United States
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Economic
Research
Report
Number 94

March 2010

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National Agricultural Library Cataloging Record:

Energy use in the U.S. food system.

(Economic research report (United States. Dept. of Agriculture. Economic Research Service) ; no. 94)

1. Food industry and trade—Energy consumption—United States—Statistics.

2. Cost and standard of living—United States—Statistics.

I. Canning, Patrick N. II. United States. Dept. of Agriculture. Economic Research Service. III. Title.

HD9004

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United States Department of Agriculture

Economic Research Report Number 94

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A Report from the Economic Research Service

www.ers.usda.gov

Energy Use in the U.S. Food System

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Abstract

Energy is an important input in growing, processing, packaging, distributing, storing, preparing, serving, and disposing of food. Analysis using the two most recent U.S. benchmark input-output accounts and a national energy data system shows that in the United States, use of energy along the food chain for food purchases by or for U.S. households increased between 1997 and 2002 at more than six times the rate of increase in total domestic energy use. This increase in food-related energy flows is over 80 percent of energy flow increases nationwide over the period. The use of more energy-intensive technologies throughout the U.S. food system accounted for half of this increase, with the remainder attributed to population growth and higher real (inflation-adjusted) per capita food expenditures. A projection of food-related energy use based on 2007 total U.S. energy consumption and food expenditure data and the benchmark 2002 input-output accounts suggests that food-related energy use as a share of the national energy budget grew from 14.4 percent in 2002 to an estimated 15.7 percent in 2007.

Keywords: energy use, energy technologies, food expenditures, input-output analysis, population change, structural decomposition analysis, supply chain analysis

Acknowledgments

The authors greatly benefited from the reviews of Elise Golan, Michael LeBlanc, Abebayehu Tegene, Laurian Unnevehr, and Paul Westcott of USDA's Economic Research Service; James Duffield of USDA's Office of the Chief Economist; Behjat Hojjati of the U.S. Department of Energy's Energy Information Administration; Satish Joshi of Michigan State University; and Hayri Önal from the University of Illinois. Thanks also to John Weber and Susan DeGeorge for editorial and design assistance.

*Patrick Canning is a senior economist, Arnold Waters is a database administrator, and Ainsley Charles is a former student intern with USDA's Economic Research Service. Co-authors Karen R. Polenske and Sonya Huang worked on this project through a cooperative agreement with the Massachusetts Institute of Technology.

Contents

Recommended citation format for this publication:

Canning, Patrick, Ainsley Charles, Sonya Huang, Karen R. Polenske, and Arnold Waters. *Energy Use in the U.S. Food System*, ERR-94, U.S. Dept. of Agri., Econ. Res. Serv. March 2010.

Summary

Energy is used throughout the U.S. food supply chain, from the manufacture and application of agricultural inputs, such as fertilizers and irrigation, through crop and livestock production, processing, and packaging; distribution services, such as shipping and cold storage; the running of refrigeration, preparation, and disposal equipment in food retailing and foodservice establishments; and in home kitchens. Dependence on energy throughout the food chain raises concerns about the impact of high or volatile energy prices on the price of food, as well as about domestic food security and the Nation's reliance on imported energy. Use of energy in the food chain could also have environmental impacts, such as through carbon dioxide emissions.

What Is the Issue?

A number of Government and academic studies over the past four decades have examined food-related energy use in the United States. Taken together, these studies indicate that food-related energy use has remained a substantial share of the total national energy budget, that food-related energy use of households has been the largest among supply chain stages, and that food-related energy flows may have increased significantly over the past decade. These results, however, do not explain why energy use has changed over time and may not provide a valid measure of these changes since the various studies rely on different data sources and different model assumptions.

This report compares estimates of energy use in 1997 and 2002 by using data exclusively from two Federal agencies and employing the same energy-flow model over each year of analysis. A projection of food-related energy use in 2007 is also reported. This approach complies with well-established international "best practices" for the measurement of energy use throughout a national economy and facilitates valid comparisons of energy flows over two or more periods. The report provides policymakers and analysts with information to assess which stages of the food supply chain and what industries are the largest energy users, which stages and industries have experienced the fastest rates of energy-use growth, what factors have influenced increases in energy use in the food sector, and what factors are likely to influence changes in the future.

What Did the Study Find?

During 1997-2002, per capita energy use in the United States declined 1.8 percent, while per capita food-related energy use in the United States increased by 16.4 percent. The population of the United States grew by more than 14 million over the period, pushing total energy use up by 3.3 percent and effecting an increase in total food-related energy use of 22.4 percent. As a share of the national energy budget, food-related energy use grew from 12.2 percent in 1997 to 14.4 percent in 2002.

Several economic factors can influence the use of energy throughout the U.S. food system, such as labor and energy costs, the ability to substitute between these inputs as their costs change, the time availability of households for food-related activities, and household affluence. Findings suggest that about half of the growth in food-related energy use between 1997 and 2002 is

explained by a shift from human labor toward a greater reliance on energy services across nearly all food expenditure categories. High labor costs in the foodservices and food processing industries, combined with household outsourcing of manual food preparation and cleanup efforts through increased consumption of prepared foods and more eating out, appear to be driving this result. Increases in per capita food expenditures (adjusted for inflation) and population growth also helped drive up food-related energy use over this period, with each trend accounting for roughly a quarter of the total increase.

Energy use and growth varied across all stages of the U.S. food supply chain (agriculture, processing, packaging, transportation, wholesale/retail, foodservice, and household). Household operations accounted for the highest food-related energy use in 1997 and 2002. Food processing, however, showed the largest growth in energy use over this period, as both households and foodservice establishments increasingly outsourced manual food preparation and cleanup activities to the manufacturing sector, which relied on energy-using technologies to carry out these processes. Over this period, the food processing and foodservice industries faced increasing labor costs, while energy prices in this period were lower and far less volatile than they have become since 2002. In agriculture, the largest percentage increases in energy use were attributed to producers of vegetables and poultry products. The freight services industry accounted for a small share of the increase in overall food-related energy use but a substantial share of the increase attributed to some food commodities—particularly fresh fruit and poultry products.

A projection of food-related energy use based on 2007 total U.S. energy consumption and food expenditure data and the benchmark 2002 input-output accounts suggests that food-related energy use as a share of the national energy budget grew from 14.4 percent in 2002 to an estimated 15.7 percent in 2007. Although energy prices were high and volatile over the 2002-07 period, households and the foodservice industry continued to outsource food preparation through the purchase of prepared foods with high energy-use requirements.

How Was the Study Conducted?

Using a framework known as input-output material flow analysis, this study traced the measured flows of all energy sources used as fuel in the United States to final markets in three interrelated steps: (1) measure all known quantities of energy directly used in each domestic production activity, including household operations, organized into roughly 400 industry classifications; (2) trace the flow of energy embodied in each of the energy-using industry products throughout the production economy and into a complete accounting of final market sales; and (3) identify all food-related final markets and assess the food-related energy embodied in all final market sales. This analysis uses data from two Federal sources: the Bureau of Economic Analysis Benchmark Input-Output tables and the Energy Information Administration's State Energy Data System.

Introduction

Energy is used throughout the U.S. food supply chain, from the manufacture and application of agricultural inputs, such as fertilizers and irrigation; through crop and livestock production, processing, and packaging; distribution services, such as shipping and cold storage; the running of refrigeration, preparation, and disposal equipment in food retailing and foodservice establishments; and in home kitchens. Dependence on energy throughout the food chain raises concerns about the impact of high or volatile energy prices on the price of food, as well as about domestic food security and the Nation's reliance on imported energy. Use of energy throughout the food chain could also have environmental impacts, particularly in relation to national emissions of carbon dioxide.

In 2003, the United Nations, the European Commission, the International Monetary Fund, the Organisation for Economic Co-operation and Development, and the World Bank jointly issued a handbook that provides economic accounting guidelines for member nations and recommends input-output material flow analysis, including energy flow analysis, as a best practice for achieving "a consistent analysis of the contribution of the environment to the economy and of the impact of the economy on the environment" (United Nations et al., 2003, p. iii). In accordance with this guidance, this report presents an input-output material flow analysis (IO-MFA) of food-related energy flows in the United States between 1997 and 2007. A food system energy flow analysis measures the units of energy services that are used throughout an entire food system, where energy services are obtained from the energy industries' conversion of primary fuel stocks (coal, crude oil, natural gas, and renewable and fissionable fuels) into more useful forms, such as refined petroleum and electric current.

Over the past four decades, a number of Government and academic studies have examined food-related energy flows[1] in the United States. In 1973, a U.S. Government-sponsored study (see Hirst, 1974) found that domestic food system energy flows accounted for 12 percent of the 1963 national energy budget of the United States. Two recent studies—one by researchers at the University of Michigan using data from the mid-1990s (see Heller and Keoleian, 2000) and another by researchers at Cornell University using data from the mid-2000s (see Pimentel et al., 2008)—suggest that these energy flows rose significantly over the past decade, reaching 19 percent of the national energy budget by the mid-2000s. These two recent studies use a life-cycle process analysis that identifies the main processes and inputs associated with the food system and then compiles the direct energy uses across the identified processes. However, each relies on different data sources and different model assumptions, so a comparison of results from the two studies may not provide a valid measure of the change in food-related energy flows over the period.

[1]Several units of measurement are applicable to energy flows, but the one used throughout this report is the British thermal unit (Btu), defined as the quantity of energy flow required to raise the temperature of 1 gallon of water by 1 degree Fahrenheit.

This report uses data from two Federal sources: the Bureau of Economic Analysis (BEA) Benchmark Input-Output tables and the Energy Information Administration (EIA) State Energy Data System. The same IO-MFA model is applied over each year of analysis. This approach facilitates valid comparisons of energy flows over two or more periods and allows for a complete systemwide assessment (for a discussion of energy flows beyond the domestic food system, see box, "Toward a Food System Life Cycle Assessment"). In its analysis, this report addresses three basic questions:

- Where does energy flow in the U.S. food system and how is this flow measured?
- What are current food-related energy flows and why has this level changed over time?
- What factors will determine future energy flows in the U.S. food system?

Toward a Food System Life-Cycle Assessment

The boundary of a national input-output material flow analysis (IO-MFA) is the domestic food system; however, a full life-cycle assessment (LCA) of food system energy flows would extend beyond national boundaries and would not end with the consumption of final market goods. Lower and upper bounds of the remaining LCA energy flow measures can be attained using the IO-MFA model employed in this report.

Upstream. Food-related energy embodied in imported products reflects international energy use that was dedicated to the production of goods and services used to accommodate U.S. food-related expenditures. This would include both food imports and imported products, such as fertilizers and transportation equipment. Based on calculations using the associated U.S. technologies as a proxy for foreign energy use, food-related energy embodied in imports is estimated to have increased by about 200 trillion British thermal units (Btu) between 1997 and 2002, or about 70 percent. The international freight system facilitated these shipments, and over 85 percent of international freight imports, by weight, were transported by deep sea barges and by rail in 2001 (USDOT, 2003). Domestic food-related freight services used a little over 10 percent as much energy as did the food-related agricultural and processing industries they serviced. International barge and rail services are considerably more energy efficient than domestic services, so it would be reasonable to expect that international freight services added between 5 and 10 percent of the energy flows embodied in the cargo being shipped, amounting to the addition of another 10 to 20 trillion Btu to the increased upstream energy flows over this period, for a total of between 210 and 220 trillion Btu.

Downstream energy flows. Waste disposal is an energy-consuming activity, and a proportion of solid waste is food-related. Estimates by the U.S. Environmental Protection Agency (EPA, 2008) indicate 12.5 percent of total municipal solid waste disposal (by weight) represents food scrap. Using the IO-MFA approach, total U.S. energy use for the collection and disposal of household waste declined by roughly 100 trillion Btu between 1997 and 2002, reflecting greater energy efficiency in these services. If the food scrap share of solid waste remained the same, at least 12.5 trillion Btu of this efficiency gain is food-related. These estimates do not account for recycling, in terms of both the energy requirements and the energy savings associated with the process.

