goal represents a roughly 60% reduction from the US baseline under territorial accounting, and a similar or even larger reduction on a consumption-based accounting. Longer-term, this 8 MgCO_2e figure must itself be cut at least in half. This can be achieved through more spartan changes in lifestyle under current conditions, through investment in renewable energy at the household level, and/or via major changes in American infrastructure. For those with the financial resources, household-level emissions can be dramatically reduced by investing in rooftop solar and alternative drive-train vehicles (hybrid-electric or electric). Since, on average, household emissions increase markedly with income, it is not unreasonable, in my view, to ask this of higher earners. If one does make this investment, one must still be mindful of the embedded emissions that go into residential construction: even a fully solar-powered house still embodies significant carbon if it is very large.

Through individual and household behavior and consumption changes alone, getting to a short-term US/Annex I fair share is actually quite doable; getting to a short-term global fair share (e.g. an 80% reduction from the US baseline) is challenging but can be largely achieved with some sacrifice and care. Such reductions alone would amount for the greater part of global emissions, would be of profound benefit to the planet, and are urgently needed. Ultimately, however, those last few metric tons of emissions need to disappear as well, and achieving this at the individual level is much more difficult: it will require a larger society-wide investment in low-carbon infrastructure.

1.3 Goals

> The man of knowledge in our time is bowed down under a burden he never imagined he would ever have: the overproduction of truth that cannot be consumed...it is strewn all over the place, spoken in a thousand competitive voices. Its insignificant fragments are magnified all out of proportion, while its major and world-historical insights lie around begging for attention.
>
> *Ernest Becker, The Denial of Death*

My most basic goal is to present to the reader a thorough analysis that shows how human activity causes greenhouse gas emissions, quantifies the direct and indirect contributions of individual (or household) level activities to these emissions, and further quantifies how the magnitude of emissions may be reduced through generally achievable changes in lifestyle. An overarching theme is to then put these numbers into a simple framework that gives a sense of their ultimate significance. That framework is the typical and "fair-share" per-capita emissions that I have discussed in this introduction. It is not enough, I think, to tell someone in isolation that behavior x will reduce their emissions by, say, one metric ton of CO_2. But this can be useful when one has a framework for the actual magnitude, and importance, of household emissions.

The approach I have taken in this book is to review major categories of household-level activity and determine how emissions are ultimately generated from these activities. To fully understand this, requires, to give just a few examples, reviews of oil extraction and combustion, electricity-generating technologies, large-scale water provision projects, the thermodynamic principles of heat engines, various agricultural practices, and high altitude jet fuel combustion. Therefore, each category of consumption serves as a springboard for a variety of discussions much deeper than might be immediately apparent. While my major focus is climate change throughout, I do review other major environmental problems associated with certain technologies, for example, the ecological effects of pesticides, and the effects of fracking for natural gas upon water supplies.

In all chapters of this book I have relied as exclusively as possible upon the peer-reviewed scientific literature, as well as IPCC publications and several major governmental surveys and reports, but ultimately present my own analyses and conclusions concerning the problems at hand. While likely beyond the interest of many general readers, I have included a large amount of technical detail in this text, an exercise that is meant to show how I have arrived at my conclusions, and to point the interested reader to further resources. It is not, I think, enough simply to know the bottom line, but how one arrives there.

Furthermore, by providing a broader background on most issues that meaningfully affect global warming, I hope to equip the reader to put into context environmental news stories and to *critically* evaluate the wide variety of claims made by both the political right and left. Finally, I hope that those reading this take it upon themselves to, to the extent possible, honestly evaluate their own participation in the systems driving climate change and then alter their behaviors in a meaningful way, and moreover, understand that such acts are not mere vanity, but a potentially powerful counter to the fundamental drivers of the environmental crises we face today.

