POTENTIAL PRODUCTION OF AGRICULTURALLY PRODUCED FUELS

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ABSTRACT. *Developing fuel sources from agriculture that can make a significant impact on the large petroleum consumption of the United States will require utilization of every available biomass resource and will require a large capital investment. Vegetable oil, ethanol, and methane have a significant potential for reducing this petroleum consumption. Vegetable oil could be used to replace an equivalent of the 10.6 GL [2.8 billion (10^9) gal] of diesel fuel used per year in production agriculture, requiring 7 to 8% of the agricultural land, with the additional potential for doubling this production. The current U.S. ethanol production of 3.8 GL (1 billion gal) per year could be increased to blend with all of the gasoline used in the United States at the 10% rate yielding 37.9 GL (10 billion gal), requiring 16.2 Mha (40 million acre) of crop land for the feedstock. There is also the potential for doubling this ethanol production. Methane equivalent to 17 GL (4.4 billion gal) of gasoline per year could be produced if all animal waste currently collected was digested. Each of these agriculturally produced fuels have one or more of the following advantages: renewable, biodegradable and/or cleaner burning than their petroleum counterparts. Disadvantages are cost of production, lack of production facilities, and use of agricultural land currently used for food. Development of reasonable amounts of each of these fuel sources could allow agriculture to achieve full production. Energy is a crop that could never be produced in surplus.*

Keywords. *Fuels, Vegetable oil, Biodiesel, Ethanol, Methane, Energy.*

The United States is almost totally dependent upon petroleum for gas and liquid energy sources. Stout (1984) reported that 71.5% of U.S. energy is from oil and natural gas while only 2% comes from biomass. In 1989, the U.S. used about 509,000 m^3 (3.2 million bbl/d) of distillate fuel and 1.2 Mm^3 (7.4 million bbl/d) of gasoline (U.S. DOE, 1989). For agriculturally produced renewable fuels to make a significant contribution to this mammoth energy use will require the use of every foreseeable agriculturally produced alternative energy source which can be developed. This article reviews the status and contribution of three widely discussed alternative fuels from agriculture: vegetable oil, ethanol, and methane. In addition to their energy contribution, each of these fuels have one or more other environmental benefits such as being biodegradable, reduced toxicity, cleaner burning (reduced smoke and gaseous emissions), renewable and/or safer to handle (Peterson and Reece, 1994; Peterson et al., 1994; Obert, 1973).

VEGETABLE OIL FUELS

Vegetable oils have potential as a substitute for diesel fuel. Of the more than 350 oil bearing crops, those with the greatest production potential are sunflower, safflower, soybean, cottonseed, rapeseed, canola, corn, and peanut oil (Goering and Daugherty, 1982; Peterson, 1986). Modifying these oils to produce the methyl or ethyl ester has been shown to be essential for successful engine operation over a long term (Zhang et al., 1988). Development of vegetable oil as an alternative fuel would make it possible to provide energy for agriculture from renewable sources located close to the area where it could be used.

PRODUCTION

As of 1987, the active cropland in the United States consisted of 160.2 million ha (395.9 million acre); an additional 27.6 million ha (68.1 million acres) of cropland was idle (USDA, 1993). Rapeseed at 2.24 t/ha (1 ton/acre) is equivalent to 935 L/ha (100 gal/acre) of oil and approximately 1345 kg/ha (1200 lb/acre) of meal (Peterson et al., 1980; Peterson et al., 1983). On this basis, if every hectare (acre) of available cropland were to be put into rape production approximately 175 GL (46.4 billion gal) of fuel per year could be produced. These calculations do not take into account the methyl or ethyl alcohol required in the transesterification process (approximately 10% on a volume basis of the vegetable oil produced.) The maximum vegetable oil production is equivalent to 1.8 times the current annual consumption of diesel in transportation.

