Assessment of Energy Use and Greenhouse Gas Emissions in the Food System: A Literature Review

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Introduction

Amid growing concerns about climate change and long-term petroleum reserves, the food system looms large as a major user of fossil fuels and, as a result, producer of greenhouse gases (GHG). Indeed, these twin problems may be the significant drivers that catalyze change in the food system in the 21st century. Already we are witnessing a stream of new policies aimed at reducing greenhouse gases, including a sweeping new law in California that requires a 20% reduction in greenhouse gas emissions across all sectors by 2020 and 80% by 2050.

The most recent energy studies available suggest that the food system consumes close to 16 percent of the total energy use in the U.S. (Hendrickson 1996). Since fossil fuels serve as the dominant energy source driving the U.S. economy, significant greenhouse gas emissions emanate from the food system, creating a large “carbon footprint”. Individual foods, however, vary tremendously in how they are produced, processed, packaged, and transported, and therefore vary tremendously in their carbon footprint. For example, Eshel and Martin (2006) demonstrate that the GHG emissions, on a per kilogram basis, associated with the production of different animal-based food products differ from one another quite substantially. According to their calculations, substituting certain animal products for others (such as poultry or eggs for red meat), or substituting plant-based foods for animal-based foods, can potentially result in as large a difference in one’s personal carbon footprint as choosing to drive an ultraefficient hybrid (Toyota Prius) instead of an average sedan (Toyota Camry). Changes in consumer food choices, therefore, hold the potential to make a substantial impact on the overall energy audit and GHG emissions of our food system on a national and global scale.

In order to make such choices, however, food services providers and consumers require guidelines that are based on a systematic analysis of the detailed differences in energy use and GHG emissions of individual foods, taking into account variables such as differences in production systems (e.g. organic versus conventional) in different locations, different processed forms of food, transport distances from farm to processor to retail, and so on. Such overall guidelines are not currently available in the U.S.; nor, in many cases, are the comprehensive data sets needed to construct such guidelines. This literature review presents a broad overview of work on this topic to date, for the purposes of framing the issues, identifying potential data sources that might prove useful in formulating general guidelines, and identify crucial gaps in knowledge.

Energy Use within Specific Sectors of the Food System

Energy use in food production, processing, transport, and consumption has long been a topic of study. Some of the most widely cited work on the topic originated with Pimentel and Pimentel (1979, updated 1996; also Pimentel 1980), who used an input/output model to quantify energy requirements of industrial food production methods relative to kilocalories produced, and compared these ratios to those in non-industrialized systems. This research resulted in energy coefficients which are still in use in food energy research today.

Production

More recent work on energy use in the production sector has compared different production systems, such as organic and conventional farming in industrialized nations. Several studies show that organic farming relies on lower per hectare fossil fuel inputs than conventional systems, with much of this difference attributable to the high energy requirements of the Haber-Bosch process in the manufacture of synthetic nitrogen fertilizer (Livingston 1995, Kaltsas et al. 2007, Nielsen et al. 2003). In fact, Heller and Keoleian (2000) estimate that the manufacturing of synthetic fertilizers and pesticides accounts for almost 40 percent of the energy used in all of U.S. agriculture. The difference between conventional and organic systems has been demonstrated not just for crop production but also for dairy farms (Refsgaard et al. 1998, Cederberg and Mattsson 2000), where the relatively greater use of concentrated feed as opposed to pasture in conventional systems ultimately also increases their dependence on fuel-intensive crop inputs like synthetic fertilizer. A relatively lower dependence on high-energy inputs in organic agriculture also translates into carbon dioxide emissions being 48 to 66 percent lower, on a per hectare basis, than in conventional systems (El-Hage Scialabba and Hattam 2002). In addition, Cederberg and Mattsson (2000) suggest that total nitrous oxide emissions, associated in large part with the application of synthetic fertilizer, in some conventional production systems may even outweigh total CO_2 emissions associated with fossil fuel use. When calculated on the basis of unit of food produced, however, differences in energy use and GHG emissions depend critically on yield differences in organic versus conventional systems. In some commodities, substantially lower yields in organic systems have the potential to cancel out per hectare energy efficiency gains (Livingston 1995). With organic yields steadily increasing for many crops (Liebhardt 2001) and the use of high-tech inputs also increasing in organic systems, the complex tradeoffs between energy-intensive inputs and relative yields, and how these tradeoffs ultimately effect net energy- and GHG-efficiencies in these systems, require careful consideration.

