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Reducing Energy Inputs in the US Food System

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Abstract Petroleum and natural gas are the primary fuels in the US food system. Both fuels are now in short supply and significant quantities are being imported into the USA from various nations. An investigation documented that fossil energy use in the food system could be reduced by about 50% by appropriate technology changes in food production, processing, packaging, transportation, and consumption. The results suggest that overall, farmers benefit as well as consumers.

Keywords Agriculture · Energy conservation · Food packaging · Food system · Food transport · Land resources · Nutrients · USA

Introduction

Petroleum, natural gas, coal, and other mined fuels currently provide the USA with nearly all of its diverse energy needs at a cost $700 billion/year (USCB 2007). Given that more than 90% of US oil deposits have been depleted, the country now imports over 65% of its oil at an annual cost of $200 billion (USCB 2004–2005; Deffeyes 2001). These figures indicate the magnitude of the economic and energy challenges associated with supplying food for the US population.

Further, the usage of oil and natural gas has peaked at a time when oil and gas reserves are predicted to last only 40 to 50 more years (Duncan and Youngquist 1999; Deffeyes 2001). As oil and natural gas supplies decline, the USA will have to depend on coal and a variety of renewable energy technologies. Best estimates are that coal supplies are only capable of providing the USA with 50 to 100 years of energy (USCB 2007). With the US population continuing to grow close to its current rate, it is projected to increase from 317 million to one billion in about 100 years, further exacerbating strains on coal and oil supplies (Abernethy 2006). However, it is unlikely that such a population could be sustained with the diminishing availability of fossil fuels.

The American food supply is driven almost entirely by non-renewable energy sources. In total, each American requires approximately 2,000 l/year in oil equivalents to supply their food, which accounts for about 19% of the total energy use in the USA. Agricultural production, plus food processing and packaging, consumes 14%, while transportation and preparation use 5% of total energy in the USA (Pimentel *et al.* 2007).

In this analysis, we focus on the many sectors of the food system and examine potential strategies for maintaining an adequate food supply, while reducing the inputs to the food system by 50%.

Food Consumed by Americans

The average American consumes 1,000 kg (2,200 lb) of food per year containing an estimated 3,747 kcal per day (Table 1). A vegetarian diet of an equivalent 3,747 kcal per day requires 33% less fossil energy than the average American diet (Pimentel and Pimentel 1996). The Food and Drug Administration (FDA 2007) recommends an average daily consumption of 2,000 to 2,500 kcal a day, much less than provided by the typical American diet (Vaclavik *et al.* 2006). Reducing the calorie intake to a lower level would significantly reduce the energy used in food production.

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Table 1 Current US food consumption of 3,747 kcal per day and a recommended food consumption of 2,503 kcal per day without junk foods included in either diet (FAOSTAT 2004)

Food	Kilocalories/day	Kilograms/year	% reduction	kcal/day	Kilograms/year
Current diet			Reduced consumption diet		
Grains	1,509	157	15	1283	133
Starchy roots	136	63	15	116	54
Sweeteners	282	140	65	100	49
Nuts	15	2	0	15	2
Fats and oils	581	86	65	203	30
Vegetables	80	131	0	80	131
Fruits	126	124	0	126	124
Meat	526	94	50	263	47
Fish	28	21	50	14	11
Milk	403	241	40	242	145
Eggs	61	17	0	61	17
Total	3,747	1,076		2,503	743
Lacto-ovo diet					
Grains	1579.75	164.36	45	865	89.67
Starchy roots	264.5	122.29	12	230	107.07
Sweeteners	282	140	51	100	49
Nuts	100	13.33	0	100	13.33
Fats and oils	168.3	24.91	39	102	15.07
Vegetables	222	363.53	0	222	363.53
Fruits	234	230.285	0	234	230.29
Meat	0	0	100	0	0
Fish	28	21	100	0	0
Milk	560.2	335	3	543	325.35
Eggs	204	56.85	0	204	56.85
Total	3,614.75	1,565.6		2,500	1,250.16

The fossil energy required to produce the relatively high level of animal products consumed in the average American diet are estimated to be 50% of the total energy inputs, while to produce staple foods such as potatoes, rice, common fruits and vegetables, uses about 20% of the fossil energy inputs (Table 1). These data differ from the thoroughly studied Dutch diet where staple foods account for 12% of the total energy input and animal products account for another 36% (Gerbens-Leenes *et al.* 2002).

Based on preliminary data, Block (2004) estimates the average American consumes 33% of their total calories in junk food. Reducing junk food intake from 33% to 10% would reduce caloric intake to 2,826 kcal, conserve energy, and improve health (Table 2). Consider that a kilogram of potato chips has 5,667 kcal of food energy, whereas a kilogram of potatoes has only 548 kcal of food energy (USDA 1976).