Computations of the land that could be used for vegetable oil production are complicated. Certainly land must be available for domestic food production. It is also logical to assume that some production of food for export will continue to be needed. In 1987, 27.6 Mha (68 million

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Table 1. Production, domestic use, and excess production of selected crops in the United States (1991) (USDA, 1993)

	Production		Domestic Use		Excess Production		Excess Land Area	
Crop	$10^6 m^3$	(10^6 bu)	$10^6 m^3$	(10^6 bu)	$10^6 m^3$	(10^6 bu)	Mha	(10^6 acre)
Wheat	69.8	(1981)	40.1	(1137)	29.7	(844)	10.0	(24.6)
Corn	263.0	(7475)	223.0	(6332)	40.3	(1143)	4.3	(10.5)
Sorghum	25.7	(728)	13.5	(383)	12.2	(345)	2.4	(5.82)
Barley	16.4	(464)	14.1	(401)	2.2	(63)	0.5	(1.14)
Soybeans	70.0	(1987)	47.8	(1357)	22.2	(630)	7.5	(18.4)
Rice	12.6	(358)	6.8	(192)	5.8	(166)	0.5	(1.29)
Total area used to produce excess crops							25.0	(61.8)

Table 2. Oil imports and acres of vegetable oil land equivalent [based on 935 L/ha (100 gal/acre)] (U.S. DOE, 1989)

	Barrels/D	Veg. Oil Land Hectares (Acres) Equivalent	
1989 U.S. petroleum imports			
Crude oil	5,808,000	987,178	(2,439,360)
Distillate	302,000	51,330	(126,840)
1989 OPEC petroleum imports			
Total OPEC	4,116,000	699,591	(1,728,720)
Arab OPEC	2,122,000	360,674	(891,240)
Iraq and Kuwait	608,000	103,200	(255,000)

Arab OPEC: Algeria, Iraq, Kuwait, Libya, Quatar, Saudi Arabia, United Arab Emirates.

OPEC: Ecuador, Gabon, Indonesia, Iran, Nigeria, Venezuela, and Arab members.

Table 3. U.S. gasoline and distillate fuel use and acres of vegetable oil equivalent [based on 935 L/ha; (100 gal/acre)] (U.S. DOE, 1989)

	Barrels/d	Veg. Oil Land Equivalent ha/d (acres/d)		% of Total U.S. Crop Land per Year
Gasoline	7,436,000	N.A.		
Distillate				
Residential and commercial	770,000	130,876	(323,400)	25.4%
Industrial	570,000	96,882	(239,400)	18.8%
Transportation	1,750,000	297,445	(735,000)	57.8%
Electric utilities	70,000	11,898	(29,400)	2.3%
Total distillate	3,160,000	535,400	(1,323,000)	104.4%

acre) of cropland were reported as idle (USDA, 1993). This idle cropland could produce 25.8 GL (6.8 billion gal) of vegetable oil per year or 27% of the diesel used in transportation. An estimate of additional crop land potentially available for vegetable oil production was made by comparing crop production for several of the major crops with domestic use. Any production over domestic use was termed excess and, using the national average production for that crop, an estimate of excess crop production land of 25 Mha (62 million acre) was calculated as shown in table 1.

Providing sufficient liquid fuel to replace U.S. petroleum imports is a priority; and, because of potential world unrest, replacing that from the Arab OPEC countries such as Kuwait and Iraq is of especially high priority. Petroleum imports are shown in table 2. The U.S. distillate fuel and gasoline fuel use is shown in table 3.

In 1991, 10% of the U.S. cropland was planted to vegetable oil crops (table 4). Currently the U.S. is the largest vegetable oil producing nation, with 13% of the world production from 1988 to 1992. Of this, 77% of the U.S. vegetable oil is from soybeans, 9% from corn, and 7% from cotton (Mielke, 1994; USDA, 1993.) Approximate U.S. vegetable oil production is shown in table 4. From 1988 to 1992, the United States exported an average of 1.67 GL (440 million gal) of vegetable oil (Mielke, 1994), equivalent to 13% of the diesel fuel used in agriculture. Another 3.78 GL (1.25 billion gal) of oil is produced in the United States from tallow, grease, butter as fat, lard, and fish oil, and 34% of this is exported (Mielke, 1994).

USE

Vegetable oil has potential as one segment of the alternative energy picture. Realistically, vegetable oil could be used to replace the 10.6 GL (2.8 billion gal) of diesel used per year in production agriculture (Stout, 1984) requiring 7 to 8% of U.S. agricultural land. Approximately 1 of 4 ha of U.S. cropland would be required to replace the oil imported from Iraq and Kuwait in 1989 (fig. 1). Table 5

Table 4. 1991 U.S. production of vegetable oil from the five important oil seed crops – potential* and actual† (calculated from USDA, 1993)