Water is also directly used for residential food preparation, after meal cleanup, and for waste disposal. A substantial portion of U.S. water supply and sewage system maintenance-related energy flows are food-related. Overall, these residential services required about 100 trillion fewer Btu in 2002 than in 1997, largely due to energy-efficient technologies.

Private direct investment requires energy services, and farm, food processing, and foodservice industries accounted for a little over 5 percent of total U.S. private direct investment in 1997 (BEA, 1997 benchmark IO accounts). Domestic energy flows to accommodate total private direct investment declined by about 700 trillion Btu between 1997 and 2002. If the share of investment by purpose changed little, the food system would be expected to realize energy savings of at least 35 trillion Btu, or 5 percent of total investment-related energy flow reductions.

Estimated change in food-related energy flows upstream and downstream to the domestic food system, 1997 to 2002

Item		Upstream imports	Solid waste disposal	Municipal water treatment	Private direct investment
		Trillion Btu			
Energy flow change:	Lower bound	210		-100	
	Upper bound	220	-13		-35

Source: USDA, Economic Research Service.

Identifying and Measuring Food System Energy Flows

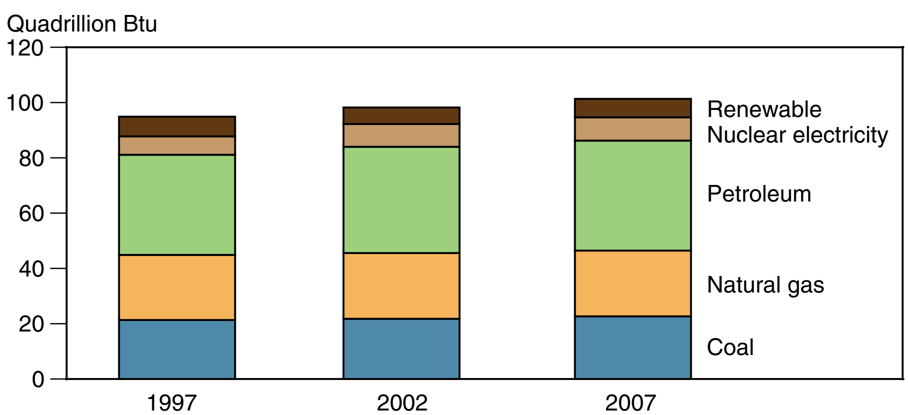
In 2007, the U.S. economy used slightly over 100 quadrillion Btu of energy (fig. 1). Of this amount, 85 percent came from fossil fuels, about 8 percent came from nuclear fuel, and the remainder came from various renewable sources (hydroelectric, biomass, geothermal, solar, and wind). About a third of total U.S. energy flows during the period were imported, and over 80 percent of these imports were in the form of crude oil and petroleum products. Between 1997 and 2007, annual energy use in the U.S. economy grew at an average annual rate of 0.7 percent, with the fossil fuel share of total energy remaining fairly constant and the nuclear and import shares increasing over the period (U.S. Department of Energy, 2008). Still, on a per capita basis and on a per dollar of real (inflation-adjusted) Gross Domestic Product basis, annual energy use in the U.S. declined between 1997 and 2007.

Energy flows in the U.S. food economy

Energy plays a large role in the life cycle of a food product. For example, consider energy's contribution to a hypothetical purchase of a fresh-cut nonorganic salad mix by a consumer living on the East Coast of the United States. In this case, fresh vegetable farms in California harvest the produce to be used in the salad mix a few weeks prior to its purchase. The farms' fields are seeded months earlier with a precision seed planter operating as an attachment to a gasoline-powered farm tractor. Between planting and harvest, a diesel-powered broadcast spreader applies nitrogen-based fertilizers, pesticides, and herbicides, all manufactured using differing amounts of natural gas and electricity and shipped in diesel-powered trucks to a nearby farm supply wholesaler. Local farmers travel to the wholesaler in gasoline-powered vehicles to purchase farm supplies. The farms use electric-powered irrigation equipment throughout much of the growing period. At harvest, field workers pack harvested vegetables in boxes produced at a paper mill and load them in gasoline-powered trucks for shipment to a regional processing plant, where specialized machinery cleans, cuts, mixes, and packages the salad mixes. Utility services at the paper mill, plastic packaging manufacturers,

Figure 1

Total U.S. energy flows by source of primary fuel



Source: USDA, Economic Research Service using data from *Annual Energy Review*, 2007, U.S. Department of Energy, Energy Information Administration.

and salad mix plants use energy to produce the boxes used at harvest and the packaging used at the processing plant, and for processing and packaging the fresh produce. The packaged salad mix is shipped in refrigerated containers by a combination of rail and truck to an East Coast grocery store, where it is placed in market displays under constant refrigeration.

To purchase this packaged salad mix, a consumer likely travels by car or public transportation to a nearby grocery store. For those traveling by car, a portion of the consumer's automobile operational costs, and his or her associated energy-use requirements, help facilitate this food-related travel. At home, the consumer refrigerates the salad mix for a time before eating it. Subsequently, dishes and utensils used to eat the salad may be placed in a dishwasher for cleaning and reuse—adding to the electricity use of the consumer's household. Leftover salad may be partly grinded in a garbage disposal and washed away to a wastewater treatment facility, or disposed, collected, and hauled to a landfill.[2]

The consumer in the example purchased one of many units of this specific salad mix product sold each day in supermarkets nationwide, and this mixed salad product is one item among 45,000 distinct items with unique energy-use requirements available in a typical U.S. supermarket.[3] Aside from the roughly constant 140,000 retail food and beverage stores operating in 2002 and 2007, there were also over 537,000 food and beverage service establishments in the United States in 2007, a 12-percent increase from 2002 (BLS, *Quarterly Census of Employment and Wages*). Each establishment purchases, stores, prepares, cleans, and disposes of food items. Other establishments, such as movie theaters, sports arenas, and hospitals, also perform some of these food-related services.

All food-related items purchased by or for U.S. households require energy services to facilitate their availability for purchase.[4] This report refers to food-related purchases by or for U.S. households as "food-related expenditures." Total energy services associated with the items are referred to as "U.S. food-related energy flows." Similarly, all other goods and services purchased by both U.S. households and U.S. Government offices plus all purchases for investment or export purposes are hereafter referred to as "other final market expenditures." Total energy services associated with these expenditures are referred to as "other U.S. energy flows." Total final market sales, or final demand, are equal to food-related expenditures plus other final market expenditures. Total U.S. energy flows, or the national energy budget, equal food-related energy flows plus other U.S. energy flows. Figure 2 summarizes annual final market sales in the United States for the 3 study years in this report—1997, 2002, and 2007. Over this period, food-related final market sales decreased from 9.3 to 8.6 percent of total final market sales.

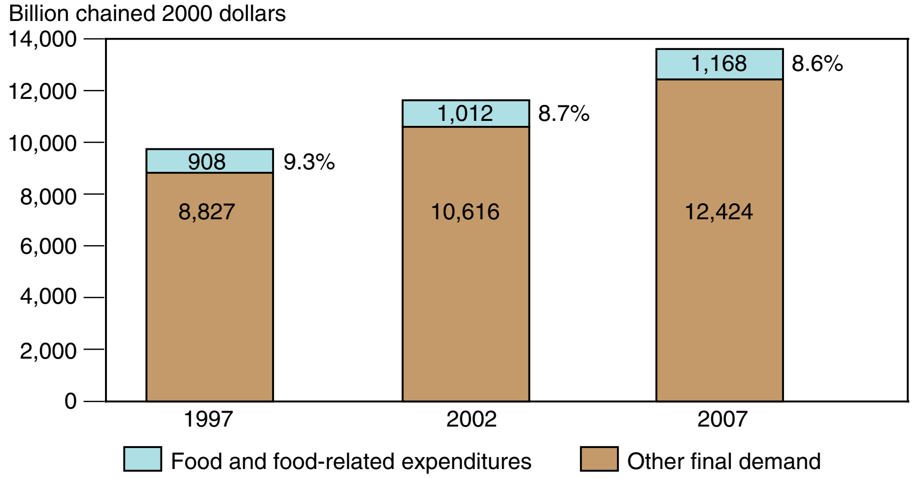
Although production of food and ingredients that are exported to other countries represents substantial energy use by the U.S. food system, these energy flows are not tied to the purchasing choices of U.S. food consumers. This study focuses on energy flows tied to the purchasing choices of U.S. consumers only. Some of these food-related purchasing choices relate to the energy flows embodied in the food-related commodities produced in other countries; however, the international input-output (IO) data necessary for measuring the embodied energy imported into the U.S. food system are not

[2]This salad mix example illustrates but is not a comprehensive accounting of all energy services related to producing, distributing, serving, and disposing of this product.

[3]Food Marketing Institute, Supermarket Facts: UPC (www.fmi.org).

[4]ERS publishes a statistical series on the "food dollar" that reports the marketing costs and the farm share of U.S.-farm-originated domestic food sales (www.ers.usda.gov/data/farmtoconsumer/marketingbill.htm). The energy costs included in the ERS food dollar estimates are much lower than those implied by the analysis in this report because they include only the direct energy expenses (e.g., utility expenses for electricity and natural gas) of the food processors that market U.S. farm products to U.S. consumers, not total energy expenses throughout the food chain, including household food-related energy use.

Figure 2
Personal consumption expenditures on U.S. food and related household operations* and other final demand**



*Food-related household operations include energy use for storage, preparation, cleanup, and food-related travel, plus purchases of appliances, dishware, flatware, cookware, and tableware, as well as a small percentage of certain auto expenses to cover food-related travel.
**1997 and 2002 data from Bureau of Economic Analysis (BEA) Benchmark IO accounts; 2007 data use BEA GDP statistics for 2002 and 2007 to update 2002 IO data.
Source: USDA, Economic Research Service using data from U.S. Department of Commerce, Bureau of Economic Analysis.

readily available, so this information is not reflected in the analysis of this report. In lieu of international IO data, imposing an assumption that similar energy technologies are used in countries supplying commodities for use in the U.S. food system provides an approximation for this measure (for a discussion and estimates of imported food related energy flows in 1997 and 2002, see box on page 2).

Measuring energy flows

Material flow analysis is the study of how materials and energy flow into, throughout, and out of a system. The study of material flows throughout a national economy came into prominence in the late 1960s with the realization that environmental pollution and its control is a material balance problem inextricably linked to the production and consumption processes of a national economy (Ayers and Kneese, 1969). For example, in the case of fossil fuels, the net flows of carbon dioxide emissions into the atmosphere have grown, and economic processes, including those associated with the food economy, contribute to this growth.

An important concept underlying the measurement of energy flows throughout an economy is the "conservation of embodied energy" (Bullard and Herendeen, 1975), which states that energy burned or dissipated by a process is passed on, embodied in the products of that process. Since final demand is considered the output of an economic system in the context of IO analysis, conservation of embodied energy implies that all energy entering into an economy is entirely embodied in an economy's final market sales of goods and services. To measure the energy embodied in these final market sales, social scientists and engineers have come to rely on an extension of IO analysis.

Input-output and material flow analysis. IO analysis facilitates the study of interdependencies, both among industries throughout an economy and between industry and final market sales. In the IO framework, an "industry" is a group of establishments that produce similar products, and "final market sales" are all industry sales of goods or services other than sales for use by a domestic industry for the production of another good or service during the current accounting period. Examples of final market sales are the food and nonfood consumption expenditures of domestic households, procurement expenditures of domestic governments, export sales, and investment sales, such as new housing construction, government infrastructure projects, or industry machinery purchases.

Every 5 years, the BEA publishes a detailed benchmark input-output table for the U.S. economy, covering the production, import, and sales activities for all U.S. establishments, grouped into over 400 industry classifications. The BEA's two most recent benchmark IO accounts are the 2002 IO table, released in 2008, and the 1997 IO table, released in 2003. For IO analysis using these detailed BEA tables, three subaccounts make up the economic model:

1. A final market sales vector, **f**, is a column of data itemizing total final market sales of commodities sold by each of the 400+ U.S. industries.
2. A total industry output vector, **x**, is a column of data itemizing total available products for sale of commodities associated with each of the 400+ U.S. industries.
3. A total requirement matrix, **L**, also known as the Leontief matrix[5] is a table with the same number (400+) of columns and rows, where each element of the matrix summarizes total sales required by an industry (such as grain farming) per dollar of final market sales of commodities (such as bakery products).

