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Energy in Synthetic Fertilizers and Pesticides: Revisited

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FOR THE UNITED STATES
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ENERGY IN SYNTHETIC FERTILIZERS AND PESTICIDES: REVISITED

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ABSTRACT

Agricultural chemicals that are derived from fossil-fuels are the major energy intensive inputs in agriculture. Growing scarcity of the world's fossil resources stimulated research and development of energy-efficient technology for manufacturing these chemicals in the last decade. The purpose of this study is to revisit the energy requirements of major plant nutrients and pesticides. The data from manufacturers energy survey conducted by The Fertilizer Institute are used to estimate energy requirements of fertilizers. Energy estimates for pesticides are developed from consulting previously published literature. The impact of technical innovation in the fertilizer industry to US corn, cotton, soybean and wheat producers is estimated in terms of energy-saving.

The weighted average energy uses in production of nitrogen and phosphorous (as P_2O_5) nutrients under 1987 technology were in GJ/mt 55.48 and 4.52, respectively. Under 1985 technology, energy requirement of potash (K_2O) was 4.80 GJ/mt. The total energy needs of nitrogen, phosphorous and potash for production, packaging, transportation and application are estimated to be in GJ/mt 64.08, 14.32 and 12.10, respectively. Energy requirements for nitrogen and phosphorous nutrients have considerably declined over the period from 1979 to 1987, whereas the same for potash has increased. Because the average energy requirement and plant application rate of nitrogen are significantly higher than that of phosphorous and potash, even a small reduction in its energy use will have substantial impact on agriculture's dependence on non-renewable fossil resources. More than 80 percent of nitrogen's energy requirements is in the form of natural gas. Unit energy consumption in producing active ingredients of major US herbicides, insecticides, and fungicides were in GJ/mt 214.93, 245.06 and 356.39, respectively.

As a result of energy-efficient technical change in fertilizer industry, producers of major US crops have gained *real* energy-saving benefits in terms of nitrogen and phosphorous individually, and all the three nutrients together during the period 1979-87. Only in case of potash nutrient, has there been an increase in the *real* energy consumed. For some of the crops and nutrients, this *real* energy saving -- which represents a saving attributed to innovation in the fertilizer industry -- has been much more than what was *actually* saved over the study period.

In an absolute sense, there were significant real energy savings in the form of nitrogen on corn, cotton and wheat (in GJ/ha 1.26, 0.58, 0.52 during 1979-87, respectively). This is a significant achievement particularly from environmental and resource scarcity points of view. Energy saving on nitrogen especially for corn and wheat translated into substantial energy savings at the national level since these two crops are the greatest in terms of hectarage planted in 1987. These energy savings on nitrogen for corn and wheat have resulted in substantial reduction in not only dependence on fossil sources but also greenhouse gas emission.

Although the results of this study indicate that substantial energy efficiency is achieved in manufacturing agricultural chemicals, further investigation is needed on the economic cost of achieving such efficiency. As Mudahar and Hignett (1987b, p. 154) state, *saving energy for the sake of saving does not provide a very strong economic justification for large capital investments.* The economic implications that energy-efficient technology might have on capital investment, employment, cost of training operators, and disposal of excess steam energy need serious consideration while making further investment in energy-saving technology.

I. INTRODUCTION

Fossil-based agricultural chemicals are an important input in agricultural production. There is a direct relationship between energy use in the form of agricultural chemicals and productivity of land. For instance, U.S. crop yields have increased more than three times during the last 60 years, whereas fossil energy input consumption has increased 40 times (Pimentel and Dazhong, 1988). The fossil energy expended on the food system alone constituted 17 percent of the total energy supply in the U.S. (Pimentel, 1984). It was estimated that if the U.S. rate of energy input consumption in agriculture and the U.S. agricultural technology prevailed over the entire world, the total known deposit of world's fossil fuel would last only another five years. This clearly signals the scarcity of the world's non-renewable energy resource.

Among all the fossil-based agricultural chemicals, fertilizers and pesticides alone account for 45-55 percent of the total energy involved in world crops production (Helsel, 1987, p. vii). The use of these inputs is more intense in developed countries. Increasing demand for food supply from the world's fast growing population constantly calls for more use of these chemicals, and in turn, more fossil energy consumption. When the world energy prices soared in the 1970s and 1980s, one of the measures suggested to narrow down the gap between increasing demand for and depleting supply of fossil energy was encouraging energy-efficient way of manufacturing fossil-based inputs. The fertilizer and pesticide manufacturing processes were the ones that came into scrutiny from an energy-saving point of view in both developed and developing countries.

Since fossil energy has become an integral part of the modern agriculture, the fluctuations in the prices of fuel-energy have impacts on food prices. As Mudahar and Hignett (1987b) denote, energy costs account for a large share of fertilizer production costs. Energy-efficient agricultural inputs will lower the production costs. As input manufacturing costs decline, the productivity of agriculture's fixed capital will increase. Thus, an increase in energy use efficiency in agricultural chemical industry has a direct impact on agricultural productivity and its returns.

From an environmental point of view, agriculture is considered as one of the largest contributors of greenhouse gases (Goodman *et al.*, 1989). The emission occurs indirectly as fossil-fuel is extracted for manufacturing agricultural chemicals. Any energy savings in producing these chemicals help reduce the emission of greenhouse gases, while maintaining the required level of input use in agriculture.

