Energy Use In American Food Production

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Introduction

Dale Pfeiffer (2006, 29) opens the fifth chapter of his book *Eating Fossil Fuels* with the statement, "Current civilization is founded upon an abundance of cheap energy derived from hydrocarbons." He presents the natural extension of that premise to food production in the opening of his sixth chapter, "Modern industrial agriculture is unsustainable. It has been pushed to the limit and is in danger of collapse" (Pfeiffer 2006, 39). The infrastructure and inputs used to supply Americans with their expected bounty of food are indeed highly dependent on fossil fuel energy sources in every aspect of food production, processing, distribution, preparation and preservation. Given the complex issues surrounding the security and availability of fossil fuels in the future, the thoughtful reaction to Pfeiffer's statements should certainly be one of deep concern and, perhaps, even fear for ourselves, our children and our civilization.

However, energy use by Americans for food only constitutes 12% to 17% of total current American energy usage. Given the overriding importance of food for daily existence and the integral role that food plays in human social life, it is not unreasonable to believe that present and future generations would accept a significant increase in that now-small share of energy in order to preserve essential portions of our reliable, diversified and mechanized food production and distribution system during and after a transition to renewable energy sources. Diets and food practices may undergo changes and other optional items in current American life may face reductions in availability, such as cheap imported plastic goods and expansive, inefficient single-family homes on large suburban plots. However, issues surrounding land, water and mineral resources as well as problems caused by environmental degradation, climate change and population growth will probably be considerably more disruptive to the American food system than the replacement of fossil fuels with renewables.

Concerns for the environment have given rise to an increased attention to carbon emissions and a cottage industry has developed for determining and promoting the "carbon footprints" or "food miles" of various products. However, the complexity of the American food production and distribution system makes realistic calculation of such values for specific products more of an exercise in philosophy than one of science. And a focus on individual products and isolated shopping decisions can lull activists into a false sense of satisfaction that distracts from the larger issues we can only address collectively as a country. While carbon is a serious problem, it is merely a symptom of a more serious disease involving the profligate use of cheap fossil fuels in short-sighted and unsustainable agricultural and development practices.

This paper will present an overview of how energy is used in the current American food system in the context of total American energy usage. Because the issues surrounding energy are well beyond the scope of individual initiatives, taking a “big-picture” view permits identification of the areas where energy use is most vital and the areas that should be candidates for modification if energy becomes more expensive and less available. With this perspective, it is hoped that some of the fear can be removed from consideration of food issues and replaced with a rational context for developing the constructive ideas and public policies that will be needed to pass on a more perfect union to the generations that follow us.

American Energy Production and Use

The ability to make observations about food and energy is hampered by presentation of the quantitative information on various energy sources and uses in formats and units that do not permit ready comparison. This limits the ability to understand energy demands in the context of total energy usage and in anticipation of the sustainable energy sources that will ultimately replace fossil fuels. Therefore, in this report most energy values are converted to and expressed in quadrillion British Thermal Units (Btu) per year (“quads”). Conversions to and from Btus and quads are discussed more fully in Appendix A. Use of quads makes it possible to contrast energy usage between different commodities and end-use food items with overall American energy use.

The use of quads is also convenient because the U.S. Department of Energy (DOE) reported total 2007 energy consumption (the most recent year available) at around 101.6 quads, making it possible to also see quads roughly as percents (e.g. 17 quads is approximately 17% of total U.S. energy use).

Future Energy Use Growth Projections

The DOE projects energy consumption in the country to grow through 2030 at an average annual rate of around 0.5% to 113.56 quads (EIA 2009, 109). The Census Bureau expects a average growth rate over the same period of around 0.9% from around 303 million at the end of 2007 to 374 million in 2030.

DOE projections to 2030 make assumptions about a continuation of existing production and development practices that are probably unreasonable. Notably, they include a 49% increase in domestic crude oil production (10.7 quads to 16.0 quads) to partially offset a 30% decrease in imported oil (21.9 to 15.4 quads). Both of those assumptions are are highly questionable (Duffeyes 2001, Silverman 2004), although presumably Fischer-Tropsch fuels derived from abundant domestic coal reserves (not included in the DOE reference case) involve proven technology and may be substituted for petroleum-base fuels to prolong the fossil-fuel addiction. Regardless, fossil fuel reserves are clearly finite and the question about the transition to renewables is not “if” but “when.”

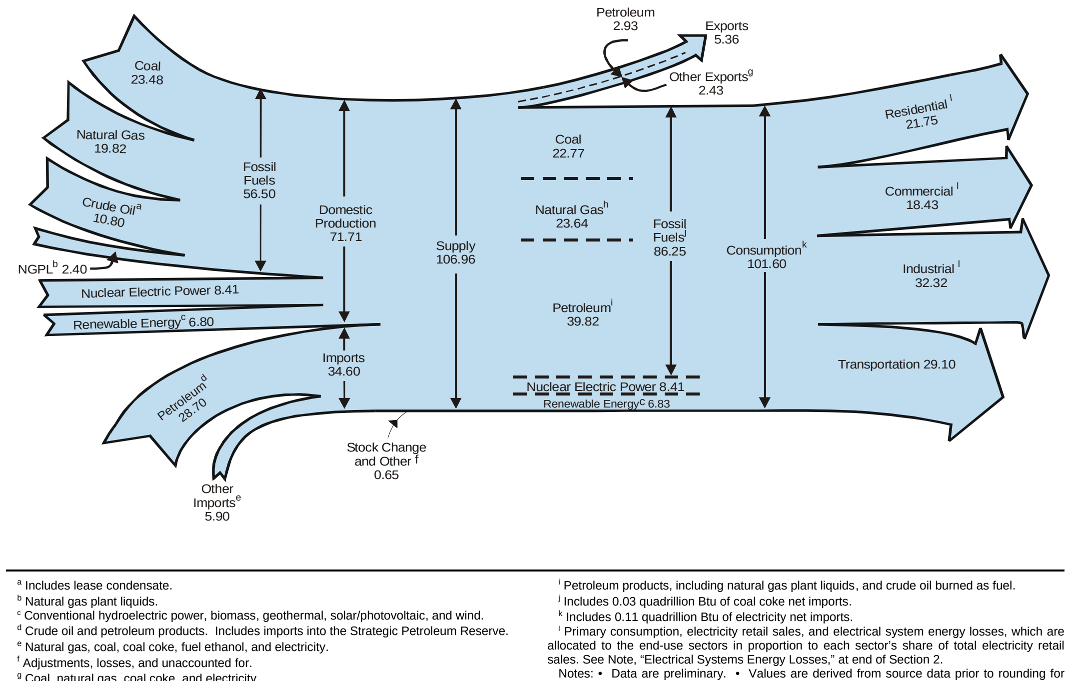

Figure 1: 2007 U.S. Energy Flow (EIA 2008)

Renewable Energy Potential

This raises the question of how much energy can reasonably and reliably be expected on an ongoing basis from domestic renewable sources. It also raises thorny logistic and political question about the timing of the transition and how food systems would adapt. This is large topic that is well beyond the scope of this paper, although it is possible to give some some hope that the energy is there if we can find the will and way to harness it:

- Hydroelectric: 2.5 quads. A 1979 U.S. Army Corps of Engineers study estimated that theoretical hydropower potential in the U.S. was 44.9 quads. Technically (and politically) feasible potential was estimated at 5.2 quads and economically viable potential at 3.7 quads, which was close to the 3.6 quad peak of hydropower generation in 1996 (EIA 2008, 279). Hydropower generation has been diminishing in the U.S. due to environmental conditions and considerations. Although small "run-of-the-river" plants are appropriate and worthy of encouragement in some situations, it is unlikely that American hydroelectric generation will increase dramatically in the foreseeable future (Pimentel 2002).

- Geothermal: 8.7 quads. The DOE estimates that the U.S. has the potential geothermal generation capacity of 100,000 MWe or 8.7 quads per year, not including more limited uses of geothermal for home heating and cooling (EERE 2008a). Current geothermal capacity is only 0.35 quads per year and significant technological breakthroughs will be needed to fully exploit available resources.

- Biomass: 12 - 20 quads. A report prepared for the DOE and the USDA estimated that 1.3 billion tons of biomass could be sustainably produced annually in the United States (Perlack et al 2005). Assuming conversion rates of 9,500,000 to 16,000,000 per tonne (depending on the type and condition of the feedstock) this could theoretically replace half of 2007 U.S.

petroleum consumption. Actual usable energy might be significantly less depending on the technology used to convert the biomass to fuel or energy, but energy loss of up to 67% is typical with current steam-cycle electrical generation, making these figures comparable to overall DOE numbers. (EIA 2008, 62). A more serious consideration is the effect of production of that much biomass on agriculture for food.

- Wind: 9 - 365 quads. The United States is estimated to have a potential capacity of 8,000 GW for terrestrial wind production and perhaps another 4,000 GW potential offshore, including resources not accessible with current technology (EERE 2008, Musial 2006). Using an average 35% capacity factor and the DOE's 2007 fossil-fuel generating heat rate (9,919 Btu/kWh), that translates to a total maximum of 365 quads reliably produced per year, not considering transmission losses and the considerable amount of energy that would be needed to construct and maintain such a massive fleet of turbines. A more realistic near-term goal is the 9 quads (300 GW) proposed by the DOE for 2030.