Other energy issues in the production sector include biophysical variables that impart “comparative advantages” to some geographic regions in producing certain crops. Such advantages might include abundance of surface water and topography that allows gravity-fed irrigation, as opposed to pumped groundwater, and temperature and humidity differences that impact a crop’s needs for water and pest control materials. Advantages might also be conferred by different farming practices and crop genetics available in a given region. For example, New Zealand apple orchards producing Braeburn apples on vigorous rootstock outyield German orchards of the same variety on a dwarfing rootstock by a factor greater than 2, which was estimated in one study to reduce the energy requirements per kg of apples produced in New Zealand by 25 percent compared to those produced in Germany (Blanke and Burdick 2005). The carbon sequestration potential of different soil management practices is also an important consideration from the perspective of GHG emissions. No-till farming as well as practices such as cover cropping, can significantly increase the potential of agricultural land to sequester carbon (West and Marland 2002; Johan Six, Dept. of Plant Sciences, UC Davis, personal communication).

Livestock production introduces the additional variables of non-fossil fuel-related nitrous oxide and methane emissions. From a climate change perspective, fluxes in these two gases are important to understand, given that N_2O has 310 times and CH_4 has 21 times the global warming potential of CO_2. In ruminant livestock production, which in the US primarily includes cattle, CH_4 emissions from the animals' digestive processes (enteric emissions) are thought to account for about 80 percent of total GHG emissions from all livestock production, while emissions from manure, including N_2O, account for approximately 20 percent (Monteney et al. 2006). Composition of the diet plays a key role in regulating CH_4 production in the rumen, with diets high in roughage, relative to soluble sugars and starches, more likely to produce more CH_4 (Cederberg and Mattsson 2000, Monteney et al. 2006). Manure management is an important factor in regulating N_2O emissions, and some evidence indicates that slurries that have been stored for several months before spreading on cropland may emit less N_2O than fresh slurry or than fresh urine deposited on grazing land (Monteney et al. 2006). These results suggest that more extensive, grazing-based systems, where animals eat a higher ration of fiber and deposit manure and urine in the open, might produce more GHG emissions than confined animal feeding operations. On the other hand, higher methane emissions from anaerobically stored manure in confinement systems can alter this balance. The large number of interdependent variables, many of which encompass large ranges dependent on specific details in farm management, requires more systems-based studies before definitive conclusions can be drawn.

Processing

In the processing sector, earlier studies have shown that canning vegetables can require up to twice as much energy in the manufacturing and processing facilities as freezing, due to the high energy use in manufacturing steel and especially aluminum cans, as well as glass jars (Whittlesey and Lee 1976, Pimentel and Pimentel 1985, Kooijman 1993). Dehydration processes and production of canned sauces can also substantially increase energy use in processing (Thompson 1985). However, these differences at the processing stage can be misleading. For example, despite the high energy costs of canning materials, the continual refrigeration requirements of frozen foods at every step from processor to retail to consumer result in an overall much higher energy use (up to 35 percent more) than canned foods, once these subsequent stages are included (Whittlesey and Lee 1976, Thompson 1985). In addition, canning materials can be recycled. Likewise, dehydrating products like milk and potatoes substantially reduces transport weight and eliminates refrigeration requirements, resulting in a 15 percent lower overall energy use when transport, retail, and consumer storage are included in the accounting (Whittlesey and Lee 1976, Pimentel and Pimentel 1985). In terms of global warming potential of food processing, the mix of energy sources used in processing plants can significantly impact the amount of GHG emissions. Some public utilities in California, for example, derive close to half of their electricity from non-GHG-emitting sources (including hydropower), resulting in relatively lower GHG emissions of processes that rely on electricity as opposed to other fuels, such as natural gas (James Thompson, Dept. of Biological and Agricultural Engineering, UC Davis, personal communication).

Transport

In the transportation sector, initial work has focused on the concept of "food miles", the distance traveled by food from where it is grown to where it is ultimately consumed (Pirog et al. 2001). Various authors over the last several decades have estimated food miles for the typical U.S. diet to range from a low of 50-75 miles for milk and eggs to 2,146 miles for fruits (Hendrickson 1996, Pirog et al. 2001). The food miles concept, however, overly simplifies energy issues in food transportation, because some modes of transport are much more fuel-efficient per unit of food transported than others. For example, rail transport is an order of magnitude more efficient than truck transport, in terms of fuel used per tonne-kilometer transported, and sea transport is about two to three times as efficient as rail transport. Air freight, on the other hand, uses about 10 times as much energy as truck transport (Hansen 2007). Consumers' car trips to the grocery store are the least efficient, especially since cars are rarely loaded to maximum capacity. Using these figures, one can estimate that the same amount of fuel can transport 5 kg of food only 1 km by personal car, 43 km by air, 740 km by truck, 2,400 km by rail, and 3,800 km by ship (James Thompson, Dept. of Biological and Agricultural Engineering, UC Davis, personal communication).