A substantial research and development effort was expended on the design of new energy-saving techniques in fertilizer plants during the late 1970s and early 1980s. Mudahar and Hignett (1987b) gave a detailed account of various fertilizer production techniques that were designed for energy savings during this period. They estimated the actual energy consumption in producing various fertilizers during 1983 and probable energy savings if the future technology known in 1983 was adopted (see Table 1). As per their estimate, the potential energy savings ranged from 22 to 32 percent over 1983 estimates for different nitrogenous fertilizer; and 65 to 186 percent for different phosphate fertilizers. In the early and middle 1980s, many large scale fertilizer plants in the United States have adopted energy-saving devices[1]. It was assumed that these new devices reduced the fertilizer energy requirements. However, there are no reliable estimates of energy-savings from technological changes that fertilizer industry experienced in the last decade. The 1983 estimates of Mudahar and Hignett (1987a) are the most current information. There are other estimates [Lockeretz (1980) and Dovring and McDowell (1980)] developed prior to 1980.

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[1] Personal communication with Dr. Balu Bumb, Leader, Fertilizer Policy Research Program, International Fertilizer Development Institute, Muscle Shoals, AL in October 1991.

Table 1. **Expected energy savings in producing nitrogenous and phosphate fertilizers from 1983 to future technology.**

Fertilizers	Average Energy Requirement		Expected Energy Saving between 1983 and Future Technology
	1983	Future	
	--------- GJ/mt --------		Percent
Nitrogenous Fertilizers:			
Ammonia	55.3	42.9	22
Urea prilled	76.3	54.2	29
Ammonium nitrate	66.6	50.7	24
UAN solution	65.3	48.4	26
Ammonium sulphate	58.0	39.3	32
Phosphate Fertilizers:			
Phosphoric acid - 42%	4.9	-4.2	186
Phosphoric acid - 54%	6.8	-2.5	137
Triple superphosphate	8.3	0.9	89
Monoammonium phosphate	14.8	3.7	75
Diammonium phosphate	20.6	7.3	65

Source: Mudahar and Hignett (1987b).

Reliable estimates of energy consumption in agriculture are essential for informed decision making and planning for promoting energy conservation programs. For instance, DOE sponsored research in the last decade demonstrated that biomass crops could become a potential alternative source of energy. However, production of these crops requires some fossil-fuel based energy inputs. An accurate evaluation of energy input-output ratio and environmental impact of these biomass feedstocks will not be possible unless we have a reliable knowledge of energy embodied in chemicals used in their production process.

The primary purpose of this analysis is to develop current estimates of energy consumption in major fertilizers and pesticides. These estimates will be compared with previous estimates available in order to assess the technological improvement that actually occurred in the agricultural chemical sector. Production of fertilizer inputs is the major focus of this study for pragmatic reasons. First, next to direct use of fuel, fertilizer is the second largest energy input in the US primary crop production. As reported by Green (1987, p. 171), fertilizer constituted 24 percent [518 Petajoules (PJ)] of the total energy consumption in 1980 as opposed to 1.6 percent by pesticides. Second, there is fairly a consistent set of data on fertilizer plants' energy consumption, available from a set of manufacturer surveys conducted by The Fertilizer Institute (TFI). The latest survey data is available for the year 1987. The institute's survey data collected for 1979 and 1983 were previously used to estimate average energy requirements of individual fertilizers and nutrients (Mudahar and Hignett, 1981; Mudahar and Hignett, 1987a). However, we also revisited their estimates using the TFI survey data for the respective years as their estimates were based on certain assumptions -- regarding composition of phosphoric acids manufactured through different processes -- which we rejected based on the latest information available to us. These energy estimates at different points in time provide us a basis for temporal comparison of energy requirements of major crops in the United States.

II. ENERGY CONSUMPTION IN MANUFACTURING FERTILIZERS

Fertilizers are applied to plants to supply three primary nutrients: nitrogen, phosphorous and potassium. There are a number of fertilizers used to supply each of these nutrients (Table 2). The type of manufacturing process, amount of raw materials, amount of energy consumed, and the amount of primary nutrient contained in the final product vary widely among fertilizer types.

Table 2 Annual average consumption of nitrogen, phosphorous and potash fertilizers in the United States for the period 1981-87.[a]

Fertilizers	Percent Nutrient $N\text{-}P_2O_5\text{-}K_2O$	Total Consumption	Consumption of Individual Nutrients		
			Nitrogen (N)	Phosphorous	Potash (K_2O)
		---------------------------- Thousand Metric Tonnes ----------------------------			
Nitrogen fertilizers:					
Ammonia[b]	82-0-0	4921	4035	--[c]	--
Urea	46-0-0	2431	1118	--	--
Ammonium nitrate	34-0-0	2009	683	--	--
Urea-ammonium nitrate	30-0-0	6582	1975	--	--
Ammonium sulphate[d]	21-0-0	663	139	--	--
Others	48-0-0	470	225	--	--
Phosphorous fertilizers:					
Single superphosphate	0-22-0	69	--	15	--
Double superphosphate	0-46-0	721	--	332	--
Others	0-44-0	204	--	90	--
Potash fertilizer:					
Muriate of potash	0-0-60	4936	--	--	2961
Mixed fertilizers:					
Diammonium phosphate	18-46-0	2266	249	1224	--
Monoammonium	11-54-0	3025	544	1391	--

[a] Source: Vroomen (1989), Tables 4 and 5, p. 23-24.
[b] Ammonia used as direct fertilizer.
[c] '--' indicates that this nutrient is not present in the specified fertilizer type.
[d] Contains 28% sulfur.