By way of example, the BEA 2002 detailed total requirement table indicates that each dollar of final market sales of Bread and Bakery products (BEA industry 31181A) required just under 5 cents worth of grain farming outputs (BEA industry 1111B0). Most of this required amount represents sales of wheat to flour mills, but smaller portions of the amount are attributed to other purposes, such as corn sales for ethanol going into the fuel used at different stages along the bakery supply chain.

These three model subaccounts are related by the simple matrix algebra identity, $\mathbf{L \cdot f = x}$, in which multiplication of the final demand vector (**f**) by the total requirement matrix (**L**) produces the industry output vector (**x**). One of the conventions of IO analysis is the assumption of linear homogeneous production technologies. This has the effect of assuming, for example, that if it took 100 bushels of wheat to accommodate the sale of 9,000 loaves of whole wheat bread to U.S. households, then 50 bushels were required for the 4,500 loaves sold to a subset of these households. If $\mathbf{f}_{food}$ itemizes the subset of each element in **f** that is food-related expenditures of U.S. households, then by the linear homogeneity property, multiplying this vector by **L** will determine the subset of total industry output required to accommodate these food expenditures.

[5]A matrix inversion procedure developed by W. Leontief produces a table of total requirement multipliers.

Input-output material flow analysis extends this concept by identifying all rows in the published IO table that represent energy commodities (coal, petroleum, electricity, natural gas) and converting their units of measurement from dollar units to energy units, such as Btu. By deriving the Leontief inverse of this hybrid IO table containing data in both dollar units and Btu, the element in any column intersection with an energy row reports total Btu output required, both directly and indirectly, to accommodate the final market sale of 1 dollar's worth of any nonenergy commodity "j." Total energy flows, **e**, are measured as[6]:

1) $\mathbf{e} = \mathbf{H} \cdot \mathbf{f}$,

where "**H**" is the submatrix from the Leontief inverse of the hybrid table containing all energy rows. To verify the accuracy of equation 1, compare the equation estimate for **e** with the published national energy flow accounts used to calibrate energy inputs; they should be identical.

Using the linear homogeneity property, food-related energy flows are measured as:

2) $\mathbf{e}_{\text{food}} = \mathbf{H} \cdot \mathbf{f}_{\text{food}}$

Starting from the published BEA detailed benchmark IO accounts, equations (1) and (2) are estimated in three steps.

Step 1 measures all known quantities of energy directly used in each domestic production activity. Annual estimates of total domestic energy flows and annual average unit prices are published each year by the U.S. Department of Energy's (DOE) Energy Information Administration (EIA), including national flow totals and prices for a set of 10 nonoverlapping fuel categories, for each of a set of 6 nonoverlapping end-user categories. Table 1 reports these statistics for 1997 and 2002. The table identifies the NAICS (North American Industry Classification System) number for each industry that either markets the primary fuel source or markets the energy services derived from them. For example, NAICS industry 32411 (petroleum refineries) sells petroleum energy products, including gasoline blends containing ethanol.

For IO table rows corresponding to the four nonoverlapping energy service industries, dollar outlays from each of the 392 domestic industry aggregates (discussed later in this section) and from final markets distinguished by residential/nonresidential are divided by the end-user prices appropriate for each industry. This provides a preliminary estimate of Btu purchases by each industry and in final markets. These values are then normalized to replicate EIA-published total energy flows for the fuels corresponding to each row, as reported in table 1. For example, the BEA figure for household expenditures on natural gas in 2002 was $38.5 billion. The 2002 average residential price of natural gas reported in table 1 was $7.71 per million Btu, so the preliminary estimate of Btu purchases of natural gas by U.S. households equals 1 mil. x 38.5 bil. ÷ 7.71 ≈ 4,995 trillion Btu. By comparison, separate EIA estimates of residential natural gas energy flows in 2002 totaled 4,994 trillion Btu.

[6]Math notation in this report is as follows: matrices are denoted with bold capitalized letters, vectors with bold lower case letters, scalars with nonbold lower case letters, sets with capitalized and italicized letters, and set elements with lower case italicized letters. Letters are from either the English or Greek alphabet.

Table 1
Energy flows to all sectors by industry source and fuel type and energy prices by industry and user

	Industry (NAICS)							
	Electricity (2211)		Petroleum (32411)		Coal (2121)		Natural gas (2212)	
	1997	2002	1997	2002	1997	2002	1997	2002
Fuel type	*Energy flows (trillion Btu)*							
All types	13,585	13,727	36,427	38,532	21,444	21,903	23,477	23,806
Geothermal	325	328						
Hydroelectric	3,640	2,689						
Nuclear	6,597	8,143						
Solar	70	64						
Wood and waste	2,919	2,397						
Wind	34	105						
Petroleum			36,264	38,400				
Ethanol			163	132				
End user	*Price ($ per million Btu)*[7]							
All uses	20.13	21.15	7.86	8.82	1.32	1.30	4.53	5.27
Transportation[1]	22.47	21.02	8.69	9.63	1.32	1.30	4.34	5.32
Commercial[2]	22.03	22.81	5.92	6.96	1.51	1.63	5.67	6.49
Electric utilities[3]			2.82	3.46	1.28	1.25	2.79	3.60
Industrial[4]	13.29	14.30	5.68	6.43	1.62	1.75	3.53	4.37
Coke plants[5]					1.79	1.94		
Residential[6]	24.71	24.75	8.91	10.37	2.48	2.59	6.75	7.71

[1]NAICS sector 48-49. [2]NAICS sectors 42 and higher, sector 22 except 2211, and all nonhousehold final demand. [3]NAICS 2211. [4]NAICS sector 31 to 33. [5]NAICS industry 324199. [6]Households. [7]In cases where no specific industry price paid by fuel type is reported by EIA, the "all uses" price is used.
Source: USDA, Economic Research Service using data from Energy Information Administration, State Energy Data System (www.eia.doe.gov/emeu/states/_seds.html).

In the case of residential natural gas purchases, the preliminary estimate is close to the independent direct measure by the EIA; however, overall, the preliminary estimates for total energy flows for each of the four energy industries are consistently below EIA figures, so they are normalized to EIA levels. These persistently low preliminary estimates can be attributed to several factors, including the loss of a substantial share of primary energy during conversion and transmission, so the figures are not reflected in industry and final market purchases of energy services. For example, the preliminary IO estimates of combined industry and final market outlays for electricity from nuclear and renewable fuel sources totaled 12.45 quadrillion Btu (Q-Btu), whereas the EIA national figure for these energy flows total 13.90 Q-Btu. Each outlay estimate in this electricity row is uniformly adjusted upward by about 11.7 percent to reconcile this difference in energy flow estimates.

To ensure the accounts from both years are describing the same industries, data for both years are aggregated to 392 common industry categories in both the 1997 and 2002 accounts. Of these 392 industries, 18 are agricultural and related industries, 11 are mining industries, 6 are utility or construction industries, 254 are manufacturing (including 32 food and beverage) industries, 14 are trade or transportation services, and the remaining 89 are predominantly service industries but also include government enterprises and the scrap/secondhand goods industry. Four industries have been identified as nonoverlapping industry sources of all energy services from the 10 primary fuel sources measured by the EIA and reported in table 1: electric power generation, petroleum refineries, coal mining, and natural gas distribution. A more detailed description of the model aggregation procedures, including a procedure to address an aggregation bias in the wholesale and retail trade industries, is presented in the appendix.

Step 2 traces total embodied energy flows to final markets. Once the hybrid IO account is obtained in step 1, the analysis proceeds as in a conventional IO analysis. That is, the hybrid IO table derived in step 1 undergoes the Leontief inverse procedure, producing a hybrid total requirement matrix including the submatrix, **H**, containing only the energy rows reporting Btu per dollar of final market sales. Each of the model accounts are derived exclusively from the 1997 and 2002 BEA and EIA data sets discussed earlier, and they facilitate the calculations described in equation 1 for the 1997 and 2002 accounts. Using the 392 industry aggregation, estimates E97 and E02 (equation 1) are found to exactly replicate the published EIA energy flows data.

Step 3 identifies food-related final demand expenditures and estimates energy flows. All consumption expenditures on food by or for U.S. households are reported annually by the BEA in its National Income and Product Account (NIPA) tables, along with bridge tables linking these expenditures to the final demand data in the IO accounts. Beyond food expenditures, household expenditures for food-related operations must also be measured and include the following household foodservice activities:

- Electricity for cooking, cleaning, and food storage
- Cooking heat other than electricity (natural gas and liquid petroleum gas (LPG))
- Auto fuel for food-related personal transportation
- Embodied energy in purchases of food storage, preparation, and serving equipment
- Part of the embodied energy in purchases of automobiles, parts, and auto services

The 1997 and 2001 Residential Energy Consumption Surveys (RECS), also enumerated by the EIA, are used to obtain estimates of food-related household operational expenditures in 1997 and 2002, respectively. According to the RECS, cooking (electric range, oven, microwave, toaster oven, and coffee makers) accounted for 6.6 percent of total household electricity consumption in 1997 and 6.5 percent in 2001. For refrigeration, the respective figures are 13 percent and 14 percent; freezing, 3.6 percent and 3.4 percent; dishwashers, 2.0 percent and 2.5 percent. Combined, these sources accounted for

25 and 26 percent of the total proportion of household electricity in 1997 and 2001, respectively.

Figures for energy spent on natural gas and LPG for cooking are not available, but the 1997 and 2001 Public Use Data Files from the RECS include the number of households using each method. Assuming each household requires the same amount of energy to cook regardless of energy source, the percentage of natural gas spent on cooking was 2.1 percent in 1997 and 3.0 percent in 2001. The percentage of petroleum (from LPG) spent on cooking was 1.0 percent in 1997 and 1.6 percent in 2001.

Federal household time-use and vehicle-use surveys measure the time spent and miles traveled for shopping purposes, but it is difficult to discern from this data the share attributed to food-related travel in 1997 and 2002. The only previous study found to address this same measure (see Hirst, 1974), while far removed in time from the current study, found 2 percent of all household vehicle miles to be food-related travel. Although this estimate may be conservative,[7] a 2-percent assumption is applied to household purchases of automobiles, auto fuel, auto tires, auto repair, lubrication, and fluids for both 1997 and 2002. Other auto-related expenses, such as insurance and accessories, are not included.

[7]A U.S. Department of Energy report, *Transportation Energy Data Book*, Edition 27, reports 14.5 percent of annual household vehicle miles are for shopping. If 1 in 7 shopping miles are food related, then 2 percent of vehicle use can be considered food related.