	Harvested Area Mha (million acres)	Average Yield t/ha (tons/acre)	Average Oil Content % Oil	Average Oil L/ha (gal/acre)	Potential Oil Production* ML (million gal)	Actual Oil Production† ML (million gal)	% of Total Crop Land
Soybean	23.5 (58.0)	2.30 (1.03)	19	476 (126)	11,200 (2,950)	6,490 (1714)	12.5
Sunflower	1.2 (2.9)	1.51 (0.67)	40	659 (174)	775 (205)	322 (85)	0.6
Cottonseed	5.2 (13.0)	1.20 (0.54)	18	236 (62)	1,236 (326)	579 (153)	2.8
Peanuts	0.8 (2.0)	2.74 (1.22)	43	1,292 (341)	1.054 (278)	120 (32)	0.4
Rapeseed‡	NA	2.13 (0.95)	42	935 (100)	NA	29 (7.6)	NA
Total	30.7 (75.9)	–	–	–	14,232 (3,760)	7,538 (1991)	16.4

* Potential production calculated assuming the total existing crop area is grown for oil.

† 1991 actual oil production from Mielke, 1994.

‡ Rapeseed production data from Peterson et al. (1980) in Pacific Northwest research plots.

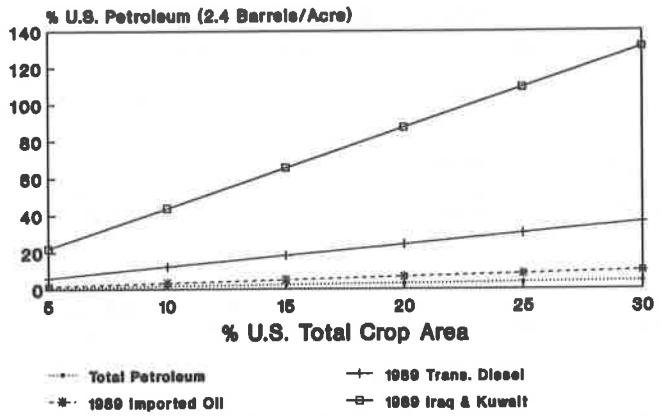

Figure 1–Potential production of rape oil ester with oil production estimated at 5.9 barrels/ha (2.4 barrels/acre).

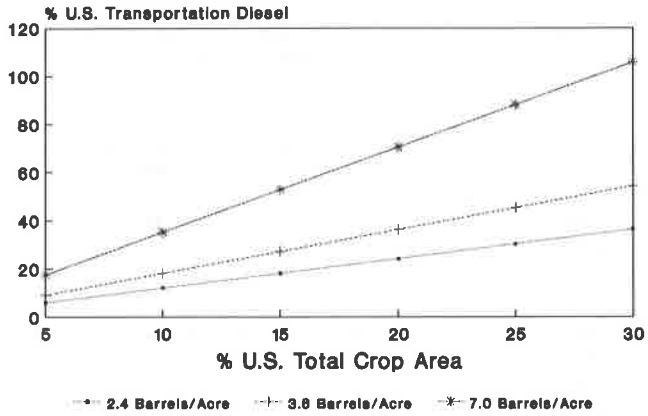

Figure 2–Production of rape oil ester at seed yields of 2.24, 3.36, and 6.72 t/ha (2,000, 3,000, and 6,000 lb/acre).

shows an estimate of the current potential for vegetable oil fuel production in the United States, indicating that annual production of vegetable oil has the potential to be more than doubled, resulting in 27 GL (7.0 billion gal) per year.

Improved varieties or higher yielding cultivars of oil seed crops could reduce the land required for vegetable oil production. Figure 2 shows how the required crop acreage would decline as yield improves.

In addition to the oil produced, a vegetable oil crop such as winter rape also produces considerable biomass. Peterson (1984) estimated a 2.24 t/ha (2000 lb/acre) crop of winter rape produces 935 L/ha (100 gal/acre) of oil, 1.4 t/ha (1250 lb/acre) of meal, and 5.6 t/ha (5000 lb/acre) of biomass normally left on the field at harvest. He estimated the energy equivalent of these by-products at 3274 L/ha (350 gal/acre) of diesel fuel equivalent to 20.6 bbl/ha (8.33 bbl/acre). The meal can be used as a high-protein livestock feed. However, if there were a major shift of land into production of vegetable oil crops for energy these by-products would likely be used for direct combustion or for production of ethanol. (Note: In this article all by-products have been assigned to ethanol production for the production estimates in table 5.) Utilization of the entire crop leads to the concept of a complete "energy" crop. Agricultural policy makers need to seriously consider means to encourage the development of these energy crops.