The unit energy requirement of an individual nutrient depends on the proportion of different fertilizer types used in supplying a given nutrient. Some of the mixed fertilizers, which are very common in the market, supply more than one nutrient. Energy requirements of these fertilizers need to be properly apportioned among the nutrients contained within them.

The estimates of energy consumption for individual fertilizers are developed based on the 1987 fertilizer plant survey conducted by The Fertilizer Institute (TFI) (The Fertilizer Institute, 1988). The results from the survey appeared to be more reliable and accurate for several reasons. First, most of the fertilizers undergo several phases before being ready for market. In some cases, the products generated in the intermediate steps would release some energy that could be used in the subsequent steps. For example, sulfur-burning sulfuric acid plants, that are generally run in conjunction with phosphorous acids, generate 2.18 Gigajoule (GJ) of steam or electrical energy per metric tonne (mt) of sulfuric acid produced, which can be used in phosphoric acid production (Mudahar and Hignett 1987a). In the production of ammonia and urea, some plants produce excess steam that is not used in the production process. Typically this steam is exported to other manufacturing industries. The TFI survey systematically investigates this type of energy adjustment within the plants. Their survey is designed such that no double counting occurs while estimating energy consumed in each subsequent step. An estimate of energy consumption in terms of fuel types such as natural gas, electricity, steam and other fuels is also provided in their survey. Finally, the reported energy estimates take into account incidental energy used for space heating, air conditioning, lighting and on-site transportation.

These estimates are based on the energy use in actual plant operation rather than the "battery-limits" claimed by designers of a specific operational unit. The actual energy consumed sometimes exceed the battery-limits by wide margin (Mudahar and Hignett, 1987a). Most often individual equipment does not operate at maximum efficiency. Thus, actual energy consumption may be more than the energy requirement specified by manufacturer of the unit. TFI survey recognizes these variations.

There is confusion in converting electrical energy into thermal energy (Mudahar and Hignett, 1987a). Conventionally, 1 kWh of electrical energy has been equated to 3.6 Megajoule (MJ) or 3413 Btu, the amount of heat produced by 1 kWh. However, the amount of energy consumed in supplying a required amount of electrical energy for fertilizer production is more relevant for this study. In a modern electrical power system, generation of 1 kWh of electrical energy requires 10.5 MJ (10000 Btu). TFI survey estimates incorporate this assumption.

The TFI survey of 1987 is the latest source of available information on fertilizer energy consumption. Similar surveys have been conducted for previous years using fairly consistent survey techniques. Thus, these annual surveys could be used to analyze the trend in energy use over a period of time.

Several input-output parameters of intermediate products and information missing in the TFI survey are required for the analysis. Information regarding these parameters are found in Mudahar and Hignett (1987a). The procedure we adopt closely follows their methodology. The interested readers are referred to Mudahar and Hignett for a detailed discussion of manufacturing processes of different commercial fertilizers.

Using the above two sources of information, we developed a spreadsheet model that is capable of estimating unit energy requirements of individual nutrients. This model estimates energy requirements of individual fertilizers. Included in these estimates are the energy expenditures in producing intermediate products from alternative production processes. Given the user-specified weights of individual fertilizer consumption/production, the model calculates per unit nutrient energy consumption. The model appropriates the unit energy consumption of mixed fertilizers among constituent nutrients while estimating energy use for individual nutrients.

Nitrogenous Fertilizers

Ammonia

Ammonia is produced from two types of processes, centrifugal and reciprocating. Centrifugal plants are the most commonly found ammonia plants. However, in this analysis, the unit energy consumption for ammonia is estimated by taking the weighted average energy consumption for both the types of plants, assuming 90 percent of ammonia produced from centrifugal plants as suggested by the TFI sample survey.

Table 3 **Average energy consumption in the production of ammonia fertilizer in 1987.**

Processing type	Natural Gas	Electricity[a]	Steam	Total
	----------	GJ/mt	----------	
A. Reciprocating				
Feedstock	25.29	--	--	25.29
Reformer process	8.69	0.44	--	9.13
Other processing	5.33	3.81	-0.42[b]	8.73
Total	39.31	4.26	-0.42	43.15
B. Centrifugal				
Feedstock	25.14	--	--	25.14
Reformer process	13.31	--	--	13.32
Other processing	2.49	0.75	-0.38	2.86
Total	40.94	0.75	-0.38	41.32
C. Weighted average	40.78	1.10	-0.38	41.50

[a] The energy for electricity is calculated based on 10.5 MJ/kWh (10000 Btu/kWh).

[b] A negative number means that steam is produced in excess of plant requirements and is available for export.

Ammonia is used as a basic ingredient for most of the nitrogen fertilizers, and also used directly as anhydrous or liquid ammonia. Natural gas is the major source of feedstock and fuel. Table 3 presents the energy use estimates for ammonia production from the two processes and their weighted average in 1987. About 98 percent of the total energy consumed in ammonia production is in the form of natural gas. A small quantity o2f energy is recovered as steam (0.38 GJ/mt of ammonia). Ammonia processing involves three main stages: reforming, purification and synthesis. In the reforming stage, natural gas (methane) and steam are combined at a desired temperature to produce carbon monoxide (CO) and hydrogen (H_2). A sufficient quantity of air that supplies nitrogen is injected into this mixture, and the mixture undergoes a purification stage. In this stage, carbon monoxide (CO) further reacts with steam (H_2) to release carbon dioxide (CO_2), which will be removed from the mixture using an absorbent. Finally, the mixture of hydrogen and nitrogen is compressed and passed through a synthesis reactor to generate ammonia.