- Solar: 39 quads by 2050, long-term unknowable. The amount of solar energy striking the earth in 40 minutes is equivalent to an entire year of current global energy consumption. All renewable sources (other than geothermal) are direct or indirect forms of solar energy. The 250,000 square miles of land in the desert Southwest suitable for solar power plant construction receives over 4,500 quads per year in solar energy and construction of solar facilities on just a small portion of that land using current technology could theoretically supply all of America's energy needs (Zweibel et al 2007). A more practical vision would also incorporate distributed solar generation throughout the United States, such as with rooftop photoelectric panels coupled with home hydrogen electrolysis units. This potential is, to some extent, limited by political and environmental issues as well as the considerable amount of energy, materials and industrial infrastructure that would be required to build and maintain a completely solar national generation system.

The transition to renewables will certainly be disruptive and will likely not be painless. Convincing arguments can be made that current governmental and industrial processes entirely dependent on fossil fuels will not be politically, socially, economically or technologically capable of constructing and supporting the massive infrastructure needed to harness renewable energy at anything close to the levels that we have become accustomed to in the fossil-fuel-era. Additional instabilities caused by overpopulation and climate change could distract humanity even further from the focused effort needed to make the transition - conceivably reversing 600 years of human development (Kunstler 2005). But we can't know where we're going until we have an understanding where we are.

And, first, we need to eat.

Overall Food Energy Use Models

The DOE, Department of Agriculture (USDA) and Department of Commerce provide a significant amount of data on energy use and economic activity in various parts of the food sector, but there is no officially released government figure on the total amount of American energy consumption directed specifically to food. Indeed, because of the complex interdependencies of our modern industrial society, it is practically impossible to definitively isolate food activity from other aspects of American life since food energy use is distributed across the residential, commercial, industrial and transportation sectors broken out by the DOE. But that hasn't stopped folks from trying.

The 1973 OPEC oil embargo precipitated an "energy crisis" that resulted in a flurry of energy research, including the beginnings of contemporary food energy analysis. Numerous studies since the 1970s have presented models suggesting that between 10% and 17% of total American domestic energy use is devoted to feeding its populace. All of these models involve a multitude of assumptions and estimates, which results in widely varying figures that are open to considerable debate.

The following pies summarizes four models of U.S. energy use for food from field to plate. Numbers from the baseline years of the studies are extrapolated forward to 2007 under the assumption that food energy use increased at approximately the same rate as population and energy use during that period. However, the extrapolation should not be viewed with any assumption of accuracy due to advances in efficiency, new packaging technologies, more complex international food flows, and changing dietary composition. The extrapolation is provided to permit comparison with other analysis and individual constituent items later in this document.

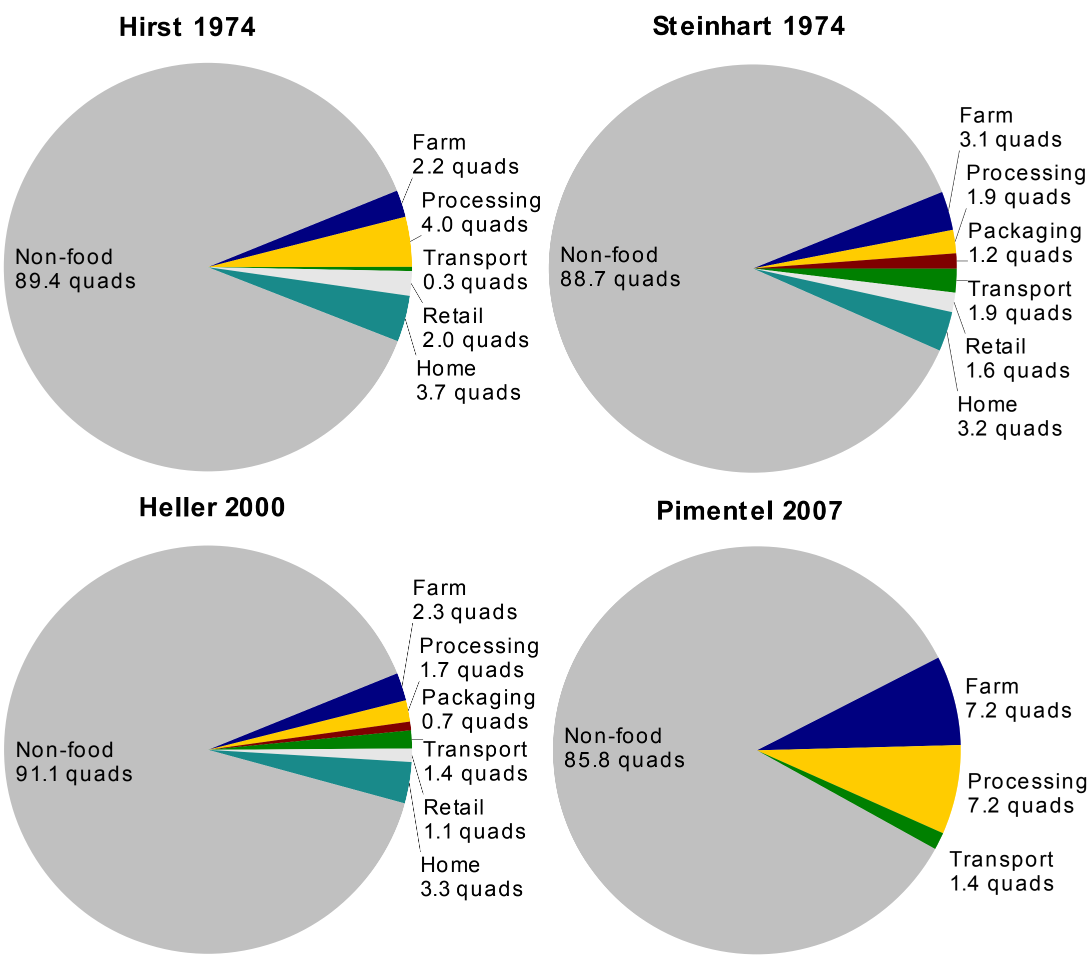

Figure 2: Percentages of total energy for different food energy models

Steinhart 1974: One of the first papers to come out of the early days of food energy analysis was a model by John and Carol Steinhart which estimated total U.S. food system energy use in 1970 at around 8.6 quads, or 12.7% of the 67.8 quads of total energy use in the country at the time. Their model is important for its level of detail and for its fairly liberal inclusion of full life-cycle costs such as the energy used in construction of farm equipment amortized over the lifetime of that equipment's service. Such inclusions of secondary energy usage give a better picture of how much renewable energy will actually be needed to maintain anything like the heavily-mechanized system to which Americans have become accustomed.

Hirst 1974: Another energy-crisis-era model was proposed by Eric Hirst. Hirst's model also claims to be as liberal as Steinharts, but the numbers are less detailed and the presentation of the model is a bit confusing. Also, Hirst uses numbers from 1963 that were already a decade old when he proposed his model, adding additional questions about how valid his model could be for use today. However, Hirst is referenced by Pimentel in 1996 via Lynch in 1976, which makes inclusion of his model valuable for comparison.

Heller 2000: A more contemporary model was released in 2000 by Martin Heller and Gregory Keoleian at the University of Michigan's Center for Sustainable Systems as a part of a study of the broad range of life-cycle issues associated with the U.S. food system. Their model estimated food system energy use at 10.2 quads or 10.4% of total U.S. energy use in 2000 (Heller and Keoleian 2000, 39-42). Their report distinguishes itself over other models in the clear details of how they reached their numbers based on official government statistics. However, the authors clearly state that they are not including estimates of energy use for equipment manufacture, which may account for why their estimate is somewhat lower than other models. There are also myriad places where current government statistics are simply inadequate for computing accurate energy values.

Pimentel 2008: David Pimentel is an agricultural sciences professor at Cornell University who has done extensive work on food energy research since the 1970s. His conclusions have often been regarded as pessimistic since the early days of his career (Gordon and Pryor 1976). He also has a tendency to use old data that gives questionable estimates when applied to more efficient contemporary agricultural conditions (Wang 2005) and some of the numbers in his published work literally do not add up (Pimentel 1996, 100, 133, 135). However, he is a widely-published and widely-cited author and his analysis is certainly worth consideration at an individual crop level even if the numbers may be a bit high when aggregated across the entire food industry.

In the third edition of his book *Food, Energy and Society* (2007, 347-348), Pimentel gives a figure of 15.8 quads annual energy usage (15.6% of total U.S. energy consumption), with 7.2 quads for production and 7.2 quads for processing. However, he gives no specific methodology for obtaining those numbers. His citation, the U.S. Census Bureau's *Statistical Abstract of the United States 2000*, does not seem to contain that specific number, although we can presume that he uses a model similar to Heller for deriving energy use from a range of statistical values. It should also be noted that Pimentel's 2007 number is slightly less than a 17% number given in the second edition of his book (1996, 8), which was based on Leach's 1976 model, which was in turn based on Hirsch's 1974 model of the U.S. in 1963.

Suspicion can be added to all the 1970s models due to dramatic improvements in farm sector energy efficiency in the post-embargo period between the mid 1970s and early 1980s (Cleveland 1995, 117).