Table 5. Current potential for alternative fuels*

Alternative Fuel	Replaced Fuel	% of Total US Crop Land Available†	Volume of Fuel from Available Land		% of Total U.S. Transportation Fuel Replaced (column 2 fuel)	% of U.S. Agric. Fuel Replaced (column 2 fuel)
			GL	(billion gal)		
Veg. oil	Diesel	16.9%	27	(7.0)	27%	250%
Ethanol	Gasoline	10.7%	94	(24.8)‡	22%‡	1800%‡
Biogas	Varies§‖	(41%)†	17‖	(4.4)‖	N.A.§	300%‖

* Assumptions: One half of current vegetable oil production used for fuel. One half of current export land area used for vegetable oil and ethanol production. All current idel cropland used for vegetable oil and ethanol production (evenly divided between vegetable oil crops and corn for ethanol).

† For biogas, this is the percent of total U.S. animal waste currently available for digestion.

‡ Includes ethanol from sources not requiring additional cropland (table 6).

§ See table 8 for biogas replacements; biogas cannot replace transportation fuels.

‖ Equivalent volume of gasoline for biogas energy content is listed in columns 4, 5, and 7 for reference.

ETHANOL

Renewable biomass resources can be converted to fuel ethanol that can be blended with or replace gasoline. Virtually all the U.S. fuel ethanol [3.9 GL (1 billion gal/year)] is made from corn, and it is estimated that an additional 18 to 23 GL/year (5 to 6 billion gal/year) of ethanol could be made from surplus corn (Goodman, 1989). In addition to corn, other grains and lignocellulosic feedstocks can be converted to fuel ethanol. Other biomass resources, such as animal wastes and sewage sludge, lend themselves more to methane production through anaerobic digestion (discussed later in this article) than to ethanol production. Conversion of grains and lignocellulosic feedstocks can make a significant contribution to satisfying our liquid fuel needs.

PRODUCTION

In the commercial process for converting corn to ethanol, the cost of corn is a major contributor to the cost of ethanol. Processes are being developed that can convert less expensive feedstocks (i.e., lignocellulosics) to fuel ethanol (Broder and Barrier, 1988.) The potential amount of ethanol that could be produced from surplus corn and lignocellulosic feedstocks is estimated as 110 to 374 GL (29 to 99 billion gal) annually as shown in table 6. Idle lands, which include set-aside and conservation reserve lands, comprised 20 Mha (50 million acre) in 1992, down from 36 Mha (90 million acre) in 1987 (U.S. Department of Commerce, 1994.) If the amount of idle lands again increase to 1987 levels these additional lands could be used to produce an additional 36 to 82 GL (10 to 22 billion gal) of ethanol each year.

After production of ethanol, the remaining solid material represents an excellent combustion fuel [about 19,500 to 23,000 kJ/kg (8,500 to 10,000 Btu/lb) on a dry basis (Broder et al., 1993.)] The lignin component also offers potential as a feedstock for high value chemicals, such as phenol formaldehyde resins and polyols for urethane foam production (Broder and Barrier, 1991.)

USE

The United States produces about 3.78 GL (1 billion gal) of ethanol each year, with most being blended with the 430 GL (110 billion gal) of gasoline used annually. If all the gasoline used in the United States were blended with

Table 6. Potential U.S. ethanol production from available biomass resources

Available Biomass	Amount Available		Ethanol Yield		Ethanol Potential/Year	
Resources	10^6 t/Year	(10^6 Ton/Year)	L/t	(Gal/Ton)	GL	(Billion Gal)
Ag residues*	54-168	(60-165)	167-375	(40-90)	7-64	(2-17)
Forestry residues†	145-349	(160-385)	167-375	(40-90)	23-132	(6-35)
Municipal solid waste‡	217	(240)	63-230	(15-55)	15-49	(4-13)
Idle lands§	273	(300)	167-375	(40-90)	45-102	(12-27)
Food processing waste‖	10	(11)	167-375	(40-90)	1.5-4	(0.4-1)
Surplus corn					19-23	(5-6)
Total					110-374	(29-99)

* Diaz and Golueke, 1981.
† Zerbe, 1988.
‡ Cook, 1988.
§ 20.2 Mha (50 million acre) planted with agricultural or short rotation woody biomass at an average yield of 13.5 t/ha (6 tons/acre) results in 273 Mha (300 million ton) of biomass per year; U.S. Department of Commerce, 1994.
‖ Weathers, 1989.

ethanol at the 10% rate, the market for ethanol would be 43 GL (11 billion gal) per year. If the blending rate were increased to 20%, this would double the ethanol market to over 86 GL (22 billion gal) each year. The potential ethanol production capacity in the United States using lignocellulosics and surplus corn could supply sufficient ethanol for a 25 to 87% blend of ethanol to gasoline.