Averaging the energy requirements for reciprocating and centrifugal processes, 40.78 GJ of natural gas is required per metric tonne of ammonia, along with small amount of electricity (1.10 GJ/mt). The process generates a small amount of steam (0.38 GJ/mt) which can be exported or re-used within the plant. Total energy required to produce a tonne of ammonia is 41.5 GJ.

Urea

Ammonia and carbon dioxide are the two main ingredients for urea production. Carbon dioxide is generally available at no cost from the ammonia plant. Every metric tonne of urea requires 0.575 mt of ammonia (Table 4). Preheated, compressed ammonia is mixed with carbon dioxide to produce the urea compound, which is further purified, condensed, and converted into prilled (small granule like) urea. A major portion of the energy consumed is for producing

Table 4 Average energy consumption in the production of urea in 1987.

	Natural Gas	Electricity	Imported Steam	Exported Steam[a]	Total
	GJ/mt				
Ammonia production[b]	23.44	0.63		(0.22)	23.86
Total liquid	1.81	0.98	1.77	(0.59)	3.98
Urea prilling	0.77	0.93	1.93		3.63
Total	26.02	2.55	3.70	(0.81)	31.47

[a] Steam energy released in the production of ammonia and urea synthesis is assumed exported to other plants and credited to total urea energy requirement.

[b] Ammonia input: 0.575 mt/mt of urea (Mudahar and Hignett, 1987a).

ammonia -- with natural gas, steam and electricity the three main energy types used in urea synthesis and prilling. Urea synthesis releases a small quantity of steam energy.

Ammonium Nitrate

Again ammonia is the major raw material for ammonium nitrate (AN) (0.434 mt/mt of AN). The procedure involves production of nitric acid with ammonia and air, neutralization of acid with ammonia, and finally prilling and storage. More than 75 percent of the energy consumed in producing nitric acid is recovered in the form of exportable steam (1.63 GJ/mt of nitric acid). Final energy consumption required to produce a metric tonne of AN is 20.76 GJ, with natural gas the major component of total energy utilized in its production (Table 5).

Urea-ammonium Nitrate

Urea-ammonium nitrate is a widely used nitrogenous fertilizer, accounting for more than 22 percent of the annual nitrogen consumed in the United States. Urea-ammonium nitrate is prepared by combining urea and AN solutions with water (0.327 and 0.422 mt/mt of urea and AN, respectively). Ammonia production requires more than 85 percent of the total energy used in production in the form of natural gas (Table 6).

Table 5 **Average energy consumption in the production of ammonium nitrate in 1987.**

	Natural Gas	Electricity	Imported Steam	Exported Steam[a]	Total
	GJ/mt				
Ammonia production[b]	17.69	0.48		(0.17)	18.01
Nitric acid	0.79	0.93	0.39	(1.63)	0.47
Synthesis	0.01	0.06	0.25	(0.02)	0.30
Prilling	0.01	0.31	1.76		2.08
Total	18.50	1.78	2.40	(1.82)	20.86

[a] Steam energy released in the production of ammonia and nitric acid, and AN synthesis is assumed exported to other plants and credited to total urea energy requirement.

[b] Ammonia input: 0.434 mt/mt of AN (Mudahar and Hignett, 1987a).

Table 6 **Average energy consumption in the production of urea-ammonium nitrate in 1987.**

	Natural Gas	Electricity	Imported Steam	Exported Steam[a]	Total
	GJ/mt				
Ammonia production[b]	15.13	0.41		(0.14)	15.40
Urea synthesis	0.59	0.32	0.58	(0.19)	1.30
AN solution	0.39	0.04	0.05	(0.03)	0.43
Mixing, storage and cooling[c]		0.25			0.25
Total	16.11	1.02	0.63	(0.36)	17.39

[a] Steam energy released in the production of ammonia, urea synthesis and preparation of AN solution is assumed exported to other plants and credited to total UAN energy requirement.

[b] Ammonia input: 0.371 mt/mt of UAN [0.188 mt of ammonia in 0.327 mt of urea plus 0.183 mt of ammonia in 0.422 mt of AN to produce every mt of UAN (Mudahar and Hignett, 1987a)].

[c] Energy requirement of for mixing, cooling and storage (0.25 GJ/mt of UAN) is assumed to be electric energy.

Ammonium Sulphate

Ammonium sulphate (AS) is produced by mixing ammonia and sulfuric acid. There are methods where AS is recovered as a by-product, but these methods are highly energy intensive (Mudahar and Hignett, 1987b). The market grade of AS contains 21 percent nitrogen and 24 percent sulfur. Average energy use in production of AS by ammonia and sulfuric acid is 11.26 GJ/mt (Table 7) with the major energy requirement for producing ammonia (0.25 mt/mt of AS) in the form of natural gas (10.48 GJ/mt of AS).

Table 7 **Average energy consumption in the production of ammonium sulphate in 1987.**

	Natural Gas	Electricity	Imported Steam	Exported Steam[a]	Total
	----------	----------	GJ/mt	----------	----------
Ammonia production[b]	10.48	0.28		(0.10)	10.67
Processing[c]		0.59			0.59
Total	10.48	0.87		(0.10)	11.26

[a] Steam energy released in the production of ammonia is assumed exported to other plants and credited to total AS energy requirement.