Energy Use in Food Life Cycle Phases

The following is a model that extends the analysis of older models to better reflect current American food energy use. Explanation of the methodology follows in this section along with analysis of and comparison to the four older models introduced above.

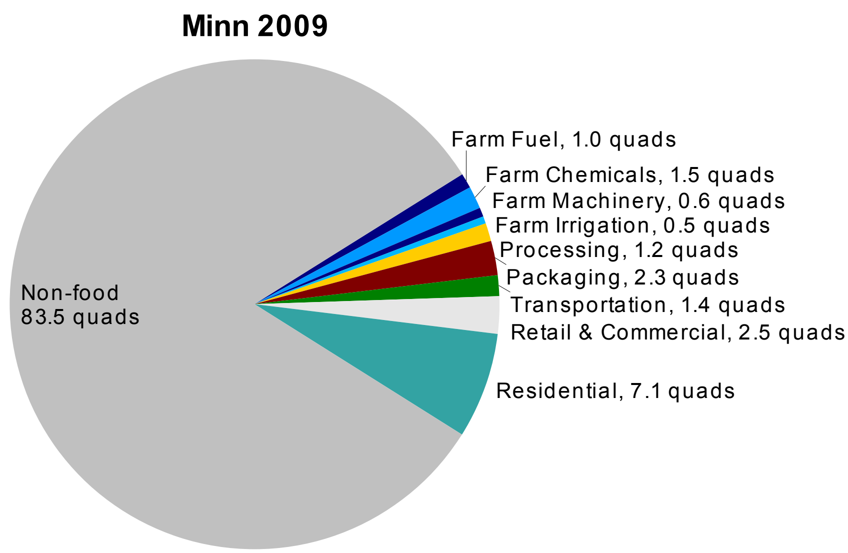

Figure 3: A proposed model for food energy use in 2007

Farming

The various older models place energy use in agricultural production between 2 and 7 quads. The Steinhart model extrapolates to 2007 at around 3.1 quads The Heller model puts agricultural energy use somewhat lower at 2.2 quads, although adding amortized energy needed to manufacture farm machinery (which is not included in the model) might put the number a bit closer to the 3.1 quad Steinhart value. The USDA estimated 1993 farm energy use (just fuel and chemicals) at around 1.5 quads (ERS 1997), which would extrapolate to 2007 as around 1.7 quads and is almost certainly low. The highest number is Pimentel's 7.2 quads, but in the absence of supporting methodology, that number cannot be explored. This model puts agricultural food production energy usage around 3.3 quads.

Farm Fuel: 1.0 quads

Unfortunately, the USDA reports farm fuel use as dollars spent on all different kinds of fuel rather than in specific fuel volumes or energy equivalents (ERS 1997, 136). Therefore, Heller had to estimate fuel use based on total fuel expenditures divided by average fuel costs and old statistics for how much of different types of fuel are typically used in farming. As such, his numbers cannot be viewed as precise. The last USDA estimate in 1993 would extrapolate forward to 2007 at around 0.9 quads.

Farm Chemicals: 1.2 quads

There are a wider variety of statistics available for farm chemical inputs, but computation of exact energy use is complicated by the wide variety of different commercial products (such as multi-nutrient fertilizers), the high percentages of inactive (filler) materials in applied products and the substantial amount of imports.

Hirst's model extrapolates forward to 2007 as 1.22 quads for farm chemical energy, significantly (and inexplicably) higher than Steinhart's 0.588 quads. While farm fuel efficiency has improved significantly since the 1970s (primarily from a switch from gasoline to diesel-powered farm machinery), efficiency improvements in farm chemical manufacture have not been as significant (ERS 1997, 136). The DOE's 2002 Manufacturing Energy Consumption Survey (MECS) reported around 0.5 quads used for domestic fertilizer manufacture and that number would extrapolate to around 1.1 quads in 2007 when imports and consumption increases are considered. Since the DOE number seems fairly close to Hirst, a figure of 1.5 is used to make an allowance for additional pesticides, fungicides and herbicides.

Fertilizers are used primarily to add nitrogen, phosphorus and/or potassium to the soil. U.S. farmers applied 58 million tons of fertilizer in 2008, which amounts to around 21 million tons of nutrients after inert ingredients are discounted. 36 million tons of that material was imported and the US exported around 12 million tons (ERS 2009a, 2009b). Imports account for half of the nitrogen and 80% of the potassium (potash), although the US is a net exporter of phosphorus rock (Huang 2004).

From an energy perspective, nitrogen is the most significant of the farm chemical inputs because it is primarily extracted from the atmosphere using the energy-intensive Haber-Bosch process. That process today is primarily driven with natural gas and U.S. imports of nitrogenous fertilizer from Trinidad/Tobago, Canada and Russia have increased because of their large supplies of natural gas. Using a manufacturing energy intensity of 24MM-34MM Btu/ton, the 13.1 nutrient tons of nitrogen fertilizers used in 2008 represent between 0.32 and 0.45 quads of total energy use (ERS 2009a; Worrell 2000, 17), much less than the the extrapolated DOE number of 1.0 quads.

Although natural gas is the primary feedstock for current implementations of the Haber-Bosch process for manufacturing fertilizer, it is possible to replace natural gas with hydrogen created via water electrolysis using renewable wind or solar energy. Ammonia also makes an excellent vehicle fuel, presenting the possibility that fully exploiting wind resources over Midwestern farms could make them both sustainable and energy self-sufficient (Hofstrand 2009).

Farm chemicals are essential to modern agricultural practices. However, their severe direct environmental impacts and questions about production sustainability (notably unrenewable mined phosphorus) are more important than the 1% to 1.5% of total current U.S. energy use they now represent.

Farm Machinery: 0.6 quads

Consideration of the sustainability of mechanized agriculture must also consider the energy and infrastructure needed to produce farm machinery. Steinhart's 1974 model extrapolates to 2007 at 0.590 quads (machinery + tractors). Heller does not even attempt to calculate a value and computing a meaningful value would involve research beyond the scope of this paper.

The DOE's 2002 MECS (EIA 2002) does not have a specific category for for farm equipment manufacture, although a portion of that is likely a part of the 0.429 quads used for the manufacture of transportation equipment. Of more concern are the material inputs for manufacture, which probably include parts of chemicals (6.465 quads), metals (2.120 quads), plastics and rubber products (0.351 quads), and flat glass (0.063).

The U.S. farm machinery industry shipped $13.4 billion worth of machinery in 2000 and the U.S. is a net exporter of farm machinery with 2001 exports of $3.9 billion versus $3.4 billion of imports. The economic statistics are not of much value in determining energy values, but they do indicate that computations do not need to be directly adjusted for imports (ITA 2009). However, the multi-national scope of manufacturing supply chains would not remove consideration of imports from any analysis.

A larger concern about the future of farm machinery manufacture might be the complete dependency of the steel industry on coal and natural gas. Brazil has successfully produced steel using plants fired with biomass and biomass-derived inputs (Scaife 2001), although questions can be raised about the sustainable availability of enough biomass to support all the industries and sectors that have their eyes on biomass for future use.

Farm Irrigation: 0.5 quads

Agriculture accounted for around 52 trillion gallons of water use or around 41% of fresh water withdrawals in the U.S. in 2000. Around 85% of that use was for irrigation use in 19 arid western states. 59% of irrigation withdrawals were from surface water and 41% from ground water. 96% of agricultural water use was for irrigation. Only 4% of agricultural water is used directly for livestock and aquaculture, although adding in water used to grow forage and feed dramatically increases that number. Around 55 million of the 442 million acres of cropland (12.5%) in the U.S. are irrigated (ERS 2006, 25-27).

Using estimates by Pimentel et al (1997), the energy needed to move all that water around in 2000 was 0.48 quads, a number that may still be relevant since the amount of irrigated land has actually been slowly decreasing since the mid 1970s. The Electric Power Research Institute (EPRI 2002, 1-5) estimated 2000 irrigation electricity use at 0.234 quads (23.6 MM kWh), which is significantly below Pimentel. Extrapolation of Steinhart's model from 1974 places the figure at 0.280 quads and the Heller and Hirst models do not explicitly say how or if irrigation energy is accounted for. Pimentel's pessimistic number is used in this model to be safe.

Access to water may well be the major resource issue of the 21st century (Shiva 2002, ix) and is of especially grave concern in the arid western parts of our country that supply a significant portion of our fresh fruits and vegetables. The 0.5% or less of current U.S. energy usage needed to pump that water for agriculture is the least of America's worries.

Processing: 1.2 quads

Energy for food processing is one of the few values in this report that is directly tracked by the government. The DOE's Manufacturing Energy Consumption Survey lists food manufacturing as using 1.123 quads of energy, including 0.217 quads for wet corn milling, 0.112 quads for sugar processing and 0.047 quads for fruit and vegetable canning (EIA 2002).

Based on changes in overall energy use, the DOE number would extrapolate to around 1.17 quads in 2007, which is not too far away from the extrapolation of the Steinhart model from 1974 to 1.8 quads. Pimentel's number of 7.2 quads is well beyond any of these estimates, although it may include commercial food service and retail energy, which is detailed in separate sections below.