Renewable Energy Supplies

The decline of fossil energy reserves will force the USA to rely on various renewable energy technologies to maintain a viable food supply. These include: hydroelectric, biomass (wood), wind power, solar thermal systems, photovoltaics, passive energy systems, geothermal, biogas, and methanol (Hayden 2001; Pimentel *et al.* 2002a; Pimentel 2008). Ethanol is not included in this study because it fails to provide renewable energy (Pimentel and Patzek 2005). Together, these systems could provide the USA with an estimated 46 of the 103 quads (quad=10^{15} BTU) of energy currently used per year (Pimentel 2008; USCB 2004–2005). The renewable energy systems that are projected to provide the most energy in the future are photovoltaics, biomass (thermal), and hydroelectric power (Pimentel *et al.* 2002a).

Table 2 Junk foods consumed per person and proposed reduction

Item	Quantity	Energy× 1,000 kcal	Reduced	Energy× 1,000 kcal
Soft drinks	600 cans[a]	1,300	100 cans	220
Potato chips	7.2 kg[b]	35	1 kg	4.8
Popcorn	25 kg[c]	113	2 kg	9.2

[a] 12 oz. cans (Valentine 2006)
[b] Kuchler *et al.* 2004
[c] Coelho 2006

Hydroelectric power already supplies the USA with 269 billion kWh or 7% of the nation's electricity at a cost of \$0.02 per kWh (USCB 2007). One drawback to hydroelectric plants is the substantial land requirement for water reservoirs; 75,000 ha of reservoir land and 14 trillion liters of water are needed to produce 1 billion kWh per year (Pimentel *et al.* 2002a; Sims *et al.* 2003).

Another promising renewable energy resource is bioenergy crops using solar thermal energy. Of these, switchgrass, hybrid poplar and willow, which utilize cultivation practices similar to traditional crop agriculture, seem to be the most efficient (De La Torre Ugarte *et al.* 2000). The cost of producing 1 kWh of electricity from woody biomass is ~\$0.058 (Pimentel *et al.* 2002a). Although these bioenergy crops are expected to compete with traditional crops for land 5.2 Mha (3.8% of cropland) of the land needed for bioenergy crops in the USA might come from areas under the Conservation Reserve Program (CRP; McLaughlin *et al.* 2002).

Wind power possesses promise as a renewable energy resource. In an ideal location, a wind turbine might provide an efficiency of 30% (AWEA 2000). Wind power has the capability to produce about 20% of current annual US electrical use (AWEA 2000; Pimentel 2008).

Photovoltaic cells have shown great potential to provide a significant portion of US energy, especially those made from silicon (Pimentel *et al.* 2002a; Sims *et al.* 2003). Although tests cells have reached efficiencies of 20–25% in laboratories, commercially available photovoltaic cells are only 12–17% efficient, depending on whether they are monocrystalline or multicrystalline modules (Pimentel *et al.* 2002a; Sims *et al.* 2003). In order to meet current US demand a photovoltaic array covering 26,000 km^2 would be needed (Sims *et al.* 2003), but less than 1% of this exists today (Hoffert *et al.* 2002).

The production of 46 quads per year from renewable energy technologies would require at least 17% of total land area not counting cropland in the USA (Pimentel *et al.* 2002a). Only some pasture and forestland was used in the renewable energy scheme (Pimentel *et al.* 2002a). The renewable energy systems that are projected to provide the most energy in the future are photovoltaics, biomass (thermal), and hydroelectric power (Pimentel *et al.* 2002a). None of these renewable energy sources produce liquid fuels. Hydrogen could potentially serve as viable liquid fuel in the future, but at present it is very costly. Compressed hydrogen requires about 4.2 kWh of electrical energy to produce the equivalent of 1 kWh in hydrogen (Pimentel *et al.* 2002a). Also, hydrogen is difficult to handle because of its explosive nature and it cannot be used as aircraft fuel. A liter of hydrogen has an energy density of only 2,100 kcal (liquid hydrogen) whereas a liter of gasoline has an energy density of 8,300 kcal. Producing gasoline from coal is a possibility, but the carbon dioxide produced would have to be pumped underground to avoid contributing to global warming.

In addition to the monetary and natural resource requirements necessary for these renewable energy systems, there are various environmental impacts associated with each of them. Nonetheless, impacts from renewable energy systems are less destructive than those currently caused by fossil fuel energy systems (Pimentel *et al.* 2002a). Renewable energy sources such as those described here are capable of producing sufficient energy to replace at least half of US fossil fuel consumption, even though they present challenges, notably significant land requirements. None of this energy would be liquid fuels.

Land Availability

Land is a major concern when attempting to modify fossil energy usage as land provides 99.9% of the human food supply (measured in calories; FAOSTAT 2004). As the population expands, more land is needed to meet nutritional needs, yet the per capita availability of world cropland has declined by 20% in the past decade (Worldwatch Institute 2001). This decrease is due in part to the loss of viable cropland caused by wind and water erosion at a rate of ten million hectares per year (Preiser 2005). In addition, another ten million hectares are abandoned annually worldwide due to severe salinization as a result of irrigation (FAO 2006).