[b] Ammonia input: 0.257 mt/mt of AS (Mudahar and Hignett, 1987a).

[c] Processing energy of 0.59 GJ/mt of AS is assumed to be electric energy.

Other Fertilizers

All other straight nitrogen fertilizers, including sodium nitrate, consumed in the U.S. are reported under this category. This category supplies 2.5 percent of the average annual nitrogen consumed. For lack of information on energy requirements of individual grades under this category, an average of all the major fertilizers discussed so far is taken as average energy requirement for this category. Thus, the energy requirement for other fertilizer category is calculated to be 24.49 GJ/mt of fertilizer (51.02 GJ/mt of nitrogen) with more than 91 percent in the form of natural gas.

Phosphate Fertilizers

Phosphate fertilizers usually are consumed in the form of single superphosphate (SSP) and triple superphosphate (TSP). In recent years, much of the elemental phosphorous is supplied to crops in the form of mixed fertilizers, which will be discussed in the next subsection.

Manufacturing of market grade phosphate fertilizers involves several intermediate stages. Phosphate rock and sulfuric acid are the major ingredients required for the production of phosphate fertilizers. A flow-chart representing the production of these fertilizers is presented in Figure 1. Phosphate rock is a naturally available basic ingredient, which will be processed into either dry or wet rock phosphate. Sheldrick and Steir (1979) reported that about 8 percent of the world's phosphate fertilizer is in the form of direct phosphate rock. Sulfuric acid is manufactured from elemental sulfur or pyrite ore in conjunction with phosphoric acid and phosphate fertilizers. The next phase is to prepare phosphoric acid from phosphate rock and sulfuric acid. Phosphoric acid is processed into different grades such as filter grade (less than 30% P_2O_5), TSP grade (42% P_2O_5) and merchant grade (54% P_2O_5), depending on its end use. Further, phosphoric acids of different grades are mixed with phosphate rock to obtain required grades of phosphate fertilizers.

Each of the intermediate products developed in the process of phosphate fertilizers can be produced in several ways and/or forms. Based on the production process involved, the unit energy requirement of the final products will vary. Therefore, a more detailed discussion of these ingredient products is in order, before estimating the final energy requirement.