For use as a neat (100%) fuel, about 538 GL (142 billion gal) of ethanol would displace the existing gasoline consumption since ethanol can provide approximately 80% of the mileage of gasoline on a volumetric basis. An additional market of 30.3 GL (8 billion gal) of ethanol is potentially available for use as a solvent and as a feedstock for making ethylene and other chemicals (Wyman, 1990). These liquid fuel and chemical feedstock markets show that potential markets for ethanol exceed the U.S. potential production capacity.

METHANE

Methane is the simplest member (CH_4) of the paraffin family of hydro-carbons. Methane occurs commonly in natural gas, where it comprises from 60 to 98% of the gas (Obert, 1973). Its energy content in a combustible mixture is 3240 kJ/m^3 (87 Btu/ft^3) (Obert, 1973), about 90% that of gasoline. Methane is clean burning and is an excellent fuel for spark ignition (SI) and gas-diesel engines, with good antiknock characteristics (Obert, 1973).

In agriculture, methane is a primary decomposition product of the anaerobic degradation (digestion) of organic material. Biogas from the anaerobic digestion of livestock wastes typically contains between 55 to 70% methane, with the majority of the remainder being carbon dioxide (Parsons, 1984). The accumulation of animal wastes at concentrated livestock production facilities provide a large source of organic material for potential digestion.

PRODUCTION

Two alternatives exist for digesting animal waste. Conventional anaerobic digesters (Parsons, 1984) consist of a sealed container with the substrate (waste) added either in a batch or continuously. The digester's contents are mixed periodically to improve heat transfer and substrate presentation. Biogas is collected in the digester headspace above the digesting mixture. Mixed tank reactors, operating in the mesophilic or thermophilic temperature (20° to 50° C, 70° to 120° F) range, have been much studied, but little used, for livestock waste in the United States. An alternative is the covering of anaerobic lagoons, which are in wide use for animal waste treatment in the United States (Safley et al., 1992). Lagoons, often several acres in size, can be covered with industrial fabrics to collect the biogas (Chandler et al., 1983; Safley and Westerman, 1988), and are essentially large anaerobic digesters operating mainly in the psychrophilic temperature range [less than 20° C (70° F)]. Digestion in low temperature lagoons will be slower than at higher temperatures, but the ultimate methane yield should be about the same as conventional digesters when appropriate extended retention times are used (Safley and Westerman, 1988). This type of reactor is limited to climates with a mean annual ambient temperature of about 13° C (55° F) or above (Chandler et al., 1983; Safley and Westerman, 1988; Safley and Lusk, 1990.)

The potential methane production from a given animal waste is directly related to the amount of volatile solids [VS (kg/d/head; lb/d/head)] present in the waste. Typical volatile solids concentrations for different animal wastes are documented (ASAE, 1991.) Representative values for the ultimate methane yield, B_o (m^3/kg-VS; ft^3/lb-VS), from the volatile solids of major animal types are also documented (Safley et al., 1992). These values may be combined with animal population data to determine the **maximum potential** methane production, TM (Tg/year; 10^6 ton/year), for each animal type in the United States using:

$$TM = 365 \times N \times VS \times B_o \times \rho \times 10^{-9} \qquad (1)$$

where
N = number of animals
VS = volatile solids, kg-VS/d/head (lb-VS/d/head)
B_o = ultimate methane yield, B_o (m^3/kg-VS; ft^3/lb-VS)
ρ = density of methane, 0.662 kg/m^3 (0.041 lb/ft^3)

Data related to methane emissions to the atmosphere from animal wastes have been reviewed and compiled by Safley et al. (1992). They presented estimates for the total animal waste production for the major livestock types in the United States as well as estimates of the amount of the waste handled with the different types of waste