Loss of soil is insidious; one rain or wind storm can remove 1 mm of topsoil and nearly 14 tons of total soil per hectare. This 1 mm of erosion can easily go unnoticed by farmers. Soil erosion occurs at rates ranging from 10 t ha^{-1} year^{-1} in the USA and Europe to 30 t ha^{-1} year^{-1} in Africa, South America and Asia. Approximately 75 billion tons of topsoil is lost each year worldwide (Pimentel 2006a; Wilkinson and McElroy 2007). Additionally, rapid deforestation (at a rate of 11.2 million ha/year) is occurring as more forest is claimed to replace lost and degraded cropland (Pimentel *et al.* 2005).

At present, the global availability of land per capita is 0.23 ha for cropland and 0.5 ha for pastureland (Pimentel and Pimentel 2006). However, the USA and Europe have 0.5 ha of cropland and 0.81 ha of pasture available per capita, which is the minimum amount of land required to support their diverse food systems (Pimentel and Wilson 2004; USDA 2004). Cropland now occupies 17% of the total land area in the USA, but little additional land is available or even suitable for future agricultural expansion (USDA 2004). As the US population increases to a projected 1 billion people (120 years), US fossil energy resources will run out and reduce per capita land area to only 0.17 ha of cropland and 0.3 ha of pasture land, both values below current global land availability. It is notable that currently the Chinese, who live primarily as vegetarians and import large quantities of grain to supplement their diets, have only 0.08 ha of cropland per person, a much lower value than that projected for the USA in 100 years (Pimentel and Wen 2004).

There are several different conservation technologies that help control soil erosion, including: crop rotations, cover crops, contour planting, ridge till, mulch, terraces, grass strips, and no-till. Some investigators claim that no-till saves energy but this is usually only accounted for in tractor fuel reductions. These investigations seldom account for the added nitrogen, added corn seed, plus the added pesticides required in no-till production (Pimentel and Ali 1998; Williams *et al.* 2000; Parsch *et al.* 2001; Epplin *et al.* 2005).

In 100 years time, world population is projected to be more than twice as the number is today (6.5 billion)—about 13 billion. A World Health Organization report states that worldwide there are currently more than 3.7 billion malnourished humans, the largest number of malnourished people ever in the history of the Earth (WHO 2005). In light of this report, we should expect food shortage problems to continually worsen.

While the number of malnourished people increased worldwide over the past two decades, per capita grain production simultaneously declined (FAOSTAT 1961–2005). There are many factors that contributed to this decline, including: a rapidly growing world population (PRB 2006), a 20% decline in cropland per capita in the last decade (Pimentel and Wilson 2004), a 10% decline in irrigated land per capita (Postel 1997) and a 17% decrease in per capita fertilizer use (Pimentel and Wilson 2004). It should be noted that cereal grains make up 80% of the world's food supply.

Irrigation and Energy

Provided there is ample of irrigation water, crop production can be increased significantly in arid regions. Approximately 80% of water used in the USA is solely for irrigation to increase crop production, particularly in arid regions (Pimentel *et al.* 2004). Plants consume about two-thirds of this water while one-third is non-recoverable (Postel 1997). Irrigated corn requires about 14 million liters of water per hectare (500,000 gallons per acre) and uses about three times more energy than rain-fed corn to produce the same yield (Pimentel *et al.* 2004). Irrigation tends to be expensive both energetically and economically, costing more than $1,200 per hectare when pumping from a depth of only 100 m (Pimentel *et al.* 2004).

Reducing irrigation dependence in the USA would save significant amounts of energy, but probably require that crop production shift from the dry and arid western and southern regions to the more agriculturally suitable Midwest and Northeast. Also, as noted above, soil salinization due to irrigation causes the abandonment of ten million hectares each year worldwide (FAO 2006). The leaching of salts from the soil into rivers poses another major problem. For example, where the Colorado River flows through the Grand River Valley in Colorado, water returned to the river from irrigated cropland contains an estimated 18 t/ha of salts leached from the soil (EPA 1976), resulting in high salt concentrations in the river.

Conserving Essential Nutrients

As fossil fuels become scarce, costs for the production of synthetic fertilizers will rise. This economic pressure will force farmers to seek alternative sources to meet their nitrogen, phosphorus, and potassium demands. Nitrogen is the most vital nutrient in agricultural production and is applied at a rate of 12 million tons of commercial or synthetic nitrogen per year in the USA (GAO 2003; USDA 2004). Although 18 million tons of nitrogen were applied in 1995 in the USA, a 300% increase in the price of nitrogen fertilizer over the past decade has resulted in fewer N applications, highlighting the need to explore alternative nutrient sources. It is of equal commercial importance to provide adequate amounts of phosphorus and potassium, the other essential macro-elements needed by plants to grow well and produce high yields. As will be shown below, leguminous cover crops, manure, and other organic inputs can meet the N, P, and K demands of food production in the USA (Funderberg 2001; Schmalshof 2005).

Cover Crops Conserving soil nutrients is a priority in agricultural production because it reduces the demand for fertilizers and produces high crop yields. A crucial aspect of soil nutrient conservation is the prevention of soil erosion. Cultivation practices that build soil organic matter (SOM) and prevent the exposure of bare soil are a key part of preventing soil erosion. Cover crops help protect the exposed soil from erosion after the main crop is harvested (Troeh *et al.* 2004). Compared with conventional farming systems, which traditionally leave the soil bare, the use of cover crops significantly reduces soil erosion.