Finally, it is not necessary (or necessarily even advised) to read this book in sequential order, with the book divided into several largely independent parts, each focusing either on broad background information or a different category of consumption. It is hoped that the early sections in each major part will provide the general reader with the basic conclusions on how each particular category of consumption generates carbon-equivalent emissions and the most meaningful individual acts to mitigate this; further reading may be tailored to each individual's interests, and I encourage each reader to focus upon those sections of most personal interest or salience (I would, for example, advise a closer reading of the comparisons of hybrid, plug-in hybrid, and pure electric vehicles for those contemplating a new car purchase). Furthermore, many longer sections begin with a box of bullet points highlighting that section's major conclusions, both to motivate the subsequent material and to aid the more casual reader.

1.3.1 The technical nature of this work

This book is open to the criticism that it does not address, certainly not explicitly, how the basic structure of an industrial civilization and an economic model that demands everlasting growth drive global climate change. The fundamental imperatives of corporations, and indeed most institutions, are growth and profit. Add to this that we live in a pervasively materialistic society, one where material consumption is a general proxy for status, and indeed, where most livelihoods now depend on the material consumption of others. Furthermore, the basic relationship between man and nature is generally viewed not even so much as one of two equal antagonists (nature is no longer so mighty), but as one of master and plantation.

The proper way to live, the proper relationship we should have with "nature," how to contend with the seeming all-consuming nature of the economic system, these are fundamental questions that must be answered, and as a society we probably must answer them differently than we (implicitly) have, if there is to be any hope for the global ecology as we know it. But having the right goals is not enough to guide one's hand, one needs the basic facts to know what course to take. That is why this book is mostly technical in nature. It is meant to be a rigorous guide for those interested in a particular path, and not, primarily, a meditation on what path to take.

Chapter 2

General principles

In this chapter, I introduce some generally qualitative principles that (I hope) can serve as a guide to thinking when I turn to the gritty quantitative work that dominates the rest of this book, preventing one from, too much, getting lost in the weeds of numbers.

2.1 The profound importance of transition

M. King Hubbert, a geophysicist most famous for his theory of "Peak Oil," (discussed at further length in Section 3.7.3), was an early and deep thinker on the subject of the energetic basis for civilization. He recognized that, by virtue of their finite nature and rapid exploitation, fossil fuel use must, on the timescale of human civilization, rapidly peak and decline to zero, the continuation of an industrial civilization depending on whether societies successfully develop alternative solar-based technologies in the energy-rich window provided by fossil fuels. It is worth quoting him at length, from the conclusions of his famous 1949 paper in Science [12] (emphasis added):

> These sharp breaks in all the foregoing curves [showing a rapid rise and fall in fossil energy over geologic time] can be ascribed quite definitely, directly or indirectly, to the tapping of the large supplies of energy stored up in the fossil fuels. The release of this energy is a unidirectional and irreversible process. It can only happen once, and the historical events associated with this release are necessarily without precedent, and are intrinsically incapable of repetition.
>
> It is clear, therefore, that our present position on the nearly vertical front slopes of these curves is a precarious one, and that the events which we are witnessing and experiencing, far from being "normal," are among the most abnormal and anomalous in the history of the world. *Yet we cannot turn back; neither can we consolidate our gains and remain where we are. In fact, we have no choice but to proceed into a future which we may be assured will differ markedly from anything we have experienced thus far.*
>
> Among the inevitable characteristics of this future will be the progressive exhaustion of the mineral fuels, and the accompanying transfer of the material elements of the earth from naturally occurring deposits of high concentration to states of low concentration dissemination. Yet despite this, *it will still be physically possible to stabilize the human population at some reasonable figure, and by means of the energy from sunshine alone to utilize low-grade concentrations of materials and still maintain a high-energy industrial civilization indefinitely.*

> Whether this possibility shall be realized, or whether we shall continue as at present until a succession of crises develop—overpopulation, exhaustion of resources and eventual decline—depends largely upon whether a serious cultural lag can be overcome. In view of the rapidity with which the transition to our present state has occurred it is not surprising that such a cultural lag should exist, and that we should continue to react to the fundamentally simple physical, chemical, and biological needs of our social complex with the sacred-cow behavior patterns of our agrarian and prescientific past. *However, it is upon our ability to eliminate this lag and to evolve a culture more nearly in conformity with the limitations imposed upon us by the basic properties of matter and energy that the future of our civilization largely depends.*