Table 7. Potential methane (biogas) production from animal wastes

	Maximum Potential			Current Potential			Minimum Potential		
	Methane		Energy*	Methane		Energy*	Methane		Energy*
Type	Tg/yr	10^6ton/yr	10^6bbl/yr	Tg/yr	10^6ton/yr	10^6bbl/yr	Tg/yr	10^6ton/yr	10^6bbl/yr
Beef	13.3	(14.6)	108	2.5	(2.8)	20	0.1	(0.11	1
Dairy	5.2	(5.7)	42	4.8	(5.31)	39	1.9	(2.11)	15
Swine	3.1	(3.4)	25	2.8	(3.11)	23	2.1	(2.3)	17
Poultry	1.5	(1.7)	12	1.5	(1.7)	12	0.2	(0.2)	1
Other	1.3	(1.4)	10	0.0	(0.0)	0	0.0	(0.0)	0
Totals	24.3	(26.8)	197	11.6	(12.9)	95	4.2	(4.7)	34

* bbl = Barrels of conventional crude oil 6.1 ×10^6 kJ/bbl (5.8 × 10^6 Btu/bbl).
Source: Safley et al. (1992).

management systems. Those data were used to estimate biogas production for tables 5 and 7. The maximum potential methane production, TM, was calculated with equation 1 using the total volatile solids production, VS, from livestock in the United States.

After calculating the **maximum potential** methane production, the **current potential** is found subtracting the amount of manure that is left on pasture, since that manure will not be used in digesters without major changes in animal production practices. Thus, the **current potential** was calculated with equation 1 using a reduced value of VS found by subtracting the manure that is left on pasture. Waste that is already handled with liquid systems would be the easiest to digest with the least change in production practice. Using just the amount of waste currently handled with liquid handling systems gives the **minimum potential** methane production in table 7. This **minimum potential** was calculated with equation 1 using a reduced value of VS found by subtracting all manure that is not currently handled with liquid handling systems. If all animal waste currently collected in the United States were digested, the methane produced would have the energy equivalent of 95 million barrels of oil per year. This current potential, based on the currently collected animal wastes, is shown with the agriculturally produced fuels in table 5.

USE

The potential methane production in table 7 does not address the question of economic feasibility, and little recent work has been done on the economics. In general, payback periods may range from 4 to 10 years depending on the size of the operation and the need for continuous supplies of energy (e.g., Safley and Lusk, 1990). Large operations with large continuous needs for energy will have better economics. Continuous uses for the biogas are required because gas storage is usually impractical. Such continuous use applications are often practical in agriculture, although they limit the options for using methane. Table 8 summarizes some potential uses for biogas. The data in table 5 indicate that potential methane production is equivalent to three times the current gasoline usage in agriculture.

CONCLUSIONS

Vegetable oil, ethanol, and methane have potential as alternative energy sources. The alternative fuel production potential shown in table 5 would have a major impact on U.S. petroleum consumption. Use of these and other alternative energy sources could contribute to a reduction in our dependence on foreign oil and a more stable supply of energy. However, the technology is still in infancy. Major production centers have not been developed. The economics of these fuels compared to traditional petroleum resources are marginal; public policy needs to be revised to encourage development of these resources. With vegetable oil, for example, development of even a small pilot plant would require a significant commitment of resources. Land for production would need to be contracted, an expression and esterification plant would be required, distribution and storage facilities constructed, and monitoring of major users for detection of problems in large scale use are all needed before the technology can be recommended for general use. The magnitude of our energy needs provides an inexhaustible market for our total agricultural production capacity at the highest possible level. We could put the farm back to work providing for our food needs and also growing crops and livestock for energy. Energy is the only crop that we could never grow in surplus.

Table 8. Potential on-farm uses for methane (biogas)

Biogas Use	Conventional Fuel Replaced	Applicable Animal Production Systems
Electricity	Coal, etc. (EPF's)	All
Pumping water	Gasoline, EPF's	All
Crop drying	Propane, fuel oil	All
Space heating	Natural gas, fuel oil, EPF's	Dairy, poultry, swine
Cogeneration*	Gasoline, diesel, natural gas, fuel oil, EPF's	Dairy, poultry, swine
Hot water	Natural gas, fuel oil, EPF's	Dairy
Absorption cooling	EPF's	Dairy

* Electricity + space or water heating from engine cooling.
EPF = any fuel used to produce electricity.

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