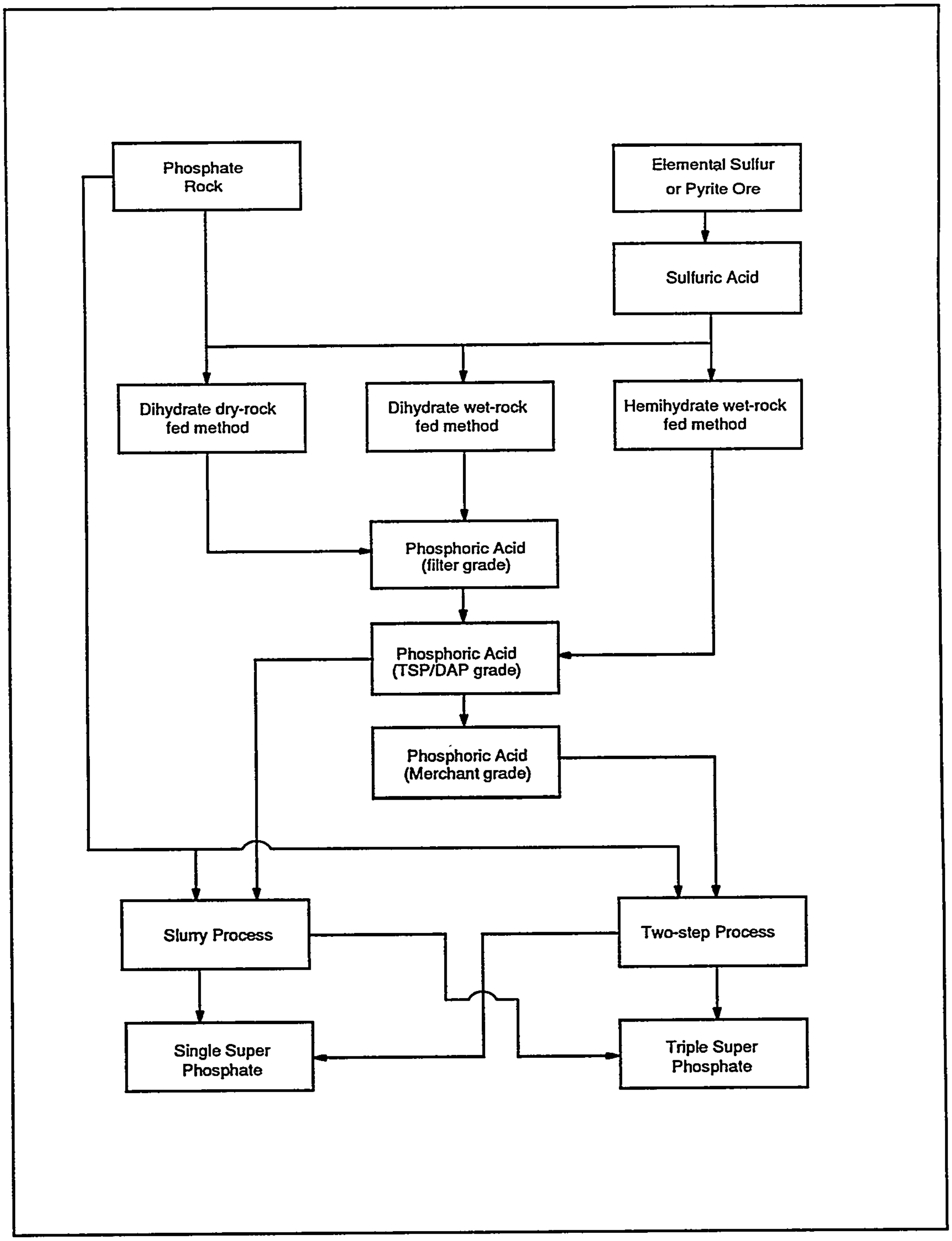

Figure 1 The flow-chart representing various stages involved in the production of phosphate fertilizers.

Phosphate Rock

Naturally available phosphate rock is mined and processed through these major steps: benefication, drying and grinding. The final form of the processed rock depends upon its intended use. As previously mentioned, a small portion of phosphate rock can be directly used. A major portion of it is processed as wet rock without drying or grinding and used in producing phosphoric acid and higher grades of phosphate fertilizers. Average energy use of phosphate rock preparation is presented in Table 8. Electricity is the major energy source utilized in both wet and dry rocks.

Table 8 Average energy consumption in the preparation of phosphate rock and sulfuric acid in 1987.

	Natural Gas	Electricity	Fuel Oil[a]	Imported Steam	Exported Steam	Total
	---- GJ/mt ----					
Mining and reclamation		0.28	0.02			0.30
Benefication	0.01	0.46				0.47
Total wet rock	0.01	0.74	0.02			0.77
Drying	0.28	0.04	0.09			0.41
Total dry rock	0.29	0.78	0.11			1.18
Sulfuric acid	0.01	0.19	0.02	0.04	(2.42)[b]	(2.16)

[a] Fuel oil includes other liquid hydrocarbons in terms of equivalent to No. 6 fuel oil.

[b] Steam energy released in the production of sulfuric acid from elemental sulfur or pyrite ore is assumed to be used in the production of phosphate fertilizers and credited to sulfuric acid's energy requirement.

Sulfuric acid

Sulfuric acid is produced mainly from Frasch-mined sulfur. Under this process, a large quantity of super heated water under pressure is pumped into an underground sulfur-bearing layer to melt the sulfur. The dissolved sulfur mixture is then pumped to the surface by an air lift. This solution is further subject to smelter operations to derive sulfuric acid. Though the mining operations requires considerable energy, conversion of sulfur into sulfuric acid releases substantial steam energy which will be normally used in preparation of phosphoric acid. The net energy released in the production of sulfuric acid is estimated to be 2.16 GJ/mt (Table 8). This estimate is very close to the estimate given by Mudahar and Hignett (1987a) for the year 1983.

Phosphoric acid

Phosphoric acid (PA) is a major intermediate product of phosphate fertilizers and mixed fertilizers. Phosphoric acid is processed into grades of different P_2O_5 concentration. As indicated earlier, the commercial grades are filter grade, merchant grade and TSP/diammonium phosphate (DAP) grade. Filter grade PA is mostly an intermediate product that is further concentrated into TSP/DAP and merchant grades. Dihydrate dry-rock-fed, dihydrate wet-rock-fed, and hemihydrate wet-rock-fed methods are the commonly known methods of producing PA. The TFI survey data for the years 1979, 1983 and 1987 indicate that in the last 15 to 20 years, the wet-rock-fed methods are being increasingly substituted for dry-rock-fed method. As per TFI 1987 sample survey, about 75 percent of PA was produced through wet-rock-fed methods and 25 percent through the dry-rock-fed method. In 1979, only 31 percent of PA was produced through wet-rock-fed methods and the remaining by the dry-rock-fed method. In the wet-rock-fed methods, although the hemihydrate method is more energy efficient one, it requires a major modification of the existing PA plants, and thus, there has been a very slow shift from dihydrate dry or wet rock-fed method to hemihydrate method.[2] To estimate the average energy use for different grades in 1987, it is assumed that 25 percent of the PA is produced from the dihydrate dry-rock method,

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[2] Personal communication with Mr. P. Whitney Yelverton, The Fertilizer Institute, Washington, D. C. 20002 in April 1993.

60 percent from the dihydrate wet-rock method, and only 15 percent from hemihydrate wet-rock method. Average energy consumptions of TSP/DAP and merchant grades produced through three different processes are estimated in Tables 9 and 10.

The differences in the energy requirements between the three manufacturing processes under both TSP/DAP and merchant grades are mainly due to the variation in the energy consumptions of dry and wet rock phosphates. In the case of hemihydrate wet rock methods, PA coming out of filtering stage itself will have a TSP grade concentration and thus, does not require any further concentration. Additional energy is required for concentrating the same to merchant grade. Electricity and steam are the two major energy sources for both the grades. Steam energy savings from sulfuric acid compensates for about a half of PA's total energy requirement.