The final point cannot be emphasized enough: the basic stoichiometry of human civilization and energy use cannot be denied. Fossil fuels represent 500 million years of sunlight trapped in minerals that may be burned away within scarcely more than the span of a few human lives. If this energy is squandered, rather than put at least in part towards a *transition* to a new infrastructure that more directly captures the sunlight falling upon earth, industrial civilization cannot persist in anything resembling its current form. Adding to the urgency of transition is the carbon budget that must not be exceeded to avoid dangerous climate change, and which will be spent far before fossil reserves are ultimately exhausted.

We must understand, then, that efficiency measures and use-reduction, while extremely important, *by themselves* will act only to push back somewhat those dates that the carbon budget is spent, and ultimately the fund of fossil energy depleted. They must be coupled to a larger energy transition to be of any long-term efficacy. Thus, we must divide our thinking into near- and medium-term time horizons, say 10–30 years, and the longer time-horizon. In the nearer-term, our goal should be to *reduce* the pressure on the climate system and energy resources, and the most efficacious actions must be evaluated with respect to the current and likely near-term energy mixes. So for example, under the *current* energy system, hybrid-electric vehicles powered by gasoline generate emissions comparable to, or even lower than, those of pure battery-electric vehicles (both yield around 40–60% the emissions of comparable gasoline-only vehicles). In the longer-term, gasoline-powered vehicles must disappear from the face of the earth, but hybrids are a rational *short-term* solution to relieve pressure.

These short-term measures can provide a window for the concurrent implementation of longer-term measures, which must include a near-complete transition of the energy system (not just electricity, but all energy) to near zero-carbon, non-fossil, sources, including wind, solar, and hydro renewables, and potentially fourth-generation nuclear technologies. Note that biomass, a leading renewable energy source, can only provide a relatively small fraction of the energy for modern civilization without devastating ecological effects. Further, existing biomass technologies are not zero- or even low-carbon over a timescale of decades to centuries, and are, in fact, probably more similar to fossil fuels than to other renewable technologies in this respect (see Sections 3.8 and 4.10).

Whether, as a global civilization, this transition is made in a way that allows a relatively high energy lifestyle for most, or even a fraction, of the globe's citizens has yet to be seen. In the meantime, the focus of this book is on understanding how the (Western, and in particular, the American) individual can help the world to meet short- and medium-term carbon reduction targets, providing precious breathing room for both the climate and industrial civilization.

2.2 Nothing is "zero-impact"

It is important to briefly emphasize that essentially every act of consumption carries a cost: there can be no zero-impact man. But the lesson is not to approach consumption fatalistically, but to rationally assess the costs and *relative* magnitude of impacts compared to reasonable alternatives. For example, it is quite true that it requires silica mining and a significant amount of energy to produce solar panels. They carry a cost, but the cost is orders of magnitude lower than that of fossil-based alternatives (natural gas or coal), and it is disingenuous to oppose renewable energy on the basis of such costs (biofuels being, in my opinion, an exception where the costs truly do often outweigh the benefits).

This principle should also warn one against a kind of rebound effect which might manifest, for example, when the owner of an electric vehicle considers his ride "zero-emissions." Yet, electric vehicles require large amounts of (surprisingly) electricity, the production and delivery of which is the single largest source of greenhouse gas emissions in the US. Compared to the alternative of a comparable gasoline vehicle, electric vehicles surely reduce carbon emissions, but by no means eliminate them.