The DOE number does not include the manufacture of food processing machinery, which the Steinberg model puts at 0.036 quads.

Packaging: 2.3 quads

Model estimates for the amount of energy spent on packaging range from Heller's 0.696 quads to Steinhart's extrapolated 1.229 quads for 2007. DOE does not break out any specific categories for packaging energy use. However, the actual amount of energy may be more in the range of 2.3 quads depending on exactly what is considered to be food packaging.

Heller's methodology assumes that almost all packaging ends up in municipal waste. Since the EPA does regular detailed analysis on what is in the municipal waste stream, the Heller model multiplies the waste figures by values from a Swiss study on energy needed to produce various types of packaging. The biggest ambiguity regards how much of the corrugated box cardboard (38% of all paper packaging) is part of the food distribution stream. Heller limits his analysis only to milk cartons and folding cartons, which may put his estimate quite a bit below a more liberal definition that includes paper towels, paper plates/cups, paper bags, and disposable diapers. Heller's number for plastics also seems quite low compared to 2007 statistics. For the purposes of the table below, all are considered plus 25% of the corrugated cardboard boxes.

	1998 (tons)	**2007 (tons)**	**MM BTU/ton**	**1998 (quads)**	**2007 (quads)**
Glass	10,610,000	11,500,000	10.6	0.112	0.122
Steel	2,860,000	2,680,000	23.1	0.066	0.062
Aluminum	1,530,000	1,870,000	82.1	0.126	0.154
Paper	5,880,000	21,327,500	45.7	0.269	0.975
Plastics	1,430,000	13,600,000	73.8	0.106	1.004
Total	22,310,000	50,977,500		0.678	2.316

Figure 4: Energy use in packaging extrapolated from US municipal waste statistics (EPA 2008)

One look at the detritus left over from a meal at a fast food restaurant says that something is wrong with the way food is packaged in America. And since none of the models deal with the energy and environmental costs of waste disposal, the energy costs of food packaging may actually be greater than the energy needed to raise the food in that packaging. This provides ample opportunity for optimization if energy costs start to make all that cheap packaging not so cheap anymore.

Transportation: 1.4 quads

Transportation in the United States accounted for 29.1 quads of energy use in 2007, the second-largest of the four major consumption sectors after industrial usage. 2002 annual freight activity totaled 3.1 trillion ton-miles, an increase of 18% since 1997.

Heller's estimate of food transportation energy use (extrapolated to 2007 at 1.4 quads) is based on the commodity flow survey in the Department of Transportation's 1997 Economic Census. Additional energy for trips to retail outlets is added based on Food Marketing Institute information on grocery shopping trips multiplied by private automobile energy usage from the DOE.

Heller's number is surprisingly close to Pimentel's implied number of 1.4 quads. Extrapolations from Hirst at 0.340 quads and from Steinhart at 1.906 quads may demonstrate the significant changes in shipping techniques and networks over the past half century, or simply the difficulty of applying such old models to contemporary conditions and technologies.

Consideration should also be made for the large amounts of energy needed to construct vehicles and maintain transportation infrastructure, although the absence of reliable data makes that impossible for this paper. Road construction and maintenance is an especially problematic area, which gives additional value to the prospect of increased use of more-efficient rail transport.

Although the concept of "food miles" is intuitively attractive, it is problematic because different transportation modes have varying levels of efficiency in the way they use energy. For example, because water shipping is considerably more efficient than long-haul truck, less energy may have been used to ship a banana to a town close to the Port of New Jersey than one shipped to Dallas, which has fewer food miles but more of those food miles traveled in a tractor trailer. Comparative freight energy values between transportation modes are discussed in Appendix A.

The dominance of energy use by transportation and the worldwide scope of the networks that provide America's food has lead to a growing movement toward "eating locally." Whatever cultural, dietary, environmental or culinary virtues there may be to the locavore movement, the geographic diversity and industrial character of the American food system has lead to an level of food security and price stability largely unknown in human history (Kinsey 2001). Abandoning that model would likely mean returning to an world with a more limited variety of foods, more widely varying prices and even areas of starvation in times of drought or flood. The 1% to 2% of total U.S. energy use for food transportation may well be worth the investment in the context of those larger issues.

Food Retail and Commercial Food Service: 2.5 quads

In contemporary American society, the phase of the food cycle between processing plants and the consumer is quite complex and different models have dealt with this phase in different ways.

Hirst provides a number for wholesale trade (extrapolated to 0.5 quads) and retail trade (1.5 quads) but no allowance is explicitly given for restaurants and other kinds of commercial food service. Steinhart has a single commercial sector value (extrapolated to 1.6 quads) and adds an additional 0.4 quads for construction of refrigeration machinery. Pimentel gives no explicit value for this phase.

Heller uses a more logical (and traceable) division between food retail and commercial food service which more intuitively reflects the two pathways through which most Americans get their food. Information for both sectors was obtained from the DOE's 1993 Commercial Buildings Energy Consumption Survey (CBECS). Figures below are from the 2006 CBECS and are multiplied by pre-combustion energy factors (see Appendix A).

Principal Building Activity	**Buildings**	**MM sq ft**	**Quads**
Office	824,000	12,208	2.620
Enclosed and Strip Malls	213,000	6,875	1.771
Education	386,000	9,874	1.610
Lodging	142,000	5,096	0.991
Warehouse and Storage	597,000	10,078	0.896
Food Service	297,000	1,654	0.881
Healthcare - Inpatient	8,000	1,905	0.778
Retail (Other Than Mall)	443,000	4,317	0.739
Food Sales	226,000	1,255	0.673
Public Assembly	277,000	3,939	0.654
Service	622,000	4,050	0.607
Other	79,000	1,738	0.498
Religious Worship	370,000	3,754	0.301
Healthcare - Outpatient	121,000	1,258	0.252
Public Order and Safety	71,000	1,090	0.214
Vacant	182,000	2,567	0.077
Total	**4,858,000**	**71,658**	**13.562**

Figure 5: 2003 commercial building energy use (EIA 2006)

Heller apparently uses the only the food service value (0.881 quads) for the commercial food service number and the food sales value (0.673 quads) for food retail. This ignores food service activity in malls, arenas, hospitals, schools and houses of worship. Energy use in food storage facilities should probably also be considered. With the crude assumption that 10% of the activity in those buildings is food oriented (explained below), this would add another 0.6 quads for a total of around 2.2 quads.

Industrial agriculture cannot exist without a corporate structure to provide management, planning, marketing and finance. Those activities typically happen in office buildings, which are collectively responsible for around 2.6 quads of energy use in the U.S. in 2003 (EIA 2006). Food and fiber accounted for economic activity of around $1.2 trillion in 2004 (Edmondson 2004) out of a gross domestic product of around $11.7 trillion (BEA 2009). Using using those numbers as the basis of an assumption that around 10% of U.S. office activity is related to the food system adds another 0.26 quads for a total commercial food sector energy use of 2.5 quads.

Heller does not consider any of the energy used for manufacture of commercial food service equipment, cleaning chemicals, worker uniforms, etc. or (perhaps most significantly) for construction and maintenance of food retail and service buildings. In 2002, concrete manufacture used 0.36 quads, wood products manufacture used 0.38 quads, metal production used 2.12 quads and machinery manufacturing use 0.18 quads (EIA 2002, USGS 2009, Mehta 2001). None of those numbers account for energy expended abroad to manufacture imported materials or equipment. In the absence of reliable data, none of those inputs are considered here, with the caveat that the indirect energy expenditure for commercial and retail food production may actually be substantial.

Household Storage and Preparation: 7.1 quads

Residential energy consumption in 2007 was around 21.8 quads or around 21% of all energy usage in the United States. Because residential energy use directly affects consumers and is under their direct control, quite a bit has been written about uses and wastes of energy in the home. Accordingly, while there are still ambiguities, estimating how much of that energy is connected with food storage and preparation is somewhat less difficult than determining energy use in other sectors.

Heller used DOE household energy consumption data from 1993 and 1997 to estimate home food energy use of around 3.3 quads. Extrapolations for Hirst and Steinhart are 3.7 quads and 4.8 quads, respectively.

Replicating Heller's methodology with electricity use percentage data from 2001 and total sector data from 2007 yields a significantly higher estimate of 7.1 quads. Some of the differential may be due to the use of primary electrical energy values (which include generating losses) rather than a straight transformation from household kWh to Btu. Major assumptions borrowed from Heller are that 25% of hot water and 57% of natural gas energy is used directly or indirectly for food preparation or cleanup.

Appliance	**% of Electricity**	**Quads**
Refrigerators	13.7%	2.063
Freezer	3.4%	0.519
Water Heater (25%)	2.3%	0.344
Dishwasher	2.5%	0.383
Electric Range Top	2.8%	0.423
Electric Oven	1.8%	0.278
Microwave Oven	1.7%	0.255
Electric Toaster Oven	0.2%	0.024
Coffee Makers	0.5%	0.079
Electrical food appliances	29.0%	4.368
Natural gas food appliances (57%)		2.760
Total home food energy use		**7.128**

Figure 6: 2007 home food energy use (EIA 2008, 2009a)

Heller does not consider any of the energy used for manufacture of home appliances cleaning chemicals, pesticides, garbage bags, utensils, etc. As with similar items in mentioned earlier with commercial food service, those values could not be considered here for lack of reliable data, but the amount of indirect energy needed to support those elements of the contemporary American lifestyle are likely significant.