A more careful analysis of food miles, taking mode of transport into account, therefore suggests that overall scale of the food system can figure significantly in total energy use and GHG emissions. The long distances typically associated with large-scale, centralized food distribution systems may not, in and of themselves, constitute the only sources of increased energy use and emissions per unit of food in the transport sector. Small, locally-based food systems may be most reliant on the least efficient types of vehicles. For example, Pirog et al. (2001) estimated that local food systems in Iowa based on small trucks carrying food to farmers markets and local institutions feasibly consume two to four times as much fuel as a regional food system using larger semitrailers and mid-sized trucks (both scales of transport, however, are estimated to use from only one-tenth to a quarter of the fuel consumed by the conventional, long-distance distribution system to distribute the same quantity of food). In the production sector, also, some evidence suggests that mid-sized family farms in the U.S. may be more efficient users of overall farm resources (when measured as output per unit of input) than either the largest or the smallest farms (Peterson 1997, Rosset 1999). In the processing sector, however, larger-scale facilities are likely to garner some economies of scale in terms of energy use per unit output. How food miles interact with all these other dimensions of scale in the food system requires further study.

These types of sector-specific studies are useful in identifying ways to improve key parts of individual sectors of the food system. However, they are not as useful to consumers and institutional buyers in the modern industrial food system, where decisions about which food products to purchase cut across multiple sectors at once. For example, to make a pasta sauce, a consumer could choose to purchase either fresh tomatoes transported from overseas in the off-season, or tomato paste canned from tomatoes grown regionally. Simply knowing the difference between the imported tomatoes and domestic tomato paste in terms of transport energy will not explain how this difference is offset by the increased energy use in processing the paste, let alone potential differences in energy use of the production technologies in the local versus foreign growing location.

Life Cycle Assessment across Sectors of the Food System

To obtain a more comprehensive understanding of energy use throughout the food system, across all sectors encountered by any given commodity on its journey from farm to fork, researchers have in the last 10 to 15 years begun to apply life cycle assessment (LCA) methodology to food products. LCA originated in an industrial context to assess multiple environmental impacts incurred in the manufacture, distribution, and disposal of manufactured products. When used to analyze the fossil fuel energy embodied in food products and the associated greenhouse gases, LCA must take into account farm production processes (including production of key farm inputs and equipment before they even reach the farm), transportation of the crop between all points of the market chain beyond the farm gate, any processing the crop undergoes, energy use in warehousing and retailing, and, if the consumer level is included in the study, it should also include post-retail transport, home storage, meal preparation, and waste.

A review of the literature yielded 28 case studies that used LCA methodology or related input-output methodologies to study energy use and/or GHG emissions associated with specific commodities across more than one sector of the food system (See Appendices I and II). The range of commodities studied includes carrots (Carlsson-Kanyama 1998), tomatoes (Anderson et al., 1998, Carlsson-Kanyama 1998), potatoes (Carlsson-Kanyama et al. 2001), pork (Carlsson-Kanyama 1998), rice (Carlsson-Kanyama 1998), dry peas (Carlsson-Kanyama 1998), hamburgers (Carlsson-Kanyama and Faist 2000), milk (Cederberg and Mattsson 2000), rapeseed (Mattsson et al., 2000), soybean (Mattsson et al. 2000), oil palm (Mattsson et al. 2000), sugar beets (Bentrup et al. 2001), and ketchup (Andersson et al. 1998). In addition, a substantial review of existing literature that was recently completed for the U.K. Dept. of Environment, Food, and Rural Affairs (Foster et al. 2006) gave access to insights from an even larger body of case studies. The majority of the studies completed to date are from Europe, especially Sweden, and the U.K. Very few studies were found from the U.S. and Canada.