Leguminous cover crops also add nutrients to the soil (Drinkwater *et al.* 1998; Weinert *et al.* 2002). For example, vetch, a legume cover crop grown during the fall and spring months (non-growing season), can add about 70 kg/ha of nitrogen (Pimentel *et al.* 2005; Henao and Baanante 2006).

Other studies in both the USA and Ghana have shown that nitrogen yields from legumes planted the season before were between 100–200 kg/ha (Griffin *et al.* 2000). In the organic systems at Rodale Farms in Pennsylvania, soil nitrogen levels were 43% compared to only 17% in conventional systems (Pimentel *et al.* 2005). Legumes can thus provide a significant portion of the nitrogen required by most crops.

Cover crops further aid in agriculture by collecting about 1.8 times more solar energy than conventional farming systems (Pimentel 2006b). Growing cover crops on land before and after a primary crop nearly doubles the amount of solar energy that is harvested per hectare per year. This increased solar energy capture provides extra organic matter which improves soil quality.

Soil Organic Matter Maintaining high levels of soil organic matter (SOM) is beneficial for all agriculture and crucial to improving soil quality. Carter (2002) has shown aggregated SOM to have "major implications for the functioning of soil in regulating air and water infiltration, conserving nutrients, and influencing soil permeability and erodibility" by improving the soil's water infiltration, structure, and reducing erosion.

Maintaining high levels of SOM is a primary focus of organic farming. On average, the amount of SOM is significantly higher in organic production systems than in conventional systems. Typical conventional farming systems with satisfactory soil generally have 3% to 4% SOM, whereas organic systems soil average from 5% to 5.5% SOM (Troeh *et al.* 2004). Soil carbon increased about 28% in organic animal systems and 15% in organic legume systems, but only 9% in conventional farming systems (Pimentel *et al.* 2005). This high level of SOM provides many advantages.

Increased SOM also provides soil with an increased capacity to retain water. Sullivan (2002) reported that approximately 41% of the volume of organic matter in the organic systems consisted of water, compared with only 35% in conventional systems. The large amount of soil organic matter and water present in organic systems is the major factor in making these systems more drought resistant.

Furthermore, 110,000 kg/ha of soil organic matter in an organic corn system could sequester 190,000 kg/ha of carbon dioxide. This is 67,000 kg/ha more carbon dioxide sequestered than in conventional corn systems, and equals the amount of carbon dioxide emitted by ten cars that averaged 20 miles per gallon and traveled 12,000 miles per year (USCB 2004–2005). The added carbon sequestration benefits of organic systems clearly have beneficial implications for reducing global warming.

Manure In 2005, the 100 million cattle, 60 million hogs, and nine billion chickens maintained in the USA (Table 3) produced an estimated 20.5 million metric tons of nitrogen. This nitrogen, most of which is produced by cattle, could potentially be used in crop production (Table 3). The collection and management of this nitrogen requires special attention. Approximately 50% of the nitrogen is lost as ammonia within 24 to 48 h after defecation, if the animal waste is not immediately buried in the soil or placed in a lagoon under anaerobic conditions (Troeh *et al.* 2004). The liquid nutrient material in the lagoon must be buried in the soil immediately after it is applied to the land, or again the nitrogen will be lost to the atmosphere.

We estimate 70% of cattle manure is dropped in pasture or rangeland and is not included in the total nitrogen estimate, reducing the amount of nitrogen theoretically collected for use per year to 18 million metric tons (Pimentel *et al.*, unpublished data; Table 3). Because cow manure is 80% water, this manure can only be transported a distance of about eight miles before the energy return is negative.

Conserving nutrients will be crucial to farmers in a world of high fertilizer costs. In addition, practices that center on building and conserving soil integrity can greatly improve energy efficiency in food production systems. The use of manure, cover crops, composting, and conservation tillage can contribute to such energy reductions and allow farmers to produce food sustainably.

Improving Energy Efficiency in Farming Systems

In this section we illustrate how the reduction of pesticide use, increased use of manure, cover crops, and crop rotations can improve energy efficiency in farming systems and enhance human health.

Table 3 Livestock numbers and manure and nitrogen produced per year in the USA (USDA 2004; NRAES 2004)

Livestock	Number ($\times 10^6$)	Manure produced per head kg/year	Manure tons ($\times 10^6$)	N produced per head (kg)	Total N kg ($\times 10^9$)
Cattle	100	10,000	1,000	25.00	0.75
Hogs	60	1,230	74	3.08	0.18
Chickens	9,000	31	279	0.08	0.70
Total					1.63

Reduced Pesticide Use Currently, more than one billion pounds of pesticides are applied annually to US agriculture (USDA 2004). Certified organic farming systems do not apply synthetic pesticides. Weed control is, instead, achieved through crop rotations, cover crops, and mechanical cultivation (Pimentel *et al.* 2005). Avoiding the use of herbicides and insecticides improves energy efficiency in corn/soybean production systems. For example, in organic farming, one pass of a cultivator and one pass of a rotary hoe use approximately 300,000 kcal/ha of fossil energy. Herbicide weed control (including 6.2 kg of herbicide per hectare plus sprayer application) requires about 720,000 kcal/ha or about twice the amount of energy used for mechanical weed control in organic farming (Pimentel *et al.* 2005). In addition, there are a reported 300,000 non-fatal pesticide poisonings (EPA 1992) per year in the USA, and pesticides in the diet have been shown to increase the odds of developing cancer (Horrigan *et al.* 2002).