Analysis of Current Food-Related Energy Flows

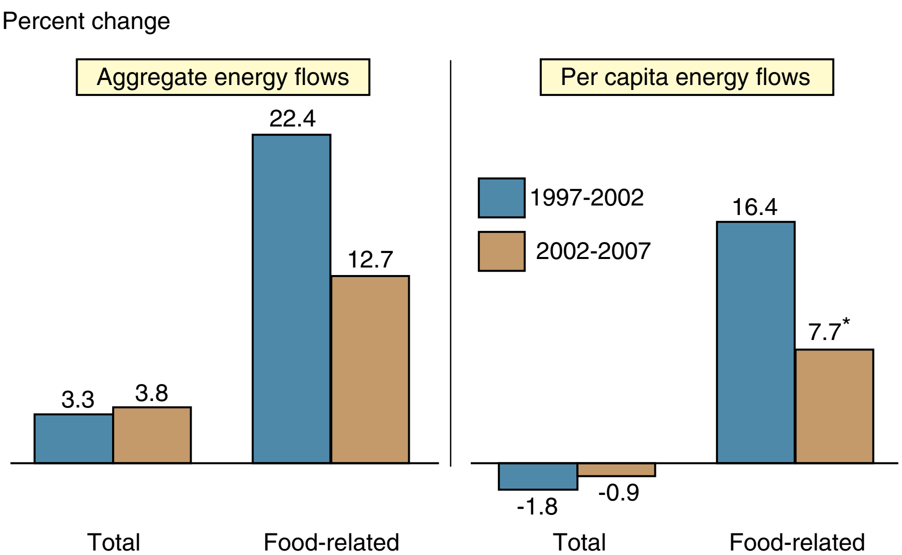
Estimates for the final demand vector (**f**) and its food-related subset ($\mathbf{f}_{food}$), as well as the energy rows from the Leontief inverse of the hybrid table (**H**) are obtained using both 1997 and 2002 annual statistics. Estimates of total energy flows (**e**) and food-related energy flows ($\mathbf{e}_{food}$) are obtained from equations 1 and 2. In overall and per capita terms, national energy flows increased 3.3 percent and declined 1.8 percent, respectively, from 1997 to 2002. By 2002, annual national energy flows totaled 97.9 Q-Btu, or about 340 million Btu per person. Based on estimates of equation 2, food-related energy flows represented 12.2 percent of national energy flows in 1997 and 14.4 percent in 2002. Food-related energy flows accounted for roughly 80 percent of national energy flow increases over the 1997 to 2002 period. Note that all personal consumption expenditures (PCE) of households, not just food-related PCE, accounted for 1.82 times the national energy flow increases between 1997 and 2002, and almost half of this increase was offset by flow reductions for final demand markets other than PCE. Even from these larger flow increases attributed to total personal consumption expenditures, food-related energy flow increases accounted for over 44 percent of this growth.

Although a 2007 benchmark IO table is not available, 2007 values for **e** are available from the EIA State Energy Data System, and values for **f** and $\mathbf{f}_{food}$ are available from the BEA National Income and Product Accounts. Using this available 2007 data and **H** from the 2002 accounts will facilitate an estimate of 2007 $\mathbf{e}_{food}$ based on 2002 technologies.

By 2007, the national energy budget rose 3.8 percent from 2002 levels, with per capita energy flows declining an additional 0.9 percent (fig. 3). Based on 2002 energy technologies, estimated food-related energy flows in 2007

Figure 3

Change in U.S. total and food-related energy flows over 5-year intervals



*2007 food-related energy flows are projections based on 2007 Bureau of Economic Analysis food-related expenditure data and 2002 energy technology levels.
Source: USDA, Economic Research Service using data from U.S. Department of Energy, Energy Information Administration.

were 12.7 percent higher than in 2002, or 7.7 percent higher on a per capita basis. This estimate puts the food-related share of the national energy budget at 15.7 percent for 2007, but it should be noted that this estimate does not account for any technology changes, including energy technologies, that may have occurred after 2002.

Structural decomposition analysis (SDA) is designed to explain sources of change in measures obtained from an IO analysis over two or more time periods (Rose and Casler, 1996). Supply chain analysis (SCA) provides a basis for assessing the contributions of different stages of food production to the overall change in energy flows over two or more periods (Leontief, 1967). Only 1997 and 2002 data are sufficiently complete for purposes of an SDA and SCA study.

A structural decomposition analysis

In the most basic formulation of SDA applied to this analysis, the measured identity $\mathbf{e}_{food}$ defined in equation 2 comprises three determinant parts: food-related budget levels, product mix, and energy technology changes. This basic application is adapted to a per capita analysis so that the budget level determinant is split into a per capita budget determinant and a population determinant. In the context of equation 2, total food-related expenditures $\mathbf{f}_{food}$ is split into three components: the per capita total food-related budget (b_{food}), the food-related product mix ($\mathbf{m}_{food}$), or food budget shares, and the total domestic population of food consumers (p). From this split, equation 2 can be restated as:

2′) $\mathbf{e}_{food} = p \cdot b_{food} \cdot \mathbf{H} \cdot \mathbf{m}_{food}$

Using the upper case Greek delta, Δ, to denote the measure of change in a variable over a discrete time period, a structural decomposition of the difference in food-related energy flows measured from equation 2′ over two periods (1997 and 2002) is estimated as follows:

3) $\Delta\mathbf{e}_{food} \approx [b_{food} \cdot \mathbf{H} \cdot \mathbf{m}_{food} \cdot \Delta p] + [p \cdot \mathbf{H} \cdot \mathbf{m}_{food} \cdot \Delta\mathbf{b}_{food}] + [p \cdot b_{food} \cdot \mathbf{H} \cdot \Delta\mathbf{m}_{food}] + [p \cdot b_{food} \cdot \Delta\mathbf{H} \cdot \mathbf{m}_{food}]$

Or,

[energy flow change] ≈ [population change]+[per capita food budget change]+ [food mix change]+[technology change]

Data already described for calculating equations 1 and 2, plus annual July 1 U.S. population estimates from the U.S. Census Bureau (www.census.gov/popest/), help facilitate the SDA in equation 3. A Marshall-Edgeworth (M-E) index is used to measure change in the four determinates: p, b_{food}, $\mathbf{m}_{food}$, and $\mathbf{H}$ (Hoekstra and Van den Bergh, 2002). This index computes each of the four determinates of change in equation 3 as the average absolute change in energy flows moving alternatively from 1997 to 2002 and from 2002 to 1997.[8] Since the analysis covers two time periods, all monetary values in equation 3 are converted to constant chained 2000 dollars[9] using PCE price indexes published by BEA (http://www.bea.gov/national/nipaweb/Index.asp).

[8]For example, adding "97" and "02" identifiers, the M-E index of the first bracketed term in equation 3 is measured as 0.5 x $[b97_{food} \cdot \mathbf{H97} \cdot \mathbf{m97}_{food} \cdot (p02\text{-}p97) + b02_{food} \cdot \mathbf{H02} \cdot \mathbf{m02}_{food} \cdot (p02\text{-}p97)]$.

[9]A constant chained 2000 dollars index reports the rate of real changes from year 2000 levels.

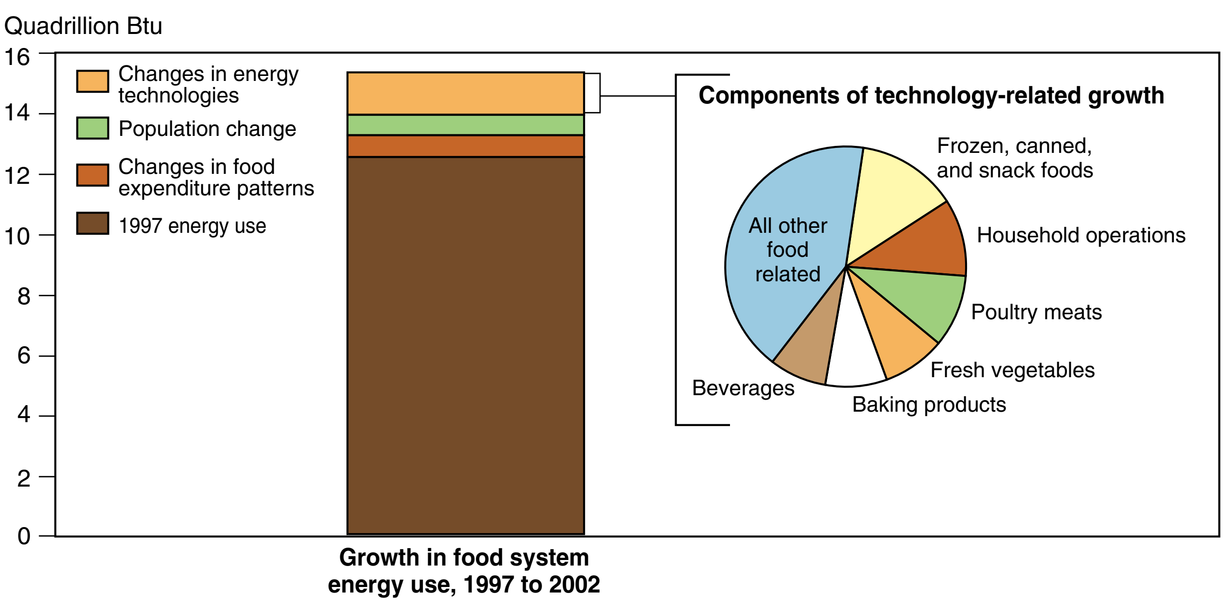
Overall, the structural determinants of change in total food-related energy flows were each found to be instrumental in changing total energy flows between 1997 and 2002 (fig. 4). Higher energy technology intensities account for about half of the increase, with frozen, canned, and snack food technologies showing the largest category share of this increase. Changes due to population growth and food expenditure patterns each accounted for roughly a quarter of the total increase. Discussions of each structural determinant follow.

Change in U.S. population. The U.S. population increased 5.1 percent between 1997 and 2002, according to the U.S. Census Bureau. Holding other factors constant, the more than 14 million food consumers added during the period would push up food-related energy flows by just under 640 trillion Btu, or less than one-quarter of the overall measured increase in food-related energy flows (see fig. 3).

Growth in domestic energy flows between 1997 and 2000 slightly outpaced population growth, but as consumer energy prices started rising sharply over the next several years, population growth started to slightly outpace national energy flows (fig. 5). The data suggest that population growth influenced growth in domestic energy flows, including food-related flows, and that this influence is likely to have persisted in the 2002 to 2007 period, even as consumer energy prices surged upward. The U.S. Census Bureau projects that the annual population growth rate between 2010 and 2050 will average 0.87 percent. Although it is highly likely that the level and mix of food-related expenditures and the energy intensity of food-related technologies will change over time, these recent population projections suggest that upward pressures on total food-related energy use may continue.

Figure 4

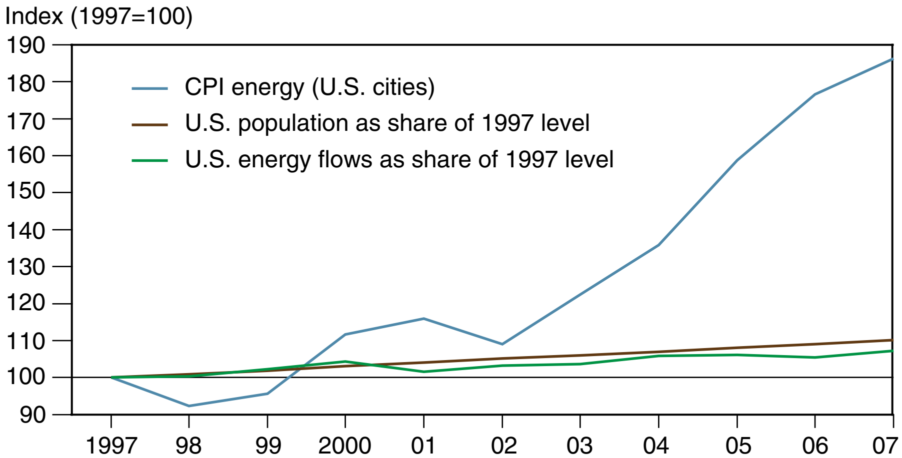
Determinants of growth in U.S. food system energy use, 1997-2002



Source: USDA, Economic Research Service.

Figure 5

U.S. indexes of energy flows, population, and consumer energy prices



Sources: USDA, Economic Research Service using data from U.S. Department of Energy, U.S. Department of Commerce, and U.S. Department of Labor.

Change in the per capita food-related budget and product mix. In 2002, real per capita annual food-related expenditures were 6.6 percent higher than in 1997, according to BEA estimates. Had the mix of food products purchased and the energy technologies remained unchanged, per capita food-related energy flows would have increased about 3 million Btu during the period. Factoring in the change in product mix of food-related purchases in 2002 reduces the increase in per capita energy flows by nearly 20 percent to 2.4 million Btu (table 2).