The following are just a few examples of some surprising conclusions arising out of these studies. Carlsson-Kanyama et al. (2003) found that the edible parts of frozen and overseas broccoli accounted for 20 MJ/kg in energy use, a high figure due to substantial portions of wasted product, while canned vegetables varied from 8 to 18 MJ/kg, demonstrating that fresh produce is not always more energy-efficient than processed. Many cooked and processed chicken products have much lower energy inputs per kg than deep water fish, such as tuna, or farmed fish, such as salmon, which can partly be attributed to the high feed conversion ratios of poultry and the relative energy efficiency of industrialized confined rearing methods (Carlsson-Kanyama et al. 2003). In a study on ketchup, Andersson et al. (1998) found that energy used in long-term storage in home refrigerators can dwarf energy use in any other sector of the ketchup life cycle by a factor of two or more, and fuel used for consumer shopping can be as much as fuel used in all other transportation earlier in the life cycle, on a per kg basis.

On a larger scale, some authors have used an LCA model to estimate the allocation of energy in national food systems. Among the most striking conclusions arising from such studies are that household food storage and preparation account for a very large portion of the total food energy budget, from 25 to 30 percent. Agricultural production accounts for another quarter (from 18 to 28 percent), while processing, including packaging, accounts for 20 to 28 percent (Hendrickson 1996, Heller and Keoleian 2000, and Faist et al. 2001). Furthermore, Faist et al. (2001) suggest that optimizing the efficiencies of household appliances, such as refrigerators, can yield energy savings that more than match the savings possible from relatively far-reaching adjustments to agricultural production standards. Finally, many authors have suggested that a societal shift to a more plant-based diet and away from animal foods would greatly reduce the energy intensity and GHG emissions of the food system (Dutilh and Kramer 2000, Heller and Keoleian 2000, Carlsson-Kanyama et al. 2003, Eshel and Martin 2006). These examples illustrate the importance of utilizing a more comprehensive approach such as LCA in order to pinpoint hotspot areas of high energy use and GHG emissions in the food system, as well as to be able to carry out realistic comparisons of different food products available to consumers.

To date, however, such comparisons across different foods have been severely hindered by important, unresolved methodological issues in performing LCA for food products. For example, each research team typically sets its own systems boundaries, resulting in significant variation across studies in what is included and excluded from calculations. Aspects most commonly excluded are capital goods (i.e. buildings, machinery, equipment), packaging materials, waste treatment (on-farm, processing, and post consumer), transport from the retailer to the consumer, energy use in the retail industry, embodied energy in seeds, transport of inputs/materials to the farm, and home cooking or food preparation. It is often difficult to determine the boundary for agricultural production since there are numerous inputs that all require their own life cycle assessments. Simplifying assumptions can also obscure important details; for example, calculating transport distances “as the crow flies” can result in severe underestimates when the actual locations of large, centralized distribution facilities add many more food miles to a commodity before it finally arrives at a particular retail location. Choice of functional unit is another critical issue. While many authors choose kg of the final food product as a functional unit, some authors (Carlsson-Kanyama et al. 2003) have also found that using a typical serving size for each food can make a big impact in the final analysis, especially for foods that require high energy inputs but are typically eaten in relatively small quantities, such as dried fruit, as opposed to fresh fruit. Finally, many LCA studies, lacking capacity for original field research, have relied on old data, especially Pimentel’s (1980) energy coefficients for farming operations and inputs (for a more detailed analysis of shortcomings identified in the LCA literature, see *Review of Life Cycle Assessment and Other Energy Case Studies of Food Commodities* by Erica Chernoh, ASI).

Finally, Delucchi (2006) maintains that any LCA that involves crop production must ultimately include assessments of the global warming impacts of land use changes induced by changes in consumer product choices. As he points out, it is unrealistic to assume that a choice for product X over product Y happens in a vacuum, with no significant impacts on global production and consumption portfolios. While a single consumer’s food choices are unlikely to alter supply and demand at the macro-level, larger-scale choices made by many consumers and by large food services companies will certainly impact decisions about what is grown where. Different types of crops, grown in different locations, with different production methods, and displacing different land uses, will inevitably lead to different rates of GHG emissions as well as carbon sequestration. Differences in carbon sequestration of different crops and the impacts of different land use choices appear to have been excluded from most food LCA studies to date.

Efforts to address shortcomings in food LCA are already underway, and much progress has been made in Europe to standardize Life Cycle Inventory databases, which list energy use and other environmental impacts of standard, commonly used inputs, materials, and industrial and agricultural processes (for example, see www.ecoinvent.ch, a database spearheaded by the Swiss Centre for Life Cycle Inventories). U.S. efforts have resulted in the U.S. LCI Database Project, begun in 2001 and housed at the National Renewable Energy Laboratory, but this preliminary database still requires extensive expansion in order to make it more useful for detailed food systems studies (http://www.nrel.gov/lci/). We are not aware, to date, of any research programs focusing on LCA of food systems or food commodities specifically in California.

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