If this model is correct, energy use in homes associated with food accounts for 40% of the total energy used for food in the United States. Home refrigerators and freezers alone account for account for 15% of total U.S. food energy usage. If the transition to renewables involves reduced energy availability and increased energy prices, Americans will likely pay much more attention to home appliance energy usage than they do now. We would certainly see a move to smaller and/or more efficient appliances. And there might even be a dietary transition away from fresh animal products (which are heavily dependent on refrigeration) and toward foods preserved with techniques that require less energy over their complete life cycle, such as canning and drying.

Food Imports

None of the energy use models take into account foreign energy used to produce imported food. Since the United States exports vastly more than it imports in terms of raw tonnage, consideration of import and exports may actually result in a net reduction in energy used to feed Americans. However, imports are dominated by fruit, vegetables and seafood, which are more difficult to produce in such quantities in America's temperate climate. And consideration should be given to potential adverse changes in domestic agricultural capacity and foreign political conditions that may be caused by climate change.

2007 Major Food Imports	**Tons**	**2007 Major Food Exports**	**Tons**
Fruits, fresh or frozen	9,995,457	Corn	62,606,006
Vegetables, fresh or frozen	6,574,975	Wheat	36,252,625
Malt beverages (hl)	3,830,593	Soybeans	32,870,900
Vegetable oils	3,435,474	Oil meal	9,070,624
Sugar & related products	3,325,225	Sorghum	6,236,375
Cattle & calves	2,750,228	Rice	3,848,320
Coffee & products	1,535,744	Poultry meats	3,282,485
Fruits, prepared or preserved	1,428,827	Fruits, fresh	2,917,616
Cocoa & products	1,244,733	Vegetable oils	2,806,581
Processed grains, ex. feed	1,195,126	Red meats & products	2,693,152
Beef & veal	1,095,558	Vegetables, prepared or preserved	2,344,256
Wine (hl)	949,950	Vegetables, fresh	2,132,218
Dairy products	360,858	Fruit juices	1,134,620
Total	**37,722,747**	**Total**	**168,195,779**

Figure 7: Major agricultural imports and exports in 2007 (ERS 2009c)

2007 tons	**Domestic**	**Imports**	**Exports**	**US Availability**
Edible fin fish	3,229,339	3,462,320	2,688,346	4,003,312
Edible shellfish	503,471	1,919,025	192,071	2,230,425
Industrial fin fish	876,050	244,619	647,887	472,782
Industrial shellfish	7,057			7,057
Total	**4,615,917**	**5,625,964**	**3,528,304**	**6,713,576**

Figure 8: Seafood imports and exports in 2007 (NMFS 2008)

Water

While water is only directly considered above in connection to farm irrigation, it is undeniably essential as a consumed commodity and an integral component of food processing, sales, preparation and disposal. The sale of bottled drinking water as a commercial beverage in direct competition with juices and carbonated drinks also plants water squarely in the realm of food.

Water utilities withdrew around 15.8 trillion gallons of water for public use in 2000 (USGS 2004, 9-10). Around 0.5 quads of energy (primarily electricity) were used directly by public water utilities and waste water treatment plants in 2000 (around 4% of electrical generation). This number is expected to grow to 0.8 quads by 2050 (EPRI 2002), although shortages of fresh water brought on by climate change (especially in the west) and subsequent changes in residential development patterns could change that number up or down. Fresh water shortages could also lead to more common use of energy-intensive seawater desalination, significantly increasing the amount of energy (and cost) for public water.

The rise of water sold in plastic bottles as a purchased commodity in the 1990s presents additional water-related issues. In 2007, Americans consumed around 9 billion gallons of bottled water (Arnold and Larsen 2007). In 2006, 44% of bottled water came from municipal supplies (Royte 2008, 38). Although that represents only around 0.02% of total U.S. public water supply usage, additional energy is expended to filter and bottle water. That energy is presumably included in DOE food processing energy statistics.

In 2007, manufacture of bottled water bottles required around 0.1 quads of energy for manufacture (Royte 2008, 139; Arnold and Larsen 2006). That value is presumably included above in packaging. Transportation by truck adds additional energy demands. However, the greater concern for the future of the bottled water may be a decreasing amount of petrochemical feedstock for polyethylene terephthalate (PET) bottle manufacture. The largest concern for society as a whole is not necessarily the energy used by bottled water but the problems with adding the additional tons of unnecessary single-use plastic waste bottles to the environment (Silverman 2009). Bottled water has existed as an extravagant profit-making convenience in the twilight of the fossil fuel era and, hopefully, will not survive the transition to renewables.

Selected Food Case Studies

Pimentel and others have presented a number of breakdowns of energy used in the production of different specific foods. Applying these models to total U.S. agricultural statistics in a "bottom-up" approach yields interesting results to compare with those derived from the "top-down" methodologies detailed above. However, the diversity of foods and combined food products in the American food stream, as well as the large number of assumptions included in the models, makes a bottom-up analysis for the complete American diet unrealistic.

Pimentel's general approach throughout his career has been to contrast energy inputs for producing specific foods to the amount of energy (calories) in the consumer-level product. By comparing the input/output ratios of different foods, it is then possible to identify foods that have poor conversion ratios for alternative growing options or, perhaps, reduction in dietary use. Reverse application of these models is used for some food groups below.

Grains

Grains and oilseeds accounted for around 26% of the almost $300 billion in agricultural products sold in 2007 (NASS 2008). Grains and soybeans dominate American agricultural exports, accounting for around 82% (by weight) of the 158 million tons of major agricultural product exports in 2007 (ERS 2009c). They also dominate the American diet with corn having a role at some point in much of what Americans eat (Hope 2008). Corn production alone may be responsible for as much as 7% of American food energy use, although large amounts of corn are diverted to animal feed and biofuels.

Because of their importance for food and for biofuels, energy inputs for grains and oilseeds have received quite a bit of attention in recent years. Pimentel has been at the center of controversy over the energy balance of corn ethanol (Wang 2005) and his numbers are used here.

	Total	**Corn**	**Soybeans**	**Wheat**	**Rice**	**Oats**
2007 MM Planted Hectares	88.31	37.44	26.20	22.46	1.10	1.12
2007 Production (MM lbs)	1039919	732138	160627	124020	19837	3298
2007 Availability (MM lbs)	730162	578904		132360	11849	7049
BTU / ha	101661150	32181386	7246158	10453894	43332841	8446870
BTU / lb	9140	1687	1746	2694	1678	1335
US Total quads (acreage)	1.686	1.205	0.190	0.235	0.047	0.009
US Total quads (production)	1.887	1.235	0.281	0.334	0.033	0.004
US Total quads (availability)	1.362	0.976		0.357	0.020	0.009

Figure 9: 2007 grain and oilseed production energy use (NASS 2009, Pimentel 1996, Pimentel 2005)

Terrestrial Animal Products

A consistent refrain for decades has been concern about the extraordinary resource demands needed to raise meat (Leach 1976, Pimentel 1980). There are certainly important environmental issues regarding land use, cereal grain diversion and waste disposal. Pimentel has been a long-time advocate for grass-only livestock production and has presented quantitative defense for his position.

The Pimentel's methodology for animal products is not clearly detailed and may not be entirely applicable given the changes in growing practices since his numbers were calculated. 2007 product availability numbers include imports and do not include exports.

While it is true that the input/output calorie ratio for meat production is considerably weaker than that for grains, the amount of energy needed for meat production may still be fairly small when viewed in the context of total energy use and the importance of meat to the American diet. Grass-fed alternatives can mitigate many of the resource and environmental issues (Pimentel 1980) although raising animals in unconfined settings can raise additional resource and health issues (McWilliams 2009). There are moral and health reasons to discourage excessive meat consumption, but the use of energy (or it's proxy, carbon) as a justification to promote an unrelated vegetarian agenda is distracting at best and dishonest at worst.

Product	1980 Product (MM lbs)	1980 Energy (quads)	2007 Product (MM lbs)	2007 Energy (quads)	2007 Product (%)	2007 Energy (%)
Chickens	11,067	0.072	25,537	0.167	10.0%	11.3%
Turkeys	2,293	0.025	5,275	0.058	2.1%	4.0%
Eggs	8,422	0.123	4,170	0.061	1.6%	4.2%
Sheep	1,631	0.028	342	0.006	0.1%	0.4%
Dairy	117,418	0.346	184,588	0.544	72.5%	37.0%
Pork	16,513	0.363	15,181	0.334	6.0%	22.7%
Beef	44,247	0.678	19,629	0.301	7.7%	20.5%
Total	201,591	1.636	254,723	1.471		

Figure 10: Estimated animal product production energy use (Pimentel 1996, ERS 2009d)

Seafood

Calculating food energy used for seafood is especially tricky due to the geographic dispersion of the fish stocks and the wide range of fish species used for both human and industrial consumption. Pimentel and others specify energy numbers for a handful of settings and species, but not enough to make anything close to a full accounting of energy use associated with seafood. The age of these numbers and the ever-changing amounts of transportation associated with different species makes the numbers additionally suspect.