According to BEA estimates of personal consumption expenditures (PCE), combined with Census Bureau annual population estimates, real per capita food expenditures have trended upward over the past decade, and this portends upward pressures on per capita energy flows. Yet, this finding does not agree with household food expenditure estimates from other sources, including the Bureau of Labor Statistics annual Consumer Expenditure Survey (CES). Excluding household food-related operational expenditures, the CES reports that real per capita expenditures on food and beverages by U.S. households remained virtually unchanged in the years 1997, 2002, and 2007.

Although the CES figures appear to conflict with BEA estimates, the two statistical series actually measure substantially different populations. In addition to household food expenditures, the PCE data reported by the BEA include food expenditures by or for all institutionalized food consumers, such as prison populations and those in nursing homes, plus the military population. Food supplied to employees by their employers and school lunches are also included in the BEA accounts, and because the PCE accounts are reconciled with other production and expenditures accounts, they are also likely to measure the food expenditures of undocumented food consumers. Since each of these populations is not included in the CES population sample, it is not surprising that both the level and change over time in these two data series do not converge.

Another perspective on changes in per capita food expenditures can be gained by measuring food waste flows from the food system. Estimates of the U.S. Environmental Protection Agency (EPA) indicate that per capita generation of municipal solid food waste increased 14.5 percent between 1990 and 2000 and an additional 10.1 percent between 2000 and 2007 (EPA, 2008). These increases suggest U.S. per capita food waste rose, which is consistent with increases in per capita food purchases. Although the CES survey gives a

Table 2

Impacts of changes to per capita food budgets and product mix on energy flows for food and related items, 1997-2002

Expenditure category	Food budget level impacts	Product mix (budget share) impacts	Combined budget and product mix impacts
	Per capita flow changes (thousand Btu)		
Food at home:			
Cereal products	72	-90	-18
Baking products	125	391	516
Fresh dairy	48	-41	7
Processed dairy	90	-333	-243
Fats and oils	30	-41	-10
Sugar and sweets	83	-133	-49
Fresh fruits	38	63	101
Fresh vegetables	68	75	143
Beef	84	-136	-51
Pork	66	-157	-91
Other meats	56	-86	-31
Fish	18	18	36
Poultry	104	-83	21
Eggs	20	-9	11
Processed fruits and vegetables	47	-192	-145
Frozen, canned, snack, and other	212	40	253
Nonalcoholic beverages	148	-137	11
Alcoholic beverages	200	336	537
Pet food	66	169	235
Food away from home	527	-294	233
Household operations[1]	840	75	916
Total food related	2,944	-564	2,380

[1]Energy use for major kitchen appliances, auto use for food-related trips, and home food preparation and serving equipment-related energy flows

Sources: USDA, Economic Research Service using data from U.S. Department of Commerce and U.S. Department of Energy.

more appropriate measure of per capita estimates because its sample population is well defined, the BEA series is a more appropriate sample universe for this study, which seeks to measure all food-related energy flows through the U.S. food system.

In table 2, the middle column measures the energy consumption changes due to changes in food product mix between 1997 and 2002 but holds the total food budget unchanged. Data suggest that most of the food items with 2002 food budget shares higher than in 1997, most notably fresh produce and fish, tend to be less energy intensive than the items with 2002 food budget shares smaller than in 1997, such as processed fruits and vegetables, processed dairy, beef, and pork. Had the per capita food budget remained unchanged, these budget item share changes would have resulted in a reduction in per capita energy flows of over half a million Btu. When the combined per capita energy flow changes of higher per capita food budgets and a less energy-intensive mix of food items is expanded out to the 1997 total population, the 0.65 quadrillion Btu energy flow increase it produces represents 25 percent of the total increase in food-related energy flows. This total, combined with population change, accounts for half of the total food-related energy flow increases from 1997 to 2002.

Changes in food system energy technologies. Overall, energy technologies are found to account for roughly half of total energy use increases between 1997 and 2002, which equals the combined effects of population change, per capita food budget increases, and product mix changes (table 3). In percentage terms, the largest increases in food-related energy flows were for fresh vegetables, eggs, and poultry products. Over half of the measured change in food-related energy flows attributed to energy technologies is from five expenditure categories: frozen, canned, and snack foods; food-related household operations; poultry; fresh vegetables; and baking products.

This change in energy intensity of food system technologies accounted for most of the change in food-related energy flows between 1997 and 2002. Findings point to a widespread shift toward energy services in the form of labor-saving technology adoption. Most notably, both households and food-service establishments increasingly outsourced food preparation and cleanup activities to the manufacturing sector, which relied more on energy services and less on labor services to carry out these processes.

A time-use study of adults between ages 18 and 64 found that the average time per day spent on cooking and cleaning at home was reduced from 65 minutes to 31 minutes between 1965 and 1995 (Cutler et al., 2003). This decrease in food preparation time coincides with a dramatic growth in demand for convenience foods, foods for which the manufacturer provides more processing, preparation, and packaging services than would otherwise be done by the household. Convenience-related and health attributes accounted for 7 of the top 10 categories of claims on packaged food in 2007, according to a leading international supplier of information on new packaged products. Five of these claims, including "single serving" and "quick," have ranked in the top 10 since 2001 (Martinez, 2007). Time savings at home have also been achieved through more widespread use of food preparation and cleaning appliances. According to the DOE Residential Energy Consumption Survey, the share of U.S. households with dishwashers, microwave ovens, and self-cleaning ovens increased substantially between 1997 and 2005, providing more evidence of an energy/labor tradeoff (table 4). U.S. households also outsourced part of their food preparation and cleanup to foodservice establishments. Between the late 1970s and the mid-1990s, U.S. food consumers increased their share of total caloric intake attributed to away-from-home foods from 18 to 32 percent (Stewart et al., 2006).

Foodservice establishments also increasingly outsourced food preparation to food processors. Food preparation jobs in the foodservice industry declined by roughly 16,000 workers between 1996 and 2000, while food manufacturing industries increased the number of these positions over this period by about 4,800 (Lane et al., 2003).

Table 3

Energy technology change impacts on per capita energy flows for food and related items, 1997 to 2002

Expenditure category	1997 energy flows		Change in per capita energy flows
	Btu per dollar	*Btu per capita*	*Btu per capita*
Food at home:			
Cereal products	11,365	1,057,746	144,548
Baking products	10,281	1,500,067	387,109
Fresh dairy	15,671	700,175	84,082
Processed dairy	14,544	1,376,005	275,246
Fats and oils	13,859	427,970	98,583
Sugar and sweets	11,210	1,175,037	287,604
Fresh fruits	9,834	500,985	74,491
Fresh vegetables	10,669	794,989	394,158
Beef	15,475	1,245,533	178,320
Pork	15,475	1,062,617	-907
Other meats	15,388	847,371	60,350
Fish	9,503	261,302	9,239
Poultry	13,049	1,378,924	454,372
Eggs	14,273	255,968	100,944
Processed fruits and vegetables	11,818	719,770	163,104
Frozen, canned, snack, and other	11,444	2,862,597	630,731
Nonalcoholic beverages	10,656	2,113,936	357,102
Alchoholic beverages	8,033	2,723,987	237,758
Pet food	13,775	912,053	-1,449
Food away from home	7,982	7,917,038	239,598
Household operations[1]	54,550	12,320,671	482,066
Total food related	13,480	42,154,742	4,657,049

[1]Energy use for major kitchen appliances, auto use for food-related trips, and related energy flows for home food preparation and serving equipment.
Sources: USDA, Economic Research Service using expenditure data from U.S. Department of Commerce, Bureau of Economic Analysis; population data from U.S. Department of Commerce, Census Bureau; energy flow data from U.S. Department of Energy, Energy Information Administration.

Other food system processes underwent recent structural changes in their use of energy services. Freight services are among the most energy-intensive industries serving the U.S. food supply chain. Domestic food shipments travel predominantly by truck, with most of the remainder shipped by rail (USDOT, 2008). Though the freight industry has become more energy efficient since the 1970s, its gains in efficiency stabilized over the last decade (table 5). What has changed over the past decade, however, is the intensity of freight service use by the U.S. food system. Although the increasing volume of food shipments over time is predictable, this change is compounded by significant increases in average shipping distances of most food products. Each of four broad food commodity categories averaged between a 5- and 15-mile annual increase in shipping distances between 1997 and 2002. With the exception of the produce, oilseeds, and other horticulture category, each

Table 4
Home appliance use by U.S. households

	Appliance ownership				
Year	Dishwasher	Microwave oven	Self-cleaning oven	Two or more refrigerators	Total households
			Million households		
1993	43.7	81.3	NA	14.4	96.6
1997	50.9	84.2	44.7	15.4	101.5
2001	56.7	92.1	48.2	18.1	107.0
2005	64.7	97.7	62.9	24.6	111.1
			Percent of total households		
1993	45.2	84.2	NA	14.9	100.0
1997	50.1	83.0	44.0	15.2	100.0
2001	53.0	86.1	45.0	16.9	100.0
2005	58.2	87.9	56.6	22.1	100.0

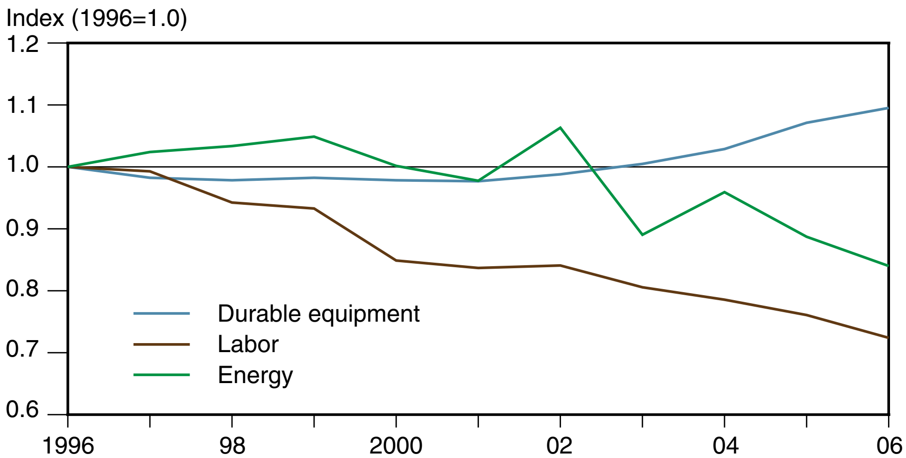
NA--Not available.
Source: USDA, Economic Research Service using data from the U.S. Department of Energy (www.eia.doe.gov).

Table 5
Freight industry characteristics

	1997	2002	2007
Commodity group:	Average distance per shipment *Miles*		
Fresh produce, oilseeds, and other horticulture	438	481	374
Meat, fish, and preparations	137	162	243
Milled grain products and preparations, and bakery products	122	189	262
Other prepared foodstuffs and fats and oils	127	179	230
Freight mode:	Energy use by freight mode *Btu*		
Energy use per truck mile	21,340	23,461	23,260
Energy use per freight car rail mile	15,784	15,003	14,990

Sources: USDA, Economic Research Service using data from the U.S. Department of Transportation (www.bts.gov), and U.S. Department of Energy (http://cta.ornl.gov/cta/).

Figure 6
Index of U.S. agricultural inputs: energy, labor, and durable equipment



Source: USDA, Economic Research Service (http://www.ers.usda.gov/Data/AgProductivity/methods.htm).

category averaged between a 10- and 16-mile annual increase between 2002 and 2007. Given the large volume of food annually transported on the domestic freight system, these distance increases translate into substantial growth in energy use by food-related freight services.

In agriculture, the long-term trend toward greater use of technology in place of manual labor continues. Farm labor inputs fell nearly 30 percent between 1996 and 2006, while services from durable farm equipment increased 10 percent over the same timeframe (fig. 6). These trends would also indicate a greater reliance on energy services, but while estimates for direct farm use of energy services did increase noticeably in 2002, they fell off substantially through 2006, coinciding with large increases in energy prices (see fig. 4). What is not evident from these data are the effects of these changes on the energy services for farm inputs. With farm machinery use on the rise and use of agricultural chemicals roughly constant, energy services for the production of farm inputs may have increased steadily over the past decade.