Moving Livestock Back to the Grain Farms Another factor in energy usage in farming is the recent proliferation of monocultures, or farms devoting large tracts of land to one crop. The movement of livestock from mixed farming systems was encouraged by the US Government as it began to provide price supports for farmers (NAS 1989). As a result, livestock were moved to concentrated animal feeding operations (CAFOs) where they could be raised in large numbers. This shift resulted in an increase in commercial fertilizer and pesticide use in crop production, plus a significant increase in soil erosion (NAS 1989). It has also raised concern that 76 million hospital cases and 5,000 human deaths may be attributable to pollution associated with CAFOs and poor waste management (CDC 2002).

Crop Rotations Crop rotations are beneficial to all agricultural production systems because they help control soil erosion (Troeh *et al.* 2004; Delgado *et al.* 2005). They also help control pests such as insects, plant pathogens and weeds (Pimentel *et al.* 1993; Troeh *et al.* 2004). In addition, when legume cover crops are used, essential nitrogen is added to the soil when they are plowed under. As mentioned above, in the Rodale study soil nitrogen levels in organic farming systems were 43% compared with only 17% in conventional systems (Pimentel *et al.* 2005).

Regulatory actions and market-based incentives could encourage the movement of livestock manure away from pollution causing CAFOs and back to the mixed farms where it can be incorporated into the soil. They could also encourage the agricultural practice of crop rotation, the use of cover crops, and reduced pesticide applications, all of which would result in increased energy savings and reduced hazards to human health.

Labor and Mechanization

Raising corn and most other crops by hand requires about 1,200 h of labor per hectare (nearly 500 h per acre; Feeding the World 2002). Modern mechanization allows farmers to raise a hectare of corn with a time input of only 11 h, or 110 times less than required for hand-produced crops (Pimentel *et al.* 2007). Mechanization requires significant energy for both the production and repair of machinery (about 333,000 kcal/ha) and diesel and gasoline fuel (1.4 million kcal/ha; Table 4). About one-third of the energy required to produce a hectare of crops is invested in machine operation (Pimentel and Patzek 2005). Mechanization decreases labor significantly, but does not contribute to increased crop yields.

Organic corn production requires mechanization. Economies of scale are still possible with more labor and the use of smaller tractors and other implements. Reports suggest that equipment quantity and size is often in excess of requirements for the tasks. Reducing the number and size of tractors will help increase efficiency and conserve energy (Grisso and Pitman 2001).

Hydrogen is the fuel most looked to as a substitute for diesel and gasoline. As discussed previously, however, this fuel is expensive in terms of the energy needed to produce, store and transport it. About 4.2 kcal of energy is required to produce 1 kcal of hydrogen by electrolysis (Pimentel 2008). Diesel and gasoline, on the other hand, require 1.12 kcal of oil to produce 1 kcal worth of fuel.

Another proposal has been a return to horses and mules. One horse can contribute to the management of 10 ha (25 acres) per year (Morrison 1946). Each horse requires one acre of pasture and about 225 kg of corn grain. Another 1.5 acres of hayland is necessary to produce the roughly 800 lbs of hay needed to sustain each animal. In addition to the manpower required to care for the horses, labor is required to drive the horses during tilling and other farm operations. The farm labor required per hectare would probably increase from 11 hours to between 30 and 40 h per hectare using draft animal power. Nevertheless, an increase in human and animal labor as well as a decrease in fuel-powered machinery is necessary to decrease fossil fuel use in the US food system.

Energy Inputs in Meat, Poultry and Dairy Production

Each year an estimated 45 million tons of plant protein are fed to US livestock producing approximately 7.5 million tons of animal protein (meat, milk, and eggs) for human consumption (Pimentel 2004). The livestock feed is comprised of about 28 million tons of plant protein from grains and 17 million tons from forage. In the USA, the

Table 4 Energy inputs and costs of corn production per hectare in the USA and potential for reduced energy inputs (Pimentel and Patzek 2007)

Inputs	Average corn production		Reduced energy inputs	
	Quantity	kcal × 1000	Quantity	kcal × 1000
Labor	11.4 h[a]	462[b]	15 h[jj]	608
Machinery	18 kg[d]	333[e]	10 kg[kk]	185
Diesel	88 l[g]	1,003[h]	60 L[ll]	684
Gasoline	40 l[i]	405[j]	0	
Nitrogen	155 kg[k]	2,480[l]	Legumes[mm]	1,000
Phosphorus	79 kg[n]	328[o]	45 kg[nn]	187
Potassium	84 kg[q]	274[r]	40 kg[nn]	130
Lime	1,120 kg[t]	315[u]	600 kg[nn]	169
Seeds	21 kg[v]	520[w]	21 kg	520
Irrigation	8.1 cm[y]	320[z]	0[oo]	0
Herbicides	6.2 kg[bb]	620[ee]	0[oo]	0
Insecticides	2.8 kg[cc]	280[ee]	0[oo]	0
Electricity	13.2 kWh[dd]	34[ff]	13.2 kWh	34
Transport	146 kg[gg]	48[hh]	75 kg	25
Total		7,470		3,542
Corn yield 9,000 kg/ha[ii]		31,612		