	2007 MM lbs	Btu / lb	2007 Quads
Shrimp (farmed)	1,712	58,549	0.100
Tuna (canned)	812	74,650	0.061
Catfish (farmed)	584	34,235	0.020
Groundfish	431	50,906	0.022
Lobsters	122	60,979	0.007
Salmon (canned)	91	34,177	0.003
Total edible seafood	12,468		

Figure 11: Estimated seafood production energy use (Pimentel 1996; Rawitscher and Mayer 1997; NOAA 2008, 63-72; NCDACS 2008, 37)

While these energy numbers seem fairly inconsequential, special attention should be paid to farmed shrimp. 92% of the shrimp consumed in America is imported (NOAA 2008, 71), meaning that much of this energy expenditure is exported as well. And the bulk of American seafood consumption is not accounted for in this table due to lack of energy information for other species. However, issues with energy use pales in comparison to problems of overfishing, species loss and ocean pollution that could result in almost complete ocean fisheries collapse by mid century (worm 2006).

Beer

Americans consumed around 7,546 million gallons of beer (35,500 tons) in 2008, which works out to about 24.8 gallons for every man, woman and child in the country. 896 million of those gallons imported and American brewers exported an additional 141 million gallons (BMI 2009).

In 2007, the New Belgium Brewing Company, a small brewer in Fort Collins, CO, engaged the

Climate Conservancy to perform a detailed assessment of the greenhouse gasses emitted across the full life cycle of their Fat Tire (R) Amber Ale. The final determined number was 3,188.8 grams (around 7.03 pounds) of CO_2 emitted at the various stages of production, distribution and sales for each six-pack of beer (72 fluid ounces total) (Climate Conservancy 2007).

While this footprint value is unique to this particular company and the carbon emissions include more than just emissions from the burning of fossil fuel, certain elements of the life cycle are common to all brands. Notably, the largest item (28.1%) is emissions (primarily coal-fired electrical generator) associated with the electricity to refrigerate the product at the retail level. The second-highest item (21.6%) results from the production of glass bottles. While only 43% of beer is sold in bottles (Jones 2008), cans (at 40%) may involve similar or greater energy consumption, depending on the level of recycled material (Koerner 2009).

Given all the caveats above, applying the New Belgium CO_2 numbers to total beer consumption yields 283 million pounds of CO_2 and 3.63 quads of energy. Even removing the 1.0 quads for retail refrigeration leaves that number at an unreasonable 15% of total food energy use in the United States. This could mean that the CO_2 analysis is too liberal or that beer is the stealth energy hog of the American diet. Or perhaps a little of both.

The Future

Economics will ultimately play a key role in how diets and food practices change during and after the transition to renewables. Indeed, the move to renewables is being delayed primarily because the direct costs to generate energy with fossil fuel have remained low in spite of numerous predictions over the past few decades that fossil fuel prices could only increase over time (Darmstadter 2003, 4).

But though the timing of the prognosticators was off, the finite nature of fossil fuels makes it inevitable that a move to renewables will come sooner or later. Fossil fuel energy prices will increase to a point where renewables become economically viable and supplant fossil fuels. Those increased energy costs will inevitably affect food costs, especially foods that are more energy intensive than others . More limited energy availability could also result in reduced food availability, with resulting non-linear food price inflation and volatility well beyond what has been experienced in America since the dawn of the "Green Revolution." Consumers (especially the most vulnerable) would likely respond to those food shortages and cost increases with coping mechanisms similar to those used today by the poor and elderly, including consumption of alternative, less-preferred foods, reducing portion size, maternal buffering, skipping meals and/or going for one or more days without food (Maxwell 1996).

However, the food price spike of 2007-2008 (in the US and globally) gives some hope that the American food system may be diverse and adaptable enough to limit how much energy cost increases would affect consumer food costs. Between January 2007 and the peak of the spike in July of 2008, a 150% spike in crude prices lead to a motor fuel price spike of 80% and an overall energy cost spike of 53%. However, food prices only increased 10% in the same period and (in a curious bit of market calculus) never dropped, even after fuel prices retreated well below their January 2007 levels (Leibtag 2008). This indicates that energy is not necessarily as overwhelming

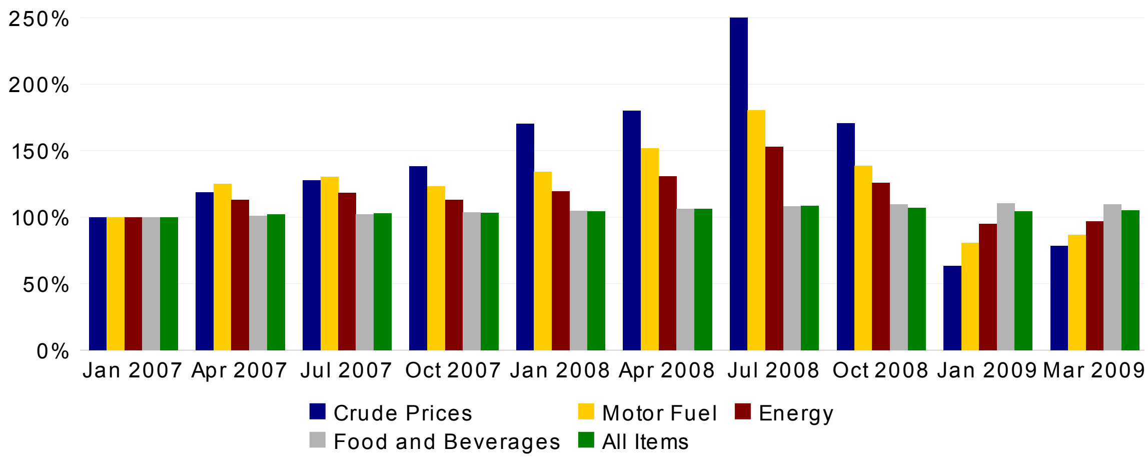

Figure 12: Indexed energy and food prices during the 2007-2008 energy price spike (BLS 2009, EIA 2009b)

a force in the food marketplace as the fossil-fuel dependency of the overall system might suggest.

Americans use twice as much energy per capita as Europeans, but that can be attributed, in part, to geography. Americans have twice the amount of per capita land, do twice as much traveling, generate twice the GDP, and average twice the per capita living space as Europeans. In Maslow's hierarchy of needs, food is one of the foundational requirements that all higher level aspects of life are subservient to (Maslow 1943). Presumably, our energy-intensive strivings for space, pleasure, freedom and achievement would take a back seat as food became more expensive and American living patterns would change accordingly. Crisis in the recent past has brought out the best in the American spirit and there is no reason to not to believe that it would do so in the future.

By putting the numbers for food energy usage beside the numbers for renewable energy potential, it is quite reasonable to assume that we can adapt to a post fossil-fuel era without having to give up much of the food convenience, variety and security that we have become accustomed to. But this is too large an issue to be solved by isolated individual purchasing initiatives alone. The primary question is whether humanity will be able to marshal the cooperation needed to make the banquet of the future as bounteous as the one bequeathed to us by our forefathers.

Appendix A: The Btu

A multitude of different units can and are used for measuring kinetic and potential energy, making it almost impossible to casually view specific figures in a larger context or in relation to other statistics. Energy contained in food is measured in calories, liquid fuel consumption is often expressed in fluid measures, and electricity generation is described in watts or watt-hours. The first law of thermodynamics states that energy may be transformed from one type to another but can never be created or destroyed (Pimentel 1996, 10-11). Following from this, conversion factors have been developed that permit different energy measurements to be similarly transformed from one unit to another.

In this document, the common unit of energy measurement is the British Thermal Unit (Btu), which was established in the late 19th century as the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit at a specified temperature (MWO 2009). This measurement is used for statistics by the U.S. Department of Energy's Energy Information Administration and, as such, is the most convenient of the multitude of options. Conversion factors to other units include:

1 Btu	1,055	Joules
1 Btu	0.252	kilo-calories (aka food "Calories")
1 Btu	778	foot-pounds
1 Quad	1,000,000,000,000,000	Btu
1 kWh electricity	3,413	Btu (direct conversion)
1 kWh electricity	9,919	Btu (fossil-fuel heat rate)

Figure 13: Btu conversions to other units of energy (ORNL 2009, BTS 2002, George 2006)

Energy Content of Various Fuels

Theoretical energy amounts present in various fuels can also be expressed in Btu's, although inefficiencies in engines, generators and transmission media make the actual amount of usable work that can be extracted from these fuels considerably smaller. The amount of energy in fuels also varies depending on formulation, quality and environmental conditions, although in some cases, standard equivalency units have been established to reflect average expectations.

Renewable kWh to Btus: Fossil Fuel Heat Rate

When dealing with DOE statistics, electricity from renewable sources (like hydroelectric and solar) is converted using a "heat rate" that represents the equivalent amount of fossil fuel that would be needed to generate a similar kWh of electricity. In 2007, the fossil fuel plant heat rate was 9,919 Btu / kWh, which reflects the fact that fossil-fuel plants on average only convert about 1/3 of the heat energy from the burning of the fuel into electricity (EIA 2007, 364). This value is calculated based on survey data from power plants and makes it possible to reasonably compare direct electrical generating capacity with comparatively inefficient thermal generation from fossil fuels. However, it adds a layer of complexity when trying to build models for a post-fossil-fuel future.