A supply chain analysis

A supply chain analysis (SCA), which is used to attain a more indepth account of increases in total food-related energy flows, includes an examination of the changes in energy flows by food production stages.[10] Unlike in conventional IO cost analysis, SCA attributes total food-related energy flows to a short list of supply chain industries. No new data are introduced. Instead, the IO accounts are partitioned into two groups: supply chain industries and non-chain subcontracting industries. The precise relationships between the supply chain and subcontracting industries are established, which allows for a clean measure of nonchain industry energy flows that are subcontracted by each supply chain industry (see appendix for derivation of the SCA).

[10]Leontief, W. 1967. "An Alternative to Aggregation in Input-Output Analysis and National Accounts," *Review of Economics and Statistics*, Vol. 49, No. 3 (Aug), pp. 412-4.

For this analysis, the domestic food supply chain is examined as follows:

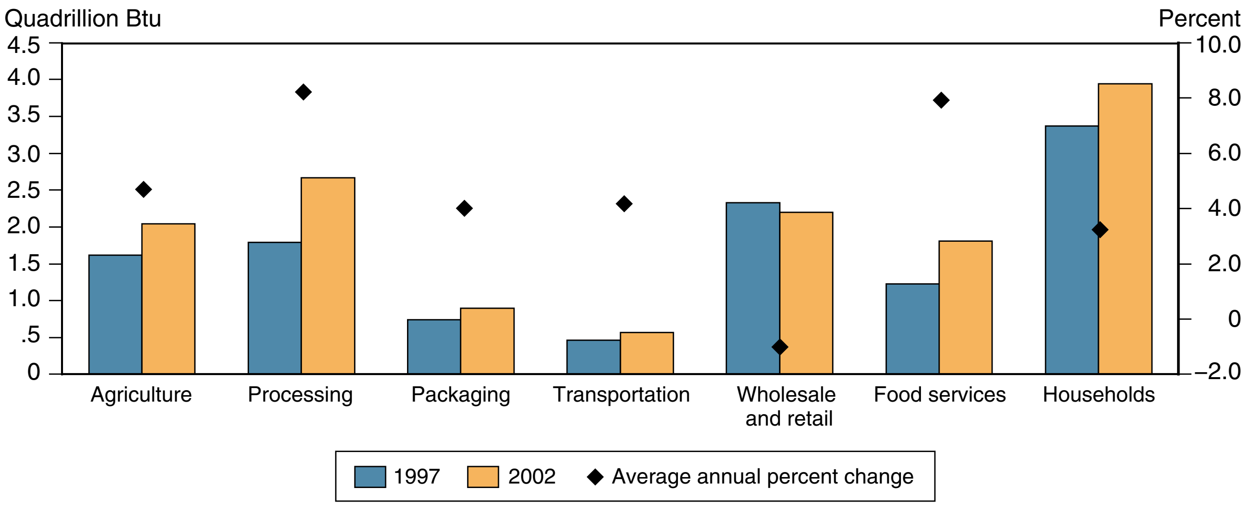
1. Farm production and agribusiness (agriculture)
2. Food processing and brand marketing (processing)

3. Food and ingredient packaging (packaging)
4. Freight services (transportation)
5. Wholesale and retail trade and marketing services (wholesale/retail)
6. Away-from-home food and marketing services (food service)
7. Household food services (households)

For accounting purposes, these food system stages are mutually exclusive. For example, energy use for all wholesale and transportation services provided both directly and indirectly to support farm production is attributed to the wholesale and transportation stages and not to the farm production stage. Aside from the direct energy consumption of these seven food system stages, all other domestic energy use by the subcontracted nonchain industries are attributed to food system stages commensurate with each stage's use of these products. For example, to the extent that the banking system provides financial services to each of stages 1 to 6, energy use by the banking industry, such as electricity and natural gas, is attributed to each of these first six stages in proportion to the share of total U.S. banking industry services provided to the six food system stages.

Analysis of the entire food supply chain (fig. 7) supports findings that indicate food preparation activities of households and the foodservice industry have been substantially outsourced to food processors. Energy flows through the processing industries increased by an annual average rate of 8.3 percent between 1997 and 2002. As a result, food processing industries surpassed wholesale/retail trade services by 2002 to account for the second largest energy flow among supply chain stages. On a per capita basis, this increase amounts to 2.7 million Btu, or roughly the equivalent of an additional 24 gallons of gasoline per person per year. Energy flows through the foodservice industry also increased significantly during the period, averaging roughly the equivalent of 16 gallons of gasoline per person annually. Household operations generated the most energy flows in both years but increased at a more modest annual rate of 3.2 percent. Together, these three stages accounted

Figure 7
Change in U.S. energy consumption by stage of production, 1997 to 2002



Source: USDA, Economic Research Service.

for about 60 percent of total 2002 food-related energy flows, up from 55 percent in 1997. Energy flows through wholesale/retail trade services actually declined at an annual rate of 1.1 percent. The growth in food services may have cut into the demand for retail services, but the rapid consolidation of grocery store chains over this period is also likely to have had an impact. Energy use in agriculture, including the embodied energy in purchased inputs, ranks third among supply chain stages in the rate of growth in energy flows. This growth increased the share of total food-related energy flowing through agriculture to 14.4 percent in 2002, up slightly from 14.0 percent in 1997. Packaging and freight services are considerably smaller users of energy overall, and the rate of growth in energy flows through these industries over the 5 years mirrored overall food-related increases. However, the overall results for the food system may obscure the role of energy flows at different stages of the supply chain for different categories of food expenditures.

Table 6 summarizes per capita energy use by stage of production for several food-at-home expenditure categories. It is difficult to assign energy flows for household operations to each of these food expenditure categories, so this stage is omitted from the table. Findings from the analysis of overall energy flows by stage of production are far more pronounced at the food commodity level.

Total energy flows passing through vegetable farms producing products for the fresh market increased by an annual average rate of 17.2 percent between 1997 and 2002, which far outpaces the rate of increase in per capita expenditures on these products. Other commodities with both substantial energy flows and high annual rates of increase in these flows at the farm stage included prepared foods and snacks (13.1 percent), eggs (12.2 percent), and poultry products (10.4 percent). All processed foods had substantial increases in energy flows passing through the food processing stage, most notably cereal and baking products. Energy flows for packaging in the poultry products and beverages categories are the only segments of the supply chain showing increases at annual rates above 6 percent, while most other commodity groups saw increased energy flow rates for packaging of 2.5 percent or less (including some decreases). For freight services, annual average increases in energy flows above 10 percent were measured for poultry and egg products and for fresh fruit shipments. Note that 10 percent or more of total energy flows for fresh fruits and fresh vegetables are for freight-related services, which is about twice the average for all foods.

Table 6
Per capita energy flows by production stage and expenditure category, 2002

Expenditure category	Farm and agribusiness	Food processing	Packaging	Freight services	Wholesale / Retail
Cereal products					
Thousand Btu in 2002	199	468	89	70	351
Avg. yearly pct. chg. from 1997	3.6	10.4	-0.5	1.6	-4.7
Share of Btu row totals, 2002	16.9	39.7	7.6	6	29.8
Baking products					
Thousand Btu in 2002	212	1,129	144	114	780
Avg. yearly pct. chg. from 1997	13.6	13	5.9	9.8	5.7
Share of Btu row totals, 2002	8.9	47.4	6.1	4.8	32.8
Fresh dairy					
Thousand Btu in 2002	284	251	46	44	162
Avg. yearly pct. chg. from 1997	-0.9	10.7	1.3	11.1	-2.2
Share of Btu row totals, 2002	36.1	31.9	5.9	5.6	20.6
Dairy products					
Thousand Btu in 2002	473	438	85	79	327
Avg. yearly pct. chg. from 1997	-1.7	7	0.3	8.8	-4.4
Share of Btu row totals, 2002	33.7	31.2	6	5.6	23.4
Fats and oil products					
Thousand Btu in 2002	131	203	38	29	113
Avg. yearly pct. chg. from 1997	6.5	7.9	2.5	-0.2	-2.8
Share of Btu row totals, 2002	25.4	39.6	7.3	5.6	22.1
Sugar and sweets					
Thousand Btu in 2002	187	632	136	71	378
Avg. yearly pct. chg. from 1997	8.5	7.6	6	1.5	-3.1
Share of Btu row totals, 2002	13.3	45.1	9.7	5	26.9
Fresh fruits					
Thousand Btu in 2002	315	14	16	68	260
Avg. yearly pct. chg. from 1997	8.4	-0.6	-0.1	12.6	3.3
Share of Btu row totals, 2002	46.9	2	2.4	10	38.7
Fresh vegetables					
Thousand Btu in 2002	672	25	29	166	428
Avg. yearly pct. chg. from 1997	17.2	11.7	2.5	5.1	5.9
Share of Btu row totals, 2002	50.9	1.9	2.2	12.6	32.4
Beef					
Thousand Btu in 2002	562	360	37	90	315
Avg. yearly pct. chg. from 1997	0.2	8.8	-4.9	5.8	-1.1
Share of Btu row totals, 2002	41.2	26.4	2.7	6.6	23.1
Pork					
Thousand Btu in 2002	410	262	27	60	209
Avg. yearly pct. chg. from 1997	-2.9	5.4	-8.4	0.5	-5.9
Share of Btu row totals, 2002	42.3	27.1	2.7	6.2	21.6

Continued—

Table 6

Per capita energy flows by production stage and expenditure category, 2002—continued

Expenditure category	Farm and agribusiness	Food processing	Packaging	Freight services	Wholesale / Retail
Other meats					
Thousand Btu in 2002	394	249	24	55	151
Avg. yearly pct. chg. from 1997	0.7	9.1	-5.8	3.5	-7.7
Share of Btu row totals, 2002	45.1	28.5	2.8	6.3	17.3
Fish					
Thousand Btu in 2002	89.2	80.9	9.3	14.8	111.1
Avg. yearly pct. chg. from 1997	9.1	8.1	-4.3	8.4	-2.5
Share of Btu row totals, 2002	29.2	26.5	3	4.8	36.4
Poultry products					
Thousand Btu in 2002	694	585	87	103	368
Avg. yearly pct. chg. from 1997	10.4	7.9	6.2	10.8	-2.9
Share of Btu row totals, 2002	37.8	31.9	4.8	5.6	20
Eggs					
Thousand Btu in 2002	201	69	9	23	63
Avg. yearly pct. chg. from 1997	12.2	7.7	-1.3	13	-2.8
Share of Btu row totals, 2002	54.9	18.8	2.5	6.4	17.3
Processed fruits and vegetables					
Thousand Btu in 2002	123	289	72	47	203
Avg. yearly pct. chg. from 1997	6.6	6.3	-3.3	-2.6	-6
Share of Btu row totals, 2002	16.7	39.4	9.8	6.3	27.7
Snack, frozen, canned and other foods, spices and condiments					
Thousand Btu in 2002	679	1,422	370	205	1,040
Avg. yearly pct. chg. from 1997	13.1	9.6	4.3	2.4	-1.2
Share of Btu row totals, 2002	18.3	38.3	9.9	5.5	28
Beverages					
Thousand Btu in 2002	135	765	600	125	857
Avg. yearly pct. chg. from 1997	2.3	6.5	6.7	1.2	-0.7
Share of Btu row totals, 2002	5.4	30.8	24.2	5	34.5
Alcoholic beverages					
Thousand Btu in 2002	217	719	596	203	928
Avg. yearly pct. chg. from 1997	3.6	7.7	4.7	4.3	0.3
Share of Btu row totals, 2002	8.1	27	22.4	7.6	34.8
Pet food					
Thousand Btu in 2002	317	335	73	63	348
Avg. yearly pct. chg. from 1997	14.7	9	2.9	5.3	-3.7
Share of Btu row totals, 2002	27.9	29.5	6.4	5.5	30.7

Source: USDA, Economic Research Service.

What Factors Will Determine Future Energy Use in the U.S. Food System?