2.3 Lifecycle assessment as a foundation

In determining the environmental impact of a particular product, fuel, or technology, etc., it is important, insofar as possible, to assess impact over the entire *lifecycle* of the item in question, and I attempt to do so throughout this book. A complete lifecycle assessment is often termed a "cradle-to-grave" analysis, while more limited assessments, e.g. a "cradle-to-factory gate" may be performed. For example, at the tailpipe, gasoline combustion generates about 8.887 kgCO_2e per gallon of fuel, but the extraction and refining of gasoline generates about 2.26 kgCO_2e/gallon, and so our "well-to-wheel" emissions factor is a larger 11.146 kgCO_2e/gallon. To more completely assess the impact of personal vehicles, we should also consider the carbon footprint of vehicle manufacture, maintenance, and disposal, and over the expected vehicle lifetime, this increases the global warming impact of driving by about 10%. We may go even further, and estimate the carbon emissions embodied in the infrastructure that supports vehicle travel (roadways, parking, etc.) for an extended lifecycle analysis.

In general, for more or less direct energy uses, including transportation fuels (gasoline and diesel), electricity, and direct fuel use (e.g. residential natural gas), lifecycle emissions are dominated by the use-phase (or generation phase, for electricity). The environmental impact of food, on the other hand, is dominated by production-level emissions.

2.4 The discipline of the mind

> You don't use science to show that you're right, you use science to become right
>
> *xkcd.com (Randall Munroe)*

I should like to briefly emphasize that it is essential to approach any study dispassionately and with the discipline of mind to (at least sincerely attempt to) reach a conclusion based only on what the data and science show, whatever one's prior ideological leanings. This is especially important in environmentalism, where any number of controversies are animated by fierce passions, such as those concerning nuclear power, alternative energy, natural gas fracking, organic and sustainable agriculture, plastic bag bans, etc. In some cases, the conclusions of my own inquiries do not necessarily conform with what might be viewed as the "default" environmentalist position, but of course in many they do, while in still others wholly firm conclusions are difficult to arrive at. Regardless, I attempt a sincere inquiry throughout this text.

2.5 The promise and peril of efficiency

- Energy-efficiency, via such technologies as high-efficiency vehicles, LED lighting, etc., can markedly reduce one's carbon footprint, but one must have a care that improved efficiency is not used as a license to increase consumption in response, a phenomenon known as rebound.
- The rebound factor (RE) quantifies the fraction of expected energy savings from an efficiency measure that fails to be realized due to an induced increase in energy use, with RE = 100% implying no net energy savings, and RE > 100% a special case, also known as Jevons' Paradox, where increased efficiency leads to a net *increase* in energy consumption.
- Energy-efficiency governmental mandates, such as CAFE fuel economy standards, are probably effective in reducing net energy use and carbon footprint and have very dramatically increased the efficiency of many major appliances over the last couple decades, but it must be noted that economy-wide energy efficiency has been increasing since the early 1800s, in the face of massive net increases in both energy and carbon emissions.
- Efficiency advances can, in an ideal scenario, synergize with reductions in overall consumption, a case where RE < 0%, and it is within the power of the individual to realize such a scenario in their own habits (e.g. both drive less and take a hybrid or upgrade the AC while changing the thermostat).

With the "oil shocks" of 1973 and 1979, Western governments, including the US, enacted various energy-efficiency measures. In the US, major legislation was first introduced in 1975, with the Energy Policy and Conservation Act (EPCA), which included the Corporate Average Fuel Economy (CAFE) standards for passenger cars, probably the most effective piece of energy-efficiency legislation in this country by a wide margin [204], and largely responsible for a 65% increase in new car fuel economy from 1973 to 1987, as well as more recent increases in fleet-average economy. Thirty years later, the Energy Policy Act of 2005 was enacted, followed closely by the The Energy Independence and Security Act (EISA) of 2007. Geller et al. [204] estimated that various energy efficiency policies and programs saved 11% of the US's primary energy use in 2002, and the EISA has been projected to reduce energy consumption by 9% in 2030, relative to a business-as-usual scenario [18]. It seems obvious then, that efficiency standards are an effective means of combating climate change and conserving resources.