[a] NASS 2003
[b] It is assumed that a person works 2,000 hrs per year and utilizes an average of 8,000 liters of oil equivalents per year.
[c] It is assumed that labor is paid $13 an hour.
[d] Energy costs for farm machinery that was obtained from agricultural engineers—tractors, harvesters, plows and other equipment that last about 10 years and are used on 160 ha per year. These data were prorated per year per hectare (Pimentel and Patzek 2005).
[e] Prorated per hectare and 10-year life of the machinery (Lazarus and Selley 2005). Tractors weigh from about 10 tons (Minnesota 2007) and harvesters about 10 tons (Amity Technology 2007), plus plows, sprayers, and other equipment.
[f] Hoffman *et al.* 1994
[g] Wilcke and Chaplin 2000
[h] Input 11, 400 kcal per liter
[i] Estimated
[j] Input 10,125 kcal per liter
[k] NASS 2003
[l] Patzek 2004
[m] Cost $.55 per kg
[n] NASS 2003
[o] Input 4,154 kcal per kg
[p] Cost $.62 per kg
[q] NASS 2003
[r] Input 3,260 kcal per kg
[s] Cost $.31 per kg
[t] Brees 2004
[u] Input 281 kcal per kg
[v] Pimentel and Pimentel 1996
[w] Pimentel and Pimentel 1996
[x] USDA 1997b
[y] USDA 1997a
[z] Batty and Keller 1980
[aa] Irrigation for 100 cm of water per hectare costs $1,000 (Larsen *et al.* 2002).
[bb] Larson and Cardwell 1999
[cc] USDA 2002
[dd] USDA 1991
[ee] Input 100,000 kcal per kg of herbicide and insecticide
[ff] Input 860 kcal per kWh and requires 3 kWh thermal energy to produce 1 kWh electricity
[gg] Goods transported include machinery, fuels, and seeds that were shipped an estimated 1,000 km.
[hh] Input 0.34 kcal per kg per km transported
[ii] USCB 2004-2005
[jj] Labor input was increased by 32% for the extra work needed (Pimentel *et al.* 2005).
[kk] Smaller tractors were used in the farm operations.
[ll] Total fuel use was reduced by about half.
[mm] Legume cover crops were used to provide the needed nitrogen as well as conserve soil and water resources (Pimentel *et al.* 2005).
[nn] Reducing soil erosion from the average of conventional corn production of about 15 t/ha/year to about 1 t ha^{-1} $year^{-1}$ helped conserved P, K, and lime.
[oo] Total inputs were reduced and thus less transport energy was required.

average protein yield of the five major grains (corn, rice, wheat, sorghum, and barley, plus soybeans) fed to livestock is about 700 kg/ha. For every kilogram of high quality animal protein produced, livestock are fed nearly 6 kg of plant protein (Pimentel 2004). Major differences exist in the inputs of feed and forage between animal products. For example, production of 1 kg of beef requires 13 kg of grain and 30 kg of forage (fossil energy input 40 kcal per 1 kcal beef protein), 1 kg of pork requires 5.9 kg of grain (14:1 kcal), and 1 kg of broiler chicken requires only 2.3 kg of grain (4:1 kcal). A kilogram of conventional milk produced in the USA requires 0.7 kg of grain and 1 kg of hay (14:1 kcal; Pimentel 2006b). In Norway, organic milk production was reported to be 43% more energy efficient (Refsgaar *et al.* 1998), since the cattle were grazed on pasture land.

When converting plant protein into animal protein, there are two principal categories of energy and economic costs: (1) the direct production costs of the harvested animal including the grain and forage fed; and (2) the indirect costs of maintaining the breeding herd. Diverse combinations of grains, forages, and legumes (including soybeans) are fed to livestock to produce meat, milk, and eggs. The major fossil energy inputs required to produce grain and forage for animals includes fertilizers, farm machinery, fuel, irrigation, and pesticides. The energy inputs vary according to the particular grain or forage being grown and fed to livestock. On average producing one kcal of plant protein for livestock feed requires about 10 kcal of fossil energy (Pimentel 2004).

Organic and conventional forage are fed to ruminant animals, like cattle and lamb, because they can convert the forage cellulose into digestible nutrients through microbial fermentation. The total plant protein produced as forage on good US pasture and fed to ruminants is about 60% of the amount of protein produced by grain-fed animals (Pimentel 2004).

There are many types of hay (dried forage); yields are about 10 t/ha with fertile soil and application of fertilizers (Pimentel and Patzek 2005). Switchgrass is a native grass used as livestock forage that yields about 10 t/ha with fertile soil and application of fertilizers (Pimentel and Patzek 2005), and provides about 14 kcal in hay feed per 1 kcal invested in fossil energy.