Current DOE baseline projections[11] of energy use, which are bounded from above and below by projection scenarios under different economic growth and energy price assumptions, include several food-related energy flow indicators. Regarding household energy flows, DOE projects energy use for refrigerators, freezers, cooking, and dishwashers will increase by 12 percent between 2009 and 2030. With the U.S. population projected to increase 22 percent over this same interval,[12] these forecasts indicate significant per capita energy-use reductions through efficiency gains for household food-related operations (excluding household food-related travel). Even with these expected efficiency gains, the 12-percent increase is substantial. Combined energy use by food retailers and foodservice establishments is projected to increase by roughly 20 percent between 2009 and 2030, which implies that per capita energy use of these industries will remain relatively flat over the period. Energy use of food processors and agriculture are projected to increase by 27 and 7 percent, respectively. While these projections do not include the energy embodied in purchased inputs to each of these production stages, the overall projections largely mirror the changes reported in this study. Specifically, food processing industries are expected to continue driving growth in energy flows, and farm-related energy flow increases are expected to show a more moderate rate of growth.

[11]*Annual Energy Outlook, 2009*, U.S. Department of Energy, Energy Information Administration, Report #:DOE/EIA-0383(2009).

[12]*2008 National Population Projections*, U.S. Department of Commerce, Census Bureau, Population Division.

Several factors could reshape the outlook of energy flows through the U.S. food system. Of these, three are considered key to reducing the rates of growth in food-related energy flows.

Adoption of energy-efficient food system technologies

From 1997 to 2002, food industry technologies grew more energy intensive, which drove up average per capita food-related energy flows. In some cases, this growth was driven by increasing use of existing technologies, such as higher per capita home refrigeration storage capacities. In other cases, the growth in energy intensity was driven by a greater reliance on added processing, such as when purchases of pre-cut vegetables and salad mix products displace purchases of unprocessed produce. If the conditions influencing energy flow changes are reversed, the potential may exist for large decreases, too. From 1997 to 2002, the conditions for change appear to have been that (1) the opportunity costs of time spent at home on food preparation and cleanup continued a long-term upward trend,[13] (2) the foodservice industry was confronted with rising labor costs for food preparation jobs, and (3) energy prices were stable. Together, these conditions made the purchase of machine-supplied food preparation and cleanup services more price-competitive and attractive to the foodservice industry and households, and the food manufacturing industry expanded its supply of these services. From 2002 to 2007, energy prices increased substantially, but labor costs remained high in the foodservices industry and the opportunity cost of time spent on home food preparation appears to have also increased. These changes have ambiguous implications for incentives to employ more manual food preparation and purchase less machine food preparation services from food manu-

[13]Higher shares of women in the workforce were found to reduce the time spent by households cooking (Cawley, 2006). In 1970, about 43 percent of women age 16 and older were in the labor force; by the late 1990s, the labor force participation rate of women had risen to 60 percent (U.S. Department of Labor, Bureau of Labor Statistics, 2007).

facturers. Since 2007, energy prices have remained volatile, further obscuring the incentives for employing manual labor and energy services.

Another potential source for energy savings is the replacement of older equipment, such as household kitchen appliances, industrial food processing machinery, and low mileage vehicles, with more energy-efficient new equipment. Many State governments are offering incentives, such as tax rebates, for purchases of energy-saving appliances, and both Federal and State governments are offering business and residential incentives for the purchase of fuel-efficient vehicles. There is some evidence of increases in the adoption of energy-saving production practices during the period of rising energy prices. For example, food-related energy use for household operations declined 15.7 percent overall and 19.5 percent per capita between 2002 and 2007. During this period, real consumer energy prices increased 70 percent, which provide a strong incentive to adopt energy-saving production practices. However, at other stages of the food supply chain, per capita energy use increased over this period, and current DOE projections indicate energy use by food manufacturers is expected to increase faster than the population over the next two decades. The relative costs of energy services, energy-saving innovations, and manual labor appear to influence the intensity of energy use but do not appear to be strongly signaling shifts away from energy use.

Food expenditure trends

Overall growth in the quantity of food-related purchases is an inevitable consequence of population growth. The findings of this report suggest that the influences of population growth and changing per capita food expenditure patterns both accounted for about a quarter of the total growth in food-related energy flows between 1997 and 2002. Increases in real per capita food-related expenditures were an important factor in this finding.

Still, findings suggest that changes to food expenditure patterns may also produce net energy savings. Adjustments in food expenditure choices could reduce net per capita food-related energy flows in the future. For example, based on 2002 energy technologies, if households choose to substitute a portion of their home meat and egg consumption with expanded fish consumption, then other things equal (such as packaging and preparation), there would appear to be a substantial savings in energy requirements. If households choose to eat out more often, they could realize energy savings associated with this choice by capitalizing on opportunities to save on home energy use. For example, eating out more often should lower the volume of home food storage, which may present opportunities to temporarily shut down second (or third) refrigerators and/or freezers. Buying more local foods could also have implications for food-related energy flows.

Although each of these examples of potential energy savings related to individual choice are logically sound, there is a paucity of empirical evidence that assesses the scale of potential net energy savings from the widespread adoption of these changes in expenditure behaviors. For example, the energy efficiency of seafood production found in this report partly reflects the fact that the commercial fishing industry harvests fish that are not raised commercially and require no commercial energy inputs before reaching harvest size.

Can the commercial fishing industry maintain a sustainable harvest if there is a large-scale increase in expenditures on fish by U.S. households? If not, the difference in demand would have to be met by the commercial aquaculture industry. The aquaculture industry, however, purchases energy-using inputs to raise fish to harvest weights and is consequently a more energy-intensive food source then the commercial fishing industry. A similar uncertainty exists concerning the net energy savings from buying locally produced foods. A greater reliance on local food sources may affect the average food miles associated with annual household food expenditures; however, findings suggest that energy flows associated with the commercial transportation of food represent less than 5 percent of total energy use by the overall food system. This share is considerably higher for some food categories, such as fresh fruits and vegetables. To maximize net energy savings through reliance on local food production, the local farm, agribusiness, and processing industries would need to be at least as energy efficient as the distant industry alternatives that they replace.

Food and energy prices

Market prices provide the most direct incentive for affecting the purchasing behaviors of consumers and the production practices of producers. For example, when the price of energy increases while the price of labor services and the availability of "leisure time" for home food preparation do not change, industry and households will explore opportunities to trade off the now-more expensive energy services for less costly labor and leisure services. Additionally, they will seek opportunities to more efficiently ration their uses of energy services. These incentives get reinforced when the prices of products requiring substantial energy services begin to increase due to the higher costs of energy. In food markets, buyers of these products will seek lower cost substitutes among those foods requiring less energy services.

To the extent that energy costs are reflected in food prices, higher energy prices should induce households to purchase more energy-efficient foods and also induce producers of foods requiring substantial energy services to use these services more efficiently and possibly substitute for more labor services or purchase more energy efficient equipment. The key to these self-correcting market interactions is the accurate reflection of energy cost changes in the selling price of all products where energy services are purchased. In this way, the higher price for energy signals all buyers of products directly or indirectly using energy services to seek alternatives that use less energy and, conversely, lower energy prices will signal these same buyers to purchase more of the high-energy-using products. Policies that seek to induce reduced energy flows in the food system through price signaling may be more effective if policy-induced energy cost changes are transmitted in proportion to total energy flowing through each stage of the food supply chain.

References

Ayers, R.U., and A.V. Kneese. 1969. "Production, Consumption, and Externalities," *American Economic Review* 59, No. 3, June, pp. 282-297.

Bullard, C., and R. Herendeen. 1975. "The Energy Costs of Goods and Services," *Energy Policy* 1, No. 4 (Dec.), pp. 268-277.

Cawley, J. 2006. "Markets and Childhood Obesity Policy," *The Future of Children* 16, No. 1, pp. 69-88.

Cutler, D.M., E.L. Glaeser, and J.M. Shaprio. 2003. "Why Have Americans Become More Obese?" *Journal of Economic Perspectives* 17, No. 3: pp. 93-118.

Heller, M.C., and G.A. Keoleian. 2000. *Life Cycle-Based Sustainability Indicators for Assessment of the U.S. Food System*, Center for Sustainable Systems Report No. CSS-0004, University of Michigan, December, http://css.snre.umich.edu/css_doc/CSS00-04.pdf

Hirst, E. 1974. "Food-Related Energy Requirements," *Science* 184 (April 12), pp. 134-38.

Hoekstra, R., and J. Van Den Bergh. 2002. "Structural Decomposition Analysis of Physical Flows in the Economy," *Environmental and Resource Economics* 23, pp. 357-78.

Lane, J., Moss, P., Salzman, H., and Tilly, C. 2003. "Too Many Cooks? Tracking Internal Labor Market Dynamics in Food Service With Case Studies and Quantitative Data," in *Low-Wage America: How Employers Are Reshaping Opportunity in the Workplace*, E. Appelbaum, A. Bernhardt, and R.J. Murnane (eds.), Russell Sage Foundation, New York, NY.

Leontief, W. 1967. "An Alternative to Aggregation in Input-Output Analysis and National Accounts," *Review of Economics and Statistics* 49, No. 3, August, pp. 412-19.

Martinez, S. 2007. *The U.S. Food Marketing System: Recent Developments, 1997-2006*, Economic Research Report No. 42, USDA, Economic Research Service, May, www.ers.usda.gov/publications/err42/

Miller, R.E., and P.E. Blair. 1985. *Input-Output Analysis: Foundations and Extensions*, Prentice-Hall, Inc., Englewood Cliffs, NJ.

Oak Ridge National Laboratory, Center for Transportation Analysis. 2008. *Transportation Energy Data Book: Edition 27*, http://www-cta.ornl.gov/data/index.shtml

Pimentel, D., S. Williamson, C. Alexander, O. Gonzalez-Pagan, C. Kontak, and S. Mulkey. 2008. "Reducing Energy Inputs in the US Food System," *Human Ecology* 36, pp. 459-471.

Rose. A., and S. Casler. 1996. “Input-Output Structural Decomposition Analysis: A Critical Appraisal,” *Economic Systems Research* 8, No. 1, pp. 33-62.

Stewart, H., N. Blisard, and D. Jolliffe. 2006. *Let’s Eat Out: Americans Weigh Taste, Convenience, and Nutrition*, Economic Information Bulletin No. 19, U.S. Department of Agriculture, Economic Research Service, October, www.ers.usda.gov/publications/eib19/

United Nations, European Commission, International Monetary Fund, Organisation for Economic Co-operation and Development, and World Bank. 2003. *Handbook of National Accounting, Integrated Environmental and Economic Accounting, Studies in Methods*, Series F, No. 61, Rev. 1 (ST/ESA/STAT/SER.F/61/Rev.1).

U.S. Department of Commerce, U.S. Census Bureau. *Annual Population Estimates 2000 to 2008*, www.census.gov/popest/states/NST-ann-est.html

U.S. Department of Commerce, U.S. Census Bureau. *Historical National Population Estimates: 1900 to 1999*, www.census.gov/popest/archives/1990s/

U.S. Department of Commerce, U.S. Census Bureau. *Economic Census 2002*, www.census.gov/econ/census02/

U.S. Department of Commerce, Bureau of Economic Analysis. *NIPA Tables*, www.bea.gov/national/nipaweb/Index.asp

U.S. Department of Commerce, Bureau of Economic Analysis. *Underlying Detail – NIPA Tables*, www.bea.gov/national/nipaweb/nipa_underlying/SelectTable.asp

U.S. Department of Commerce, Bureau of Economic Analysis (BEA). *Benchmark Input-Output Accounts*, www.bea.gov/industry/index.htm#benchmark_io

U.S. Department of Energy, Energy Information Administration. 2008. *Annual Energy Review 2007*, DOE/EIA-0384, June, www.eia.doe.gov/aer/

U.S. Department of Energy, Energy Information Administration. 2009. *Annual Energy Outlook, 2009*, DOE/EIA-0383.