However, despite the fact that the conservation measures mentioned above have clearly markedly decreased US energy consumption and carbon emissions compared to a counterfactual where such measures were not enacted, *all else being equal*, the true effectiveness of efficiency standards/increases in reducing overall energy consumption (and hence carbon emissions) has been of some controversy: increased efficiency also reduces the cost of energy use, and thus consumers and/or manufacturers have an incentive to increase energy consumption, and the degree to which the expected efficiency offset is reduced by increasing consumption referred to as the rebound effect (RE).

The rebound effect may be simply quantified as the fraction (or percentage) of the expected energy offset of increasing an energy end-use that is not ultimately realized; this can be mathematically expressed as [13]:

$$\mathrm{RE} = 1 - \frac{\mathrm{AES}}{\mathrm{PES}} \tag{2.1}$$

where PES is potential energy savings, and AES is the actual energy savings. As an example, suppose a new light duty vehicle consumes 50% less fuel per mile, but because of the reduced cost of driving the owner drives 20% more miles, and hence 20% of the energy offset that would have been achieved without this behavioral response is lost, and the RE is 20%. Thus, an RE of 0% implies the efficiency offset is exactly as expected (no behavioral or other downstream response), an RE $> 0\%$ means that at least some of the expected energy savings are lost, with an RE $= 100\%$ implying no net energy change at all (for example, a 50% reduction in fuel per mile with a concomitant doubling in miles driven). The prior example is one of a *direct* RE effect, where the expected reduction in energy use was undermined by a direct increase in the end-use made more efficient; a second example might be leaving a more efficient light bulb on for longer than one would otherwise.

The *indirect* rebound effect (potentially) arises when energy-efficiency improvements result in monetary savings on direct energy expenditures, which are then in turn put towards other goods or services that themselves embody large amounts of energy and/or emissions. However, direct energy sources, which for consumers are mainly gasoline, electricity, and natural gas, all have extremely high CO_2e per dollar emissions factors, amounting to about 4.5 $kgCO_2e/\$$ for gasoline, 5.2 $kgCO_2e/\$$ for electricity, and 7.5 $kgCO_2e/\$$ for natural gas[1] which are all about 5–10 times the $CO_2e/\$$ factors for most other consumer expenditures (except for certain food categories, such as beef; see Chapter 23 on goods and services), and this, very crudely, suggests that the indirect rebound effect, at least with respect to carbon emissions, is unlikely to exceed 10–20%, on average. Note that any direct RE also reduces the potential magnitude of the indirect RE by absorbing some of the monetary savings [17].

Finally, energy efficiency may result in an *economy-wide* rebound effect, whereby newly available energy resources may be put towards other ends, or changes in energy supply and demand promote overall energy consumption. Especially for efficiency improvements in the *production* of goods, it may be possible for RE to *exceed* 100%, the special case where total energy consumption actually increases with efficiency improvements. The notion that RE can be >100% was perhaps first elucidated (although in different terms) by the nineteenth century British economist William Stanley Jevons, whose famous paradox (which is referenced several times throughout this book), was formulated in reference to coal consumption, and can be summarized best in his own words [19]:

> *It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.*...It is the very economy of its use which leads to its extensive consumption...It needs but little reflection to see that the whole of our present vast industrial system, and its consequent consumption of coal, has chiefly arisen from successive measures of economy...Civilization, says Baron Liebig, is the economy of power, and our power is coal. It is the very economy of the use of coal that makes our industry what it is; and the more we render it efficient and economical, the more will our industry thrive, and our works of civilization grow.

Indeed, to partially reiterate the final point above, the whole industrial revolution may perhaps be regarded as a manifestation of Jevons' Paradox, with increasingly efficient uses of fossil energy leading to their global adoption across almost every sector of human activity.

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[1] Factors derived using 11.146 $kgCO_2e$/gallon and \$2.50/gallon for gasoline, \$0.13/kWh and 0.682 $kgCO_2e$/kWh for grid-average US electricity, and 0.2613 $kgCO_2e$/kWh and \$0.035/kWh for natural gas.