As mentioned previously, feeding cattle a combination of grain and forage requires 40 kcal to produce 1 kcal of beef protein. However, the production of beef protein on good organic pasture requires one-half as much energy—only 20 kcal (Pimentel 2006b). Because forage production requires significantly less energy than grain production, clearly, beef protein production on good pasture is significantly less energy intensive than producing grain-fed animal protein (Pimentel 2004).

Of the livestock systems evaluated, broiler-chicken production is the most energy efficient, with 1 kcal of broiler protein produced with an input of 4 kcal of fossil energy (Pimentel 2006b). Broilers are a grain-only livestock system. Turkey production is also a grain-only system and is next in efficiency with a 1:10 ratio. In addition, conventional milk production, based on a mixture of grain and forage feed, is also relatively efficient, with 1 kcal of milk protein requiring 14 kcal of fossil energy (Pimentel 2006b). Nearly all the feed protein consumed by broilers is from grain, while milk production uses about two-thirds grain and one-third forage. Of course, 100% of milk production could be achieved using hay and/or pasture as feed.

Conventional meat and dairy production is incredibly energy intensive. Transitions to diets lower in meat such as the Lacto-Ovo and Mediterranean diets will greatly help reduce fossil fuel energy consumption (Table 1).

Food Processing and Packaging

In the USA, processed foods account for 82% to 92% of food sales (Murray 2005; Putman *et al.* 2002; SixWise 2006). Of the energy used for the total food system, 16% is used in processing and 7% is used in packaging. In order to reduce energy inputs in processing and packaging by approximately 50%, food processors, packagers and consumers must work together to find safe and energy efficient technologies.

Energy can be saved at the processing plant level by optimizing and combining processes and systems to result in a reduced use of energy. Creating an industry energy policy and working toward established goals (an energy management program) could save 5% of current processing energy (Galitsky *et al.* 2003). This could include replacing outdated equipment with more efficient newer equipment. For example, in a processing plant, replacing a traditional boiler system with a standard gas turbine combined heat and power unit, could achieve an energy savings of 20% to 30% (Galitsky *et al.* 2003; Queensland Government 2007). According to Xenergy (1998), reducing the size of an unnecessarily large motor can save an average of 1.2% energy usage. Also, high efficiency motors help to decrease energy consumption (Galitsky *et al.* 2003). According to Easton Consultants (1995), replacing oversized pumps with appropriately sized ones can save 15% to 25% of the total energy used in a pumping system. This translates to an overall plant savings of between 2.5% to 4.1%. Furthermore, replacing incandescent lights with fluorescent lamps and similar energy saving lights can save energy at the manufacturing level. At the Westin Hotels and Resorts' St. Francis Hotel located in San Francisco, CA, 1,600 incandescent lights were replaced with compact fluorescent bulbs, which decreased lighting energy needs by 82.3%.

Table 5 Annual energy inputs for the transportation of food within the USA and transported to the USA

Transport per year	Energy Input in kcal	Kcal input/kcal food
Per person within the USA	2×10^{6}	1.4
Total USA	6×10^{14}	–
Per person imported food	6,000	4
Total USA	1.8×10^{12}	–

Foods transported within the US averages 2,400 km and to the USA from foreign countries is estimated to be 4,200 km (truck transport= 0.34 kcal/kg/km and air transport=6.61 kcal/kg/km).

The payback period for making this change was 5 months (EPA 2001).

Further options for process integration and energy savings exist at the plant level. One example of this is "heat-pinch" analysis. This finds the temperature requiring the smallest amount of external heating and cooling demands, which is designated the "pinch temperature." In order for heat-pinch analysis to effectively save energy, no external heating should occur below the heat pinch temperature, no external cooling should occur above the heat-pinch temperature, and no heating should occur at the pinch temperature (Fritzson 2005). The use of heat-pinch analysis in 20 US corn wet milling-plants showed potential cost savings from 8% to 40% (Galitsky *et al.* 2003). The time it would take for this process to pay for itself ranges from 1.5 to 3 years. Combining a new heat pump with heat-pinch analysis, which elevates the heat of objects, was able to save American Fructose, Inc. (a corn wet milling plant) in Decatur, Alabama, $300,000 annually in coal and natural gas costs (DOE 2007).

Packaging of food products insures their safe transport and storage, but it is energy intensive. In order to save energy and lower packaging costs, the packaging industry should eliminate unnecessary layers of packaging. For example, cereals and other items that are placed in multiple layers of packaging could be placed in a single, more durable package. Light-weight or thinner packaging materials also save energy. For example, County Harvest Natural Foods reduced the thickness of the plastic on their 1 kg plastic packages from 75 to 60 µm. Though a higher-grade cardboard box was then used to improve safety during transit, they achieved an overall savings of 7,000 British pounds sterling/year (Mattsson and Sonesson 2003). Increasing and improving the recycling process of certain types of packaging could also be implemented (Pagan and Lake 2000; Queensland Government 2007). Another strategy for reducing energy in the packaging process would be to establish taxes or create economic incentives to encourage reductions in waste, less energy intensive packaging, and recycling. Europe has begun to adopt waste reduction strategies such as these (Pagan and Lake 2000).