Measure	Fuel	Btu	Note
1 cubic foot	natural gas	1,027	
1 man	physical labor for a 10-hr day	42,500	
1 pound	Jet A fuel	19,970	(approx. 0.148 gallons)
1 US gallon	ethanol	75,700 - 84,000	(BFI)
1 US gallon	gasoline	115,000	(average)
1 US gallon	diesel	130,500	(average)
1 US gallon	bunker C (ship fuel)	153,600	(average)
1 bushel	corn to ethanol	200,000	(Shapouri et al 1995; BFIM)
1 barrel	oil (boe)	5,800,000	
1 cord	firewood (4'x4'x8')	15,360,000 - 23,000,000	
1 metric tonne	agricultural waste	9,500,000 - 16,000,000	
1 metric tonne	lignite coal	14,200,000	
1 metric tonne	anthracite coal	28,400,000	
1 megaton	TNT	3,965,666,831,390	

Figure 14: Energy content of various fuels (ORNL 2009, Shapouri 1995, Buffington 2008)

Consumer Btus to Source Btus: Pre-combustion Energy Factors

While DOE statistics for fuel supplies are generally converted using the average heat value of the fuel multiplied by the volume of fuel, statistics for fuels directly used by consumers (like natural gas and fuel oil) generally do not account for "upstream" losses in processing and transportation that reduce the net amount of energy that is actually available to the consumer. Losses are especially high for electricity, where fuel shipment, generation and electric lines consume around 2/3 of the energy in the source fuel burned to generate that electricity. For converting statistics for building energy use to the actual amount of energy needed to supply that energy, Heller (2000) multiplies by "Pre-combustion energy factors" so the numbers can be contrasted with energy supply statistics.

Source	Upstream Factor
Electricity	3
Natural Gas	1.12
Diesel	1.18
LPG	1.27
Gasoline	1.21
Coal	1.02
Residual Fuel Oil	1.17

Figure 15: Pre-combustion energy (upstream) factors for various fuels (Heller 2000, 59)

Efficiencies of Various Transportation Modes

By looking at overall freight tonnage and mileage along with fuel consumption, it is possible to calculate relative efficiency numbers for comparing different shipping modes. However, these numbers should not necessarily be expected in every situation since specific energy use will vary depending on cargo type, equipment condition, topography and environmental conditions (such increased energy needed to carry cargo over mountainous terrain or upstream in a domestic river).

Consideration should also be given to the unreliability of industry-reported statistics as well as the full "life cycle" energy use needed by different transpiration modes. For example, evaluations

Vehicle	Btu per ton-mile
International water	187
Freight railroad	330
Inland water	514
Long-haul truck	1,000

Figure 16: Comparative efficiencies of different transportation modes (Davis 2008, Carter 2006, RTISO 2009)

of truck transport energy use should also consider the vagaries of logistics and the considerable amount of energy expended in truck manufacture and maintenance as well as in road construction and maintenance. (Weber and Matthews 2008, Facana and Horvath 2006). International water shipping numbers may actually be as much as twice the values given below due to the unreliability of international fuel statistics (Corbett and Koehler 2003). As such, analysis based on these numbers is subject to debate.

Vehicle	Btu per ton-mile
International water	210
Oil pipeline	210
Inland water	300
Freight railroad	300
Long haul truck	2,800
International Air	10,500

Figure 17: Corrected comparative efficiencies of different transportation modes (Weber and Matthews 2008)

Carbon Footprint and Btus

The recent explosion of information on carbon emissions and carbon footprint can offer some insight in determining underlying energy use when those figures are not explicitly available. However, such an indirect analysis is unreliable both because of the differing methodologies used to generate carbon footprint numbers and because analysis data rarely includes information about sourcing from fossil fuels in enough detail to extrapolate fuel amounts or Btu equivalents.

Fossil fuels vary in average carbon content and, accordingly, vary widely in the amount of carbon released for each unit of energy contained in the fuel. The following table summarizes two sets of numbers on pounds of carbon and CO_2 computed from data provided by the Environmental Protection Agency and the DOE's Energy Information Administration for each 1 million Btu of energy content.

	EPA Carbon	EPA CO_2	EIA Carbon	EIA CO_2
1MM Btu Natural Gas			31.89 lbs	116.94 lbs
1MM Btu Gasoline / Jet A	46.01 lbs	168.7 lbs	42.63 lbs	156.29 lbs
1MM Btu Diesel	46.39 lbs	168.7 lbs	40.55 lbs	170.11 lbs
1MM Btu Coal			56.78 lbs	208.18 lbs

Figure 18: Carbon released from different fuels (EPA 2006, 3-13; EIA 2001, 140)

Appendix B: Food Energy Analysis Models

Table 1. The total costs of food in the United States, in terms of dollars, energy, and electricity in 1963.

Sector	Cost (billion $)	Energy use (trillion Btu)	Electricity use (billion kw-hr)
Agriculture			
To PCE	4.5	231	4.1
To processing*	(15.8)	(862)	(15.6)
Food processing*	51.5	2868	51.3
Transportation	2.0	170	1.0
Trade	29.9	982	26.0
Households	6.1	1868	104.4
Total	94.0	6119	186.8

* Agricultural output delivered to processing (shown in parentheses) also appears in the figures for food processing.

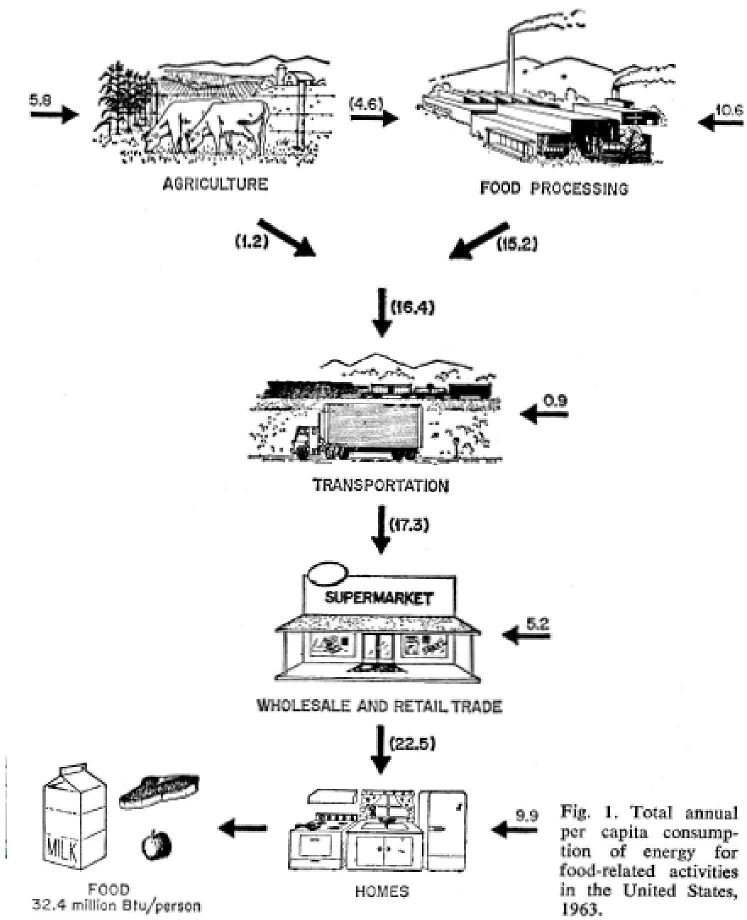

Fig. 1. Total annual per capita consumption of energy for food-related activities in the United States, 1963.

Figure 19: Hirst (1974) overall food energy model

Table 1. Energy use in the United States food system. All values are multiplied by 10^{12} kcal.

Component	1940	1947	1950	1954	1958	1960	1964	1968	1970	References
On farm										
Fuel (direct use)	70.0	136.0	158.0	172.8	179.0	188.0	213.9	226.0	232.0	(13–15)
Electricity	0.7	32.0	32.9	40.0	44.0	46.1	50.0	57.3	63.8	(14, 16)
Fertilizer	12.4	19.5	24.0	30.6	32.2	41.0	60.0	87.0	94.0	(14, 17)
Agricultural steel	1.6	2.0	2.7	2.5	2.0	1.7	2.5	2.4	2.0	(14, 18)
Farm machinery	9.0	34.7	30.0	29.5	50.2	52.0	60.0	75.0	80.0	(14, 19)
Tractors	12.8	25.0	30.8	23.6	16.4	11.8	20.0	20.5	19.3	(20)
Irrigation	18.0	22.8	25.0	29.6	32.5	33.3	34.1	34.8	35.0	(21)
Subtotal	124.5	272.0	303.4	328.6	356.3	373.9	440.5	503.0	526.1	
Processing industry										
Food processing industry	147.0	177.5	192.0	211.5	212.6	224.0	249.0	295.0	308.0	(13, 14, 22)
Food processing machinery	0.7	5.7	5.0	4.9	4.9	5.0	6.0	6.0	6.0	(23)
Paper packaging	8.5	14.8	17.0	20.0	26.0	28.0	31.0	35.7	38.0	(24)
Glass containers	14.0	25.7	26.0	27.0	30.2	31.0	34.0	41.9	47.0	(25)
Steel cans and aluminum	38.0	55.8	62.0	73.7	85.4	86.0	91.0	112.2	122.0	(26)
Transport (fuel)	49.6	86.1	102.0	122.3	140.2	153.3	184.0	226.6	246.9	(27)
Trucks and trailors (manufacture)	28.0	42.0	49.5	47.0	43.0	44.2	61.0	70.2	74.0	(28)
Subtotal	285.8	407.6	453.5	506.4	542.3	571.5	656.0	787.6	841.9	
Commercial and home										
Commercial refrigeration and cooking	121.0	141.0	150.0	161.0	176.0	186.2	209.0	241.0	263.0	(13, 29)
Refrigeration machinery (home and commercial)	10.0	24.0	25.0	27.5	29.4	32.0	40.0	56.0	61.0	(14, 30)
Home refrigeration and cooking	144.2	184.0	202.3	228.0	257.0	276.6	345.0	433.9	480.0	(13, 29)
Subtotal	275.2	349.0	377.3	416.5	462.4	494.8	594.0	730.9	804.0	
Grand total	685.5	1028.6	1134.2	1251.5	1361.0	1440.2	1690.5	2021.5	2172.0	