However, we must caution that Jevons was explicitly referring to the use of coal in manufacturing and industry and *not* its domestic consumption, even stating

> I speak not here of the domestic consumption of coal. This is undoubtedly capable of being cut down without other harm than curtailing our home comforts, and somewhat altering our confirmed national habits. The coal thus saved would be, for the most part, laid up for the use of posterity.

Thus, it is entirely sensible that increasing the efficiency by which an energy source is exploited towards productive ends may lead to an economy-wide net expansion of its use and indeed, this is not always a negative: increased efficiency of solar cells and wind turbines helps drive the wider adoption of such technologies. However, most individual and domestic uses of energy are somewhat dissimilar, where energy demands are being used toward relatively inelastic demands: one only wants/needs to drive so many miles, and the most comfortable room temperature does not change with a heater's efficiency. How efficiency improvements at the consumer-level interact with the larger productive economy is an open question, and in this case modeling studies suggest that the economy-wide RE could range from $< 0\%$ (i.e. net energy decreases beyond those expected) to $> 100\%$ [13].

One problem with many studies on the rebound effect is that they consider only the use-phase cost of efficiency measures, failing to account for the substantive up-front capital costs often associated with more efficient technologies or other energy-conservation measures: upgrading HVAC equipment costs many thousands of dollars, high-efficiency lighting is relatively expensive, insulation does not come for free, the premium for an electric vehicle is on the order of $10,000 or more, and solar panels can run into the tens of thousands as well. Such costs reduce one's spending potential (at least in the short-term), and clearly provide an incentive to maximize one's return on investment, thus quite plausibly driving both direct and indirect REs < 0. That is, there may be a greater than expected direct benefit from efficiency measures, because now the consumer is more invested in reducing use-phase energy costs, while the implementation costs counteract (short-term) any indirect rebound, possibly pushing it negative.

Furthermore, government-mandated efficiency standards for passenger vehicles and appliances, including major energy-users such as air conditioners and heaters, incur a cost to the manufacturer without any energy savings benefit at the manufacturing stage (explaining the general opposition of such mandates by industry), a fact that is typically disregarded [17], and thus we can expect a potentially negative indirect RE at the producer level, which may also act to contract the economy and force economy-wide RE < 0. Given this, we have little reason to think that such mandated efficiency advances will lead to a Jevons' Paradox. Another general problem with economy-wide studies is that they rely on general equilibrium models of the economy, and assume the existence of that fantastical beast, *homo economicus*, who always seeks to increase his utility via consumption, despite evidence that this corresponds but poorly with reality [13].

Suffice it to say that both indirect and economy-wide REs for efficiency improvements in consumer energy end-uses are highly uncertain, may even be negative once upfront capital and manufacturing costs are accounted for, and in any case, since most energy use and associated emissions in the American economy are ultimately driven by consumption, it is difficult for me to imagine that any program of collective conservation at the consumer scale could lead to anything like Jevons' Paradox, so long as our overall goal is to decrease our *total* individual energy and GHG footprint.

Returning now to the direct rebound effect, multiple studies have attempted to quantify the direct RE for automobile travel, heating and cooling, appliances, etc., and these tend to show relatively small, although positive direct REs [17], suggesting that efficiency standards and advances are indeed effective means for conservation, but with benefits slightly smaller than might be expected *prima facie.* There is a fairly extensive econometric literature devoted to quantifying the rebound effect for fuel efficiency and motor vehicles, and as reviewed in [14], the vast majority of works have concluded that the direct RE is small, in the 5–30% range (notwithstanding a few outliers); similarly, Gillingham et al. [17] found that most recent direct RE estimates for both gasoline and electricity use fall in the 5–25% range. Additionally, Small and and Van Dender [14] concluded that the RE has fallen over time, and moreover, that the RE tends to be smaller for wealthier households. As a general rule, direct energy use by the better-off is relatively independent of energy prices: the wealthy will drive what they will regardless of the price of gas or their vehicle's MPG, and condition their homes to comfort, rather than the price of heating fuel or electricity.