The most effective method for decreasing energy inputs in processing and packaging is to dramatically reduce consumer demand for products that require large energy inputs in their production. For example, a can of diet soda has only 1 kcal of food energy, yet it requires about 500 kcal to produce the soda and 1,600 kcal to produce the 12 oz. aluminum can. Thus 2,100 kcal are invested to provide zero to 1 kcal of consumable energy (Pimentel and Pimentel 2008). In addition, to the above the large energy input for transportation must be taken into account (see below).

The future of conscientious consumer purchasing is promising. Increased popularity in natural foods supermarkets and farmers markets is evidence that many consumers desire food produced in a socially and environmentally responsible manner. Among the reasons cited for purchasing these foods is decreased packaging (Bowers 2000). A study of the parents of kindergarteners in Denmark by Holm and Kildevang (1996) sheds light on some of the views consumers have with regards to food quality. A larger number of negative comments were directed at processed foods. Some of these comments included, but were not limited to: too long shelf life, unknown additives, too sterile food, lost nutrient value. Whether or not these consumers had a wide or limited knowledge of the food industry and its infrastructure, they clearly expressed an interest in moving away from processed foods and returning to fresher, less processed alternatives.

Transport of Food

In the US food travels an average of 2,400 km (1,500 miles) before it is consumed (Table 5), a practice which is obviously energy intensive. We use a head of lettuce produced in California and shipped to New York to demonstrate the energy demand of transportation, a head of lettuce weighing 1 kg has 110 kcal of food energy and is 95% water (USDA 1976). To produce this head of lettuce in California using irrigation requires about 750 kcal of fossil energy (Ryder 1980). To transport the 1 kg head of lettuce from California to New York City using a refrigerated truck (transport costs plus refrigeration costs) requires 4,140 kcal of fuel per head

Table 6 Total 50% reduced energy inputs in the US food system—summary

Item	Percentage Reduction
Reduced food consumption	30%
Junk food reduction	80%
Production technology improvements	50%
Food processing and packaging improvements	50%
Food transport reduction	50%

of lettuce (Shottenkirk 2005). It is because of this enormous fuel cost that we expect the export of vegetables and fruits from the Western and Southern USA to the East and Northeast to decline. Fruit and vegetable production will likely shift to the Midwestern and Eastern US regions.

In comparison, 1 kg head of cabbage for growing, produced in New York State requires only 400 kcal (Pimentel *et al.* 2002b). Cabbage has far more nutrients than lettuce, including vitamins C and A, and protein (USDA 1976). In addition to reducing transportation costs, cabbage (unlike lettuce) can be stored all winter long.

A very energy intensive part of the American diet is the large quantity of fruits and vegetables that are transported by aircraft. The amount of energy required to ship 1 kg of food by aircraft is 6.63 kcal/km. On the other hand, shipping by rail is only 0.12 kcal/kg/km (Pimentel 1980).

Conclusion: Prospects for Reducing Energy Inputs in the US Food System

We estimate the amount of fossil energy used in the food system could be reduced by about 50% with changes in production, processing, packaging, transport, and consumption (Table 6). Using corn production as a model crop, we estimated that total energy in corn production could be reduced by more than 50% with the following changes: (1) using smaller machinery and less fuel; (2) replacing commercial nitrogen applications with legume cover crops and livestock manure; and (3) reducing soil erosion in corn production through alternative tillage and conservation techniques. These practices would reduce phosphorus, potassium and lime applications to 33% of current levels (Table 4).

Reducing food consumption and following healthier diets would facilitate even greater energy savings, while improving the well-being of the American population. The average American consumes 3,747 kcal of food per day (Table 1), more than 1,000 cal over the recommended daily intake for a relatively active male. We suggest that the amount of meat and dairy products could be reduced by 50%, while still maintaining the necessary quality and quantity of nutrients (Table 1). This would be especially true if amounts of cereal grains, fruits, and vegetables were increased, as outlined in Table 1. Relying to a greater degree on less processed foods reduces the amount of fossil energy required in the food system.

The average distance that food is transported before being consumed by an American is 2,400 km, which requires about two million kcal per year per person (Table 5). On average this is 1.4 times the energy in the food that is consumed per person. Although a relatively small percentage of fruits and vegetables are transported by air cargo into the USA, large quantities of fossil energy are required for this category of transport (Table 5). The energy input per 1 kcal of fruits and vegetables for transport are 4 kcal. A simple but radical reduction in transport distance would lead to great savings in energy. For example, transporting strawberries from California to New York by air requires 100 kcal of oil per kcal of strawberry imported. Whenever possible, taking advantage of locally grown foods and Community Supported Agriculture (CSA) programs will conserve energy (Colenso 2008).

Finally, we illustrated how renewable energy systems, such as biomass and photovoltaic cells coupled with efficient farming practices could result in the reduction of fossil fuel use in the US food system. We have shown that the USA could potentially have a more sustainable and efficient food system with significantly less reliance on fossil fuels.

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