Triple Superphosphate

Triple superphosphate can be produced from two processes: two-step and slurry. In the slurry process, which is the more commonly adopted process, rock phosphate is mixed with TSP grade phosphoric acid (42% P_2O_5 concentration), and the resulting mixture will be dried and granulated. It is assumed that 0.388 mt of rock and 0.824 mt of TSP-grade phosphoric acid are required for every metric tonne of TSP. In the two-step process, 0.388 mt rock phosphate is mixed with 0.641 mt merchant grade phosphoric acid (54% P_2O_5 concentration) to produce a metric tonne of nongranular triple superphosphate in the first step, with granulation done in the second step. Both the two-step process and the slurry process release steam, a major by-product of the production of TSP. The two-step process requires 3.55 GJ/mt and the slurry process needs 3.09 GJ/mt (Table 11). Assuming that 90 percent of TSP is produced from the slurry process and 10 percent from the two-step process, TSP requires an average energy of 3.14 GJ/mt.

Table 9 Average energy consumption in the preparation of TSP/DAP grade phosphoric acids in 1987.

	Natural Gas	Electricity	Fuel Oil	Imported Steam	Exported Steam[a]	Total
	GJ/mt					
Dihydrate Dry-Rock Method						
Rock preparation[a]	0.92	2.50	0.37			3.78
Sulfuric acid[b]	0.04	0.53	0.05	0.11	(6.74)	(6.01)
Filter grade PA		1.33		1.06		2.39
Concentration to TSP		0.71		4.51	(0.07)	5.16
Total	0.95	5.07	0.42	5.67	(6.80)	5.31
Dihydrate Wet-Rock Method						
Rock preparation[a]	0.04	2.36	0.05			2.46
Sulfuric acid[b]	0.04	0.53	0.05	0.11	(6.74)	(6.01)
Filter grade PA		1.21	0.03	0.22		1.46
Concentration to TSP		0.71		4.51	(0.07)	5.16
Total	0.08	4.82	0.13	4.83	(6.80)	3.06
Hemihydrate Wet-Rock Method						
Rock preparation[a]	0.04	2.36	0.05			2.46
Sulfuric acid[b]	0.04	0.53	0.05	0.11	(6.74)	(6.01)
Filter grade/TSP PA[c]		1.21	0.03	0.22		1.46
Total	0.08	4.11	0.13	0.32	(6.74)	(2.10)
Weighted average for TSP grade[d]	0.30	4.77	0.20	4.37	(6.79)	2.85

[a] Phosphate rock input: 3.2 mt/mt of P_2O_5 (Mudahar and Hignett, 1987a).

[b] Sulfuric acid input: 2.78 mt/mt of P_2O_5 (Mudahar and Hignett, 1987a).

[c] PA derived from filtering is as concentrated as TSP grade.

[d] Weighted average is computed on the assumption that 25% of PA is produced from dihydrate dry-rock-fed method, 60% from dihydrate wet-rock-fed method and 15% from hemihydrate wet-rock-fed method.

Table 10 Average energy consumption in the preparation of merchant grade (MG) phosphoric acids in 1987.

	Natural Gas	Electricity	Fuel Oil	Imported Steam	Exported Steam[a]	Total
	GJ/mt					
		Dihydrate Dry-Rock Method				
Rock preparation[a]	0.92	2.50	0.37			3.78
Sulfuric acid[b]	0.04	0.53	0.05	0.11	(6.74)	(6.01)
Filter grade PA		1.33		1.06		2.39
Concentration to MG		0.47		5.99		6.46
Total	0.95	4.83	0.42	7.16	(6.74)	6.62
		Dihydrate Wet-Rock Method				
Rock preparation[a]	0.04	2.36	0.05			2.46
Sulfuric acid[b]	0.04	0.53	0.05	0.11	(6.74)	(6.01)
Filter grade PA		1.21	0.03	0.22		1.46
Concentration to MG		0.47		5.99		6.46
Total	0.08	4.58	0.13	6.32	(6.74)	4.37
		Hemihydrate Wet-Rock Method				
Rock preparation[a]	0.04	2.36	0.05			2.46
Sulfuric acid[b]	0.04	0.53	0.05	0.11	(6.74)	(6.01)
Filter grade PA[c]		1.21	0.03	0.22		1.46
Concentration to MG		0.15		1.16		1.31
Total	0.08	4.26	0.13	1.48	(6.74)	(0.79)
Weighted average for merchant grade[d]	0.30	4.59	0.20	5.80	(6.74)	4.16

[a] Phosphate rock input: 3.2 mt/mt of P_2O_5 (Mudahar and Hignett, 1987a).

[b] Sulfuric acid input: 2.78 mt/mt of P_2O_5 (Mudahar and Hignett, 1987a).

[c] PA derived from filtering is as concentrated as TSP grade.

[d] Weighted average is computed on the assumption that 25% of PA is produced from dihydrate dry-rock-fed method, 60% from dihydrate wet-rock-fed method and 15% from hemihydrate wet-rock-fed method.

Table 11 **Average energy consumption in the preparation of Triple Superphosphate in 1987.**

	Natural Gas	Electricity	Fuel Oil	Imported Steam	Exported Steam[a]	Total
	GJ/mt					
Two-step process:						
Rock for TSP[a]	0.11	0.30	0.04			0.46
Phosphoric acid[b]	0.10	1.59	0.07	2.01	(2.33)	1.44
Processing	0.33	0.57	0.43	0.32		1.65
Total	0.54	2.46	0.55	2.33	(2.33)	3.55
Slurry process						
Rock for TSP[a]	0.11	0.30	0.04			0.46
Phosphoric acid[c]	0.10	1.65	0.07	1.51	(2.35)	0.99
Processing	0.33	0.57	0.43	0.32		1.65
Total	0.54	2.52	0.55	1.84	(2.35)	3.09
Weighted average for TSP[d]	0.54	2.51	0.55	1.89	(2.35)	3.14

[a] Phosphate rock input: 0.388 mt/mt of TSP (Mudahar and Hignett, 1987a).