The final point I would like to emphasize is that, optimally, it is within the power of the consumer to approach efficiency and total consumption such that they act not to cancel (at least partially) each other out via rebound, but with synergy. For example, consider upgrading from a typical American passenger vehicle to the best hybrid on the market today, and one may increase their MPG from about 22 to 56, saving an impressive 60% of fuel emissions; reduce miles driven by 20%, and the overall fuel costs drop by nearly 70% from baseline. Upgrading HVAC equipment and insulation such that one's home uses 30% less energy for heating and cooling, *in conjunction* with reasonable thermostat strategies that also avoid 30% of heating/cooling energy from baseline yields a net 51% energy savings.

This general idea applies to other conservation measures as well. For example, in the Phoenix, AZ area I have noticed that it is common for many roof-top solar installers to promote, at least in advertising materials, the notion that solar gives a license to consume more: "Go ahead and turn down the AC, you've got solar." Now, to be sure on balance such an approach will still yield net fossil energy savings, but consider two hypothetical counterfactuals, where we begin with a household using 20,000 kWh of electricity per year, equivalent to about 13.64 $MgCO_2e$. In the first case, suppose a rooftop solar system is installed that offsets 10,000 kWh/year, and the family uses an additional 2,000 kWh (equivalent to a 20% RE), and so ultimately 12,000 kWh are drawn from the grid, yielding 8.18 $MgCO_2e$, a 40% total offset. In the second case, via efficiency improvements and behaviorial changes alone we first reduce energy consumption by 40%, to 12,000 kWh, an entirely plausible endeavor, and just as good as the final outcome in the first case. Now, adding our 10,000 kWh solar system drops final consumption to 2,000 kWh net, an impressive 90% total offset.

2.6 Is sustainability a luxury of the rich? (No)

It is common to see the idea of sustainability, especially by means of conscientious consumerism, to be derided as merely a luxury of the upper middle class. This is an absurd viewpoint almost on its face. At the national scale, carbon emissions increase strongly with GDP [4]; worldwide, per capita emissions are only about a third of US per capita emissions, and yet the US is the richest country. Within the US, household income is also strongly correlated with the household carbon footprint, which roughly doubles (on average) from the bottom to top income quintiles [2]. More wealthy households consume far more goods and services and tend to have larger houses that use more electricity and fuel. Wealthier individuals do not generally rely on public transportation, can drive more expensive cars with lower fuel efficiency, and are more free to engage in discretionary travel.

Luxury and performance vehicles tend to be very heavy, with very poor gas mileage, and in general, a higher base MSRP is correlated with a lower MPG for the top-selling vehicle brands in the US. Furthermore, lower income households have fewer vehicles per household, utilize transit more, and a greater proportion of car trips have multiple, rather than a single, occupants. Increases in income also are strongly correlated with increases in vehicle miles and more vehicles owned, with the richest households burning nearly thrice the fuel in about twice as many vehicles. Emissions from residential energy use increase by about 50% from bottom to top quintile, even when controlling for the larger size of wealthier households (see Section 11.2.4). When it comes to general goods and services, thanks to the profligate habits engendered by money, emissions of those in the top quintile of wealth are likely around 2.5 times those in the bottom quintile (again controlling for household size).

Curiously, the weakest association between wealth and consumption is found in the food category, at both the international level (although the association is still weakly positive at this scale) [4] and among US households [2]. Most food and agriculture emissions ultimately stem from animal products (organic or conventional), and the poor and rich alike eat similar amounts, with the wealthy just seeming to prefer more expensive versions of the same basic diet [2].

I will make this point again throughout the book, when appropriate, but the fundamental point is that, to a great degree, we must look to the poor as an example, and Americans must figure out how to live a lifestyle that is not so utterly dependent upon heavy energy and, indirectly, financial consumption. The American Way of Life must become negotiable.