U.S. Department of Energy, Energy Information Administration. 2005 (and previous years). *Residential Energy Consumption Survey*, http://www.eia.doe.gov/emeu/recs/

U.S. Department of Labor, Bureau of Labor Statistics (BLS). *Quarterly Census of Employment and Wages* (various years), www.bls.gov/cew/

U.S. Department of Labor, Bureau of Labor Statistics. *Consumer Expenditure Survey* (various years), www.bls.gov/cex/

U.S. Department of Labor, Bureau of Labor Statistics. 2007. *Women in the Labor Force: A Databook*, Report 1002, September, www.bls.gov/cps/wlf-databook-2007.pdf

U.S. Department of Transportation, Federal Highway Administration. *Highway Statistics 2006,* PB 2008, www.fhwa.dot.gov/policy/ohim/hs06/index.htm

U.S. Department of Transportation, Bureau of Transportation Statistics (USDOT). 2003. U.S. *International Trade and Freight Transportation Trends*, BTS03-02, www.bts.gov/publications/us_international_trade_and_freight_transportation_trends

U.S. Department of Transportation, Bureau of Transportation Statistics (USDOT). 2008. 2007 Commodity Flow Survey: Preliminary, December, www.bts.gov/publications/commodity_flow_survey

U.S. Environmental Protection Agency (EPA). 2008. *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2007*, EPA-530-F-08-018, November, www.epa.gov/osw

Appendix: Mathematical Derivation of the Input-Output Material Flows Analysis Model and Results

An energy flows application of input-output material flows analysis[14] requires the construction of a hybrid input-output table consisting of (1) inter-industry nonenergy transactions recorded in monetary units (e.g., U.S. dollars), and (2) inter-industry transactions of energy services recorded in energy units such as British thermal units, or Btu. To demonstrate the conversion of a conventional IO table into a hybrid table, the following matrix, vector, and set notation are used:

[14] A standard reference for this type of analysis is chapter 4 in Miller and Blair (1985).

- "*C*" denotes the set of all economy-wide industry aggregates, partitioned into two subsets:
  - "ε" (the Greek epsilon) is the set of all energy industries
  - "o" is the set of all nonenergy industries.
- **Z**[*C*,*C*] summarizes inter-industry transactions as a square matrix with "*C*" columns and rows
- **v**[*C*] summarizes industry outlays to primary production factors as a *C* element vector
- **m**[*C*] summarizes industry outlays for comparable import commodities as a *C* element vector
- **y**[*C*] summarizes final market commodity sales as a *C* element vector
- **x**[*C*] summarizes total final and intermediate market commodity sales as a *C* element vector
- "**i**" denotes a vector of unit values with *C* elements, used for matrix summation operations
- the prime " ′ " symbol indicates the transpose of a vector or matrix
- $\{\ \}^{-1}$ denotes a matrix inversion
- ^ above a vector transforms that vector into a square diagonal matrix
- an "*" superscript denotes a vector or matrix of material flows
- an "*h*" superscript denotes a vector or matrix of mixed material and value denominations

Each of the "*C*" domestic industries produces a unique set of commodities not produced by any other domestic industry. In this way, inter-industry transactions are represented by a commodity-by-commodity transaction table. For accounting purposes, domestic industries are attributed with the purchases and re-sale of comparable imported commodities. Final market sales of the *C* commodities include personal consumption expenditures, private direct investment, government expenditures, and export sales.

A complete input-output system is stated in matrix notation as follows:

1) $\boldsymbol{Z} \cdot \boldsymbol{i} + \boldsymbol{y} = \boldsymbol{x}$

2) $\boldsymbol{i}' \cdot \boldsymbol{Z} + \boldsymbol{v}' + \boldsymbol{m}' = \boldsymbol{x}'$

Industry proceeds from intermediate (**Zi**) and final market sales (**y**) cover total industry outlays (x) for intermediate purchases of goods (**i′Z**) and services plus total payments to primary production factors (**v′**) and total purchases of comparable import commodities for resale (**m′**). Industry outlays equal industry sales because any operating surplus or deficit is distributed to primary production factors whose payments are tied to these residual proceeds.

The hybrid IO table. In conventional IO accounting, all transactions are recorded in value units. For example, the element $\mathbf{Z}_{r,c}$ of a transaction table represents the annual value of commodity "*r*" sales to domestic industry "*c*," and $\mathbf{y}_r$ is the annual final market sales of commodity "*r*." If $w_{r,c}$ and $w_{r,y}$ represent the yearly average unit price of commodity "*r*" paid by industry "*c*" and in final markets, respectively, then the annual quantity of commodity "*r*" purchased by industry "*c*" and in final markets can be obtained:

$$3)\quad \begin{aligned} Z^*_{r,c} &= Z_{r,c} / w_{r,c} \\ y^*_c &= y_c / w_{c,y} \end{aligned}$$

The corresponding transaction table and final demand vectors are denoted Z* and y*. They measure transactions in quantity denominations as opposed to value. The total outlays for this IO quantity account is obtained by summation across commodity rows:

$$4)\quad Z^* \cdot i + y^* = x^*$$

The desired hybrid IO table for energy flows analysis is obtained by combining selected partitioned elements of the conventional IO table and the quantity IO table:

$$5)\quad Z^h = \begin{bmatrix} Z\ [o,C] \\ \hdashline Z^*[\varepsilon,C] \end{bmatrix} \quad , \quad y^h = \begin{bmatrix} y\ [o] \\ \hdashline y^*[\varepsilon] \end{bmatrix} \quad , \quad x^h = \begin{bmatrix} x\ [o] \\ \hdashline x^*[\varepsilon] \end{bmatrix}, \quad A^h = Z^h \cdot \{\hat{x}^h\}^{-1}$$

Bullard and Herendeen (1975) demonstrate how a concept called conservation of embodied energy[15] allows the properties obtained from conventional IO analysis to also hold for a hybrid IO system such as described in (5); for example:

$$6)\quad H[C,C] \cdot y^h[C] = x^h[C], \quad H = \{\hat{i} - A^h\}^{-1}$$

The common name for the inverted matrix expression denoted as "**H**" in equation 6 is the total requirement matrix. For this hybrid account derivation, each element, $\mathbf{H}_{i,j}$ of the total requirement matrix provides the total direct and indirect uses or "flows" of commodity *i* dedicated to facilitating the final market sale of each unit of commodity *j*. For all elements of the matrix in partition **H**[ε,*C*], total requirements are measured in Btu and indicate the total Btu flows dedicated to each final market unit sale of commodity **C**.

Let **p**[*C*] be a *C* element vector of percentages that identifies the share of each element in the **y**[*C*] vector that represents food-related expenditures such that all non-food-related expenditures of each element in **y**[*C*] are netted out (in many cases this means changing the value of that element to 0). Then, one can obtain the total food-related energy flows, $\mathbf{e}_{food}$, in the economy as follows:

[15]Conservation of embodied energy stipulates that energy burned or dissipated by a process is passed on, embodied in the product of that process (Bullard and Herendeen, 1975).

8) $i'[\varepsilon]\cdot\left[H[\varepsilon,C]\cdot(\hat{p}[C]\cdot y^h[C])\right]=e_{food}$

Although the term within brackets in (8) provides an itemized account of energy flows by fuel source, this detail is collapsed by the summation vector, **i**[ε], because this report does not itemize fuel use due to information gaps that preclude a cross-check of information at this level of detail.

Addressing aggregation bias. The issue of trade services aggregation was first identified in the context of a food-related energy flow analysis by Hirst, where it is noted that "energy use for food-related retail trade may be underestimated because of aggregation" (see Hirst, 1974, p. 138). In fact, an examination of annual utility costs as a share of annual gross margins of wholesalers and retailers presents a stark contrast among type of trade business. For example, annual electric utility costs for motor vehicle and parts retailers in 2002 amounted to 0.96 percent of annual gross margins, whereas the same measure for food and beverage retailers amounted to 3.89 percent, or roughly 3 cents per dollar of retail services higher than for auto parts retailers. Using data from the 1997 and 2002 Economic Census and the Annual Retail Trade survey, utility costs for electricity and for natural gas per dollar of wholesale and retail gross margins were calculated by four-digit NAICS. These ratios were used to extend the 1997 and 2002 IO accounts as follows:

1. Create two new columns (industries) in 1997 and 2002 inter-industry transaction tables:

   a. electric utility services for trade industries
   b. natural gas utility services for trade industries

2. Move electricity and natural gas outlays of wholesale and retail industry to new columns.

3 Create corresponding rows (commodities) to allocate the purchase of the two utility services costs implicit in each industry purchase of trade services, based on cost-to-gross margin ratios calculated from the business expense tables.

4. Normalize the estimated data in the two new commodity rows to replicate to expense totals from the published accounts.

The extended accounts created by these procedures make no alternations to the published IO tables, while capturing the heterogeneity of energy use in the trade services by type of service.

An aggregation procedure for supply chain analysis. A food supply chain, "*f*," consists of six stages, *s*, terminating at the point of purchase:

*s*1. Farming and agribusiness

*s*2. Food processing

*s*3. Packaging

*s*4. Transportation

*s*5. Trade (wholesale and retail)

*s*6. Food services

In this study, ERS applies an industry-based total requirement method that partitions the input-output table into two industry groups; supply chain industries (group 1) and nonsupply chain industries (group 2). Group 2 industries are eliminated from the aggregated tables, but their value-added contributions to the output of supply chain industries are exactly allocated to group 1 industries through a double matrix inversion procedure (Leontief, 1967). This method involves thinking about the other sectors as "subcontracting" sectors. The sectors of interest ("contracting") each purchase total requirements of subcontracting sectors, and those amounts are absorbed into the contracting industry's output. In Leontief's notation, group 1 is contracting industries and group 2 is subcontracting industries. Then the output/final demand relation of conventional IO analysis:

9) $$x = \{\hat{i} - A\}^{-1} \cdot y, \quad A = Z \cdot \{\hat{x}\}^{-1},$$

can be rewritten as:

10) $$\left[\begin{array}{c} x[1] \\ \hline x[2] \end{array}\right] = \left[\begin{array}{c:c} (\hat{i}[1] - A[1,1] & -A[1,2] \\ \hdashline -A[2,1] & (\hat{i}[2] - A[2,2] \end{array}\right]^{-1} \left[\begin{array}{c} y[1] \\ \hline y[2] \end{array}\right]$$

A reduced direct requirement matrix describes direct requirements of each group 1 industry only in terms of each other's outputs, as follows:

11) $$A^{\#}[1,1] = A[1,1] + A[1,2] \cdot \{\hat{i} - A[2,2]\}^{-1} \cdot A[2,1]$$

12) $$L^{\#} = \{\hat{i}[1] - A^{\#}\}^{-1}$$

The proof can be found in Leontief's paper. L# represents the total requirement matrix of the reduced system. Similarly, one can further partition the "o" block of the hybrid direct requirement matrix (equation 5) into food (f) and other (o) blocks:

13) $$A^h[o,C] = \left[\begin{array}{c:c} A^h[f,f] & A^h[f,o] \\ \hdashline A^h[o,f] & A^h[o,o] \end{array}\right]$$

and the energy rows of the direct requirement matrix into:

14) $$A^h[\varepsilon,C] = \left[\begin{array}{c:c} A^h[\varepsilon,f] & A^h[\varepsilon,o] \end{array}\right]$$

A reduced direct energy requirements matrix can then be formed as:

15) $$A^{\#}[\varepsilon,f] = A^h[\varepsilon,f] + A^h[\varepsilon,o] \cdot \{\hat{i} - A^h[o,o]\}^{-1} \cdot A^h[o,f]$$

With the exception of household food operational expenditures, all food-related final market expenditures are contained within the partitioned subvector of final demands, $\mathbf{y}^{h}[f]$, and the supply chain analysis in this report only concerns these expenditures. A total supply chain assessment of food-related energy flows is obtained by summing the energy flows through each stage, s, of production:

16) $$e_f = \sum_{s=s1}^{s6} A^{\#}[\varepsilon,s] \cdot L^{\#}[s,f] \cdot (\hat{p}[f] \cdot y[f])$$

A simple verification of the matrix reduction procedure is to evaluate expression (8) for the food commodities subset (f) and compare the results to those obtained in (16); they should be identical.