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Figure 20: Steinhart (1974) overall food energy model

Figure 5: Life Cycle Energy Use in Supplying US Food
(see Appendix B for sources and methodology)

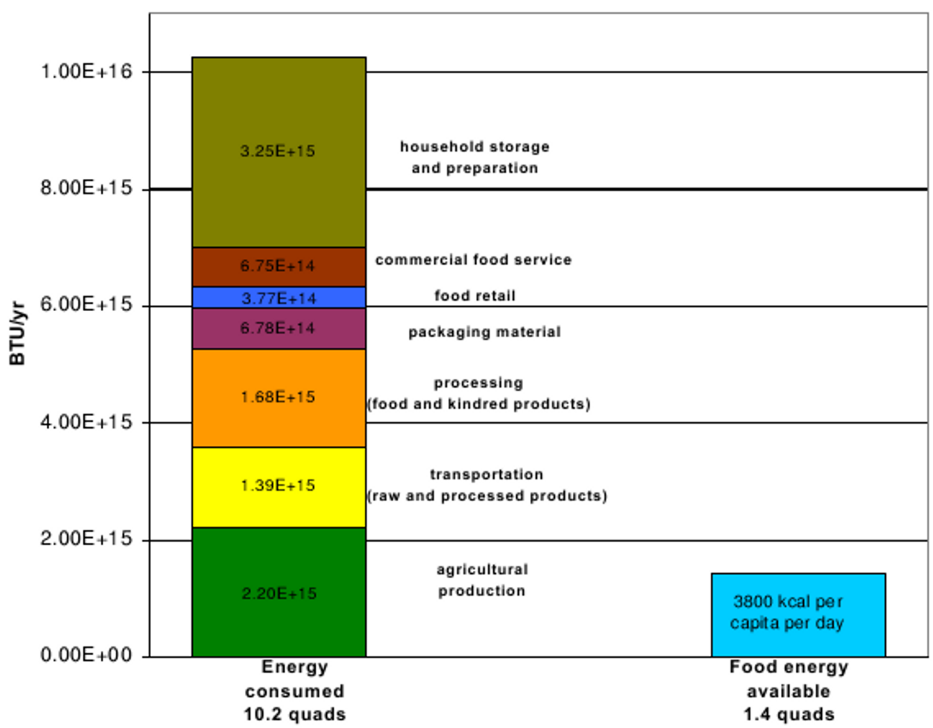

Figure 21: Heller (2000) overall food energy model

Table 8.3 Current production of animal protein systems and the required resource inputs of land, labor, and energy

Animal production system	Output per year			Input per year		
	Number (× 10³)	Product (kg × 10⁹)	Protein (kg × 10⁶)	Land (ha × 10⁶)	Labor (h × 10⁶)	Energy (kcal × 10¹²)
Chicken	2,932,711	5.02	465	2.5	18	18.24
Turkey	124,255	1.04	118	0.9	14	6.40
Eggs	64,362,000	3.82	438	4.2	78	31.14
Sheep	7,521	0.74	18	94.5	23	7.05
Dairy	11,151	53.26	1,864	16.3	825	87.22
Pork	68,687	7.49	535	15.3	168	91.51
Beef	46,870[a]	20.07	1,957	288.7	592	171.07
TOTAL			5,395	422.4	1,718	412.63

Note: [a]41,464 cattle and 5,406 calves.
Source: Pimentel et al., 1980a.

Table 8.4 Potential production of animal protein systems (forage only) and the required resource inputs of land, labor, and energy

Animal production system	Output per year			Input per year		
	Number (× 10³)	Product (kg × 10⁹)	Protein (kg × 10⁶)	Land (ha × 10⁶)	Labor (h × 10⁶)	Energy (kcal × 10¹²)
Dairy	8,015	38.47	1,346	11.8	590	38.47
Beef	40,110[a]	15.30	1,486	283.2	514	127.77
Sheep	7,521	0.74	18	94.5	23	4.58
TOTAL			2,850	389.5	1,127	170.82

Note: [a]35,616 cattle and 4,494 calves.
Source: Pimentel et al., 1980a.

Figure 22: Pimentel (2006) meat energy model

Table 9.5 Energy inputs for commercial catfish production in 1 ha ponds in Louisiana

	Quantity/ha	kcal/ha
Inputs		
Labor	120 h	63,250
Equipment	9,500,000 kcal	9,500,000
Pumping	1,667 kWh	4,343,250
Fertilizer and other chemicals	3.3 kg	60,000
Feed	5,925 kg	39,000,000
TOTAL		52,500,500
Outputs		
Catfish yield	2783 kg	
Protein yield[a]	384 kg	1,536,000
Input/Output Ratio		34.2:1

Note: [a]Assuming a dressed weight of 60% and 23% protein content.
Source: After Westoby and Kase, 1974; Mack, 1971.

Table 9.11 The energy inputs in shrimp production in Thailand

	Quantity/ha	kcal/ha
Inputs[a]		
Labor	70 h	41,475
Electricity and fuel	31,000,000 kcal	31,000,000
Seed	250 kg	125,000
Feed	6,000 kg	24,000,000
Maintenance	14,000,000 kcal	14,000,000
TOTAL		69,500,000
Outputs		
Shrimp yield	2,135 kg	
Protein yield	427 kg	1,067,500
kcal input/kcal output		69.5:1

Note: [a]The inputs were calculated from the economic data of Shang (1992).

Figure 23: Pimentel (2006) seafood energy model

Table 10.9 Energy inputs in U.S. wheat production in North Dakota

		Quantity/ha	kcal/ha
Inputs			
Labor		4.5 h	2,100
Machinery		19 kg	342,000
Diesel		46 liters	529,000
Gasoline		27 liters	269,000
Nitrogen		46 kg	807,000
Phosphorus		26 kg	78,000
Potassium		7 kg	11,000
Seeds		104 kg	313,000
Insecticides		0.3 kg	26,000
Herbicides		1.74 kg	174,000
Electricity		38,000 kcal	38,000
Transportation		183 kg	47,000
	TOTAL		2,633,000
Outputs			
Wheat yield		1,760 kg	5,816,900
Protein yield		247 kg	
kcal output/kcal input			2.2:1

Source: Biggle, 1980.

Table 10.10 Energy inputs in U.S. oats production in Minnesota

		Quantity/ha	kcal/ha
Inputs			
Labor		3.2 h	1,500
Machinery		7.7 kg	139,000
Diesel		30 liters	337,000
Gasoline		20 liters	198,000
Nitrogen		56 kg	824,000
Phosphorus		26 kg	79,000
Potassium		17 kg	27,000
Seeds		108 kg	430,000
Herbicides		0.6 kg	56,000
Transportation		155 kg	40,000
	TOTAL		2,129,500

Figure 24: Pimentel (2006) wheat and oats energy model

	Hirst 1974		Steinhart 1974		Heller 2000		Pimentel 2008
Segment	1963 (quads)	2007E (quads)	1970 (quads)	2007E (quads)	2000 (quads)	2007E (quads)	2007 (quads)
Agriculture	1.093	2.185	2.086	3.124	2.200	2.258	7.200
Processing	2.006	4.009	1.245	1.865	1.680	1.725	7.200
Packaging			0.821	1.229	0.678	0.696	
Transportation	0.170	0.340	1.273	1.906	1.390	1.427	1.400
Retail	0.982	1.963	1.043	1.562	1.052	1.080	
Home	1.868	3.734	2.145	3.213	3.250	3.336	
Total US food energy use	6.119	12.230	8.613	12.899	10.250	10.522	15.800
Total US energy use	50.833	101.600	67.844	101.600	98.975	101.600	101.600
Food % of total	12.0%	12.0%	12.7%	12.7%	10.4%	10.4%	15.8%
US Population	179,323,175	301,290,332	203,302,031	301,290,332	283,476,115	301290332	301290332
MM food Btu / person / year	34.12	40.59	42.37	42.81	36.16	34.92	52.44

Figure 25: Extrapolations of four historic U.S. food energy models to 2007

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