[b] Phosphoric acid input: 0.641 mt of MG grade (with 54% P_2O_5)/mt of TSP (Mudahar and Hignett, 1987a). For example, the total energy consumption of 1.44 GJ in the form of PA in two-step process is obtained by multiplying 0.641 mt of PA by 4.16 GJ/mt of PA times 0.54.

[c] Phosphoric acid input: 0.824 mt of TSP grade (with 42% P_2O_5)/mt of TSP (Mudahar and Hignett, 1987a). For example, the total energy consumption of 0.99 GJ in the form of PA in slurry process is obtained by multiplying 0.824 mt of PA by 2.85 GJ/mt of PA times 0.42.

[d] Weighted average is computed on the assumption that 10% of TSP is produced from two-step process and 90% from slurry process.

Single Superphosphate

Manufacture of single superphosphate is similar to that of triple superphosphate. Most single superphosphate is produced in nongranular form. Mudahar and Hignett (1987b) estimated that the energy requirement of granular single superphosphate was 70 percent higher than the nongranular form. Unlike for TSP, there is no credit given for sulfuric acid since most producers of single superphosphate use purchased acid such as spent acid or byproduct acid from the smelter operation (Mudahar and Hignett, 1987b) (Table 12).

Table 12 **Average energy consumption in the preparation of Single Superphosphate in 1987.**

	Natural Gas	Electricity	Fuel Oil	Imported Steam	Exported Steam[a]	Total
	GJ/mt					
Rock for SSP[a]	0.18	0.49	0.07			0.74
Processing[b]		0.41				0.41
Total	0.18	0.90	0.07			1.15

[a] Phosphate rock input: 0.626 mt/mt of SSP (Mudahar and Hignett, 1987a).
[b] Process energy of 0.41 GJ/mt of SSP in the form of electricity is assumed (Mudahar and Hignett, 1987a).

Potash Fertilizers

Muriate of Potash

Mudahar and Hignett (1987a) reported that over 95 percent of the commercially available potash fertilizers are in the form of muriate of potash or potassium chloride (KCl), which is 60 percent K_2O. Most commonly, potassium chloride is manufactured by first mining naturally available potash ore through a process called shaft mining, and later beneficiating the ore through crushing, followed by flotation and drying. Granulation will be done as required. The potash is sold in standard, coarse and granular forms. The latest year for which the energy requirement of muriate of potash is available for is 1985. Between 1979 and 1985, its energy requirement has increased. This is because energy use in mining potash ore increases as the depth of the mine increases and as the grade of ore decreases. Table 13 presents the energy estimates of muriate of potash for different years. The breakdown of energy by fuel type is reported for only 1979 and the same proportions of fuel types are used for later years. A metric tonne of muriate of potash required 2.88 GJ of energy in the form of natural gas and electricity.

Table 13 **Average energy consumption in the preparation of Muriate of Potash in 1979, 1983 and 1985.**

	Natural Gas	Electricity	Fuel Oil	Imported Steam	Exported Steam[a]	Total
	GJ/mt					
1979	1.42	1.12	0.00			2.54
1983[a]	1.66	1.30	0.00			2.96
1985[a]	1.61	1.27	0.00			2.88

[a] The energy breakdown by fuel type for 1983 and 1985 is based on the fuel type proportions for 1979.

Mixed Fertilizers

Nitrogen Phosphates

Nitrogen phosphate fertilizers have become popular in the last decade. Diammonium phosphate (DAP) and monoammonium phosphate (MAP) are the most commonly used nitrophosphates. Phosphoric acid and ammonia are mixed together at a suitable proportion in order to obtain the desired concentration of nitrogen and phosphorous. Then the mixture is dried and screened to obtain desired particle size. Diammonium phosphate has nutrient concentrations of 18-46-0 ($\%N-\%P_2O_5-\%K_2O$) and most monoammonium phosphate fertilizers have concentrations of 11-54-0. Both these fertilizers are produced through slurry processes.

Since ammonia is a major ingredient in nitrophosphate fertilizers, a large portion of the energy requirements of these fertilizers are in the form of natural gas. The total energy needs, which are estimated to be 7.93 GJ/mt for monoammonium phosphate and 11.43 GJ/mt for diammonium phosphate, may vary slightly depending on the type of process adopted for producing phosphoric acid (Table 14).

Table 14 **Average energy consumption in the preparation of DAP and MAP fertilizers in 1987.**

	Natural Gas	Electricity	Fuel Oil	Imported Steam	Exported Steam[a]	Total
	GJ/mt					
MAP:						
Phosphoric acid[a]	0.16	2.60	0.11	2.38	(3.71)	1.55
Ammonia[b]	5.54	0.15			(0.05)	5.64
Processing	0.14	0.34	0.01	0.26		0.74
Total	5.84	3.09	0.12	2.64	(3.76)	7.93
DAP:						
Phosphoric acid[c]	0.14	2.22	0.09	2.03	(3.16)	1.32
Ammonia[d]	9.05	0.24			(0.08)	9.21
Processing	0.16	0.36	0.07	0.30		0.89
Total	9.35	2.83	0.17	2.32	(3.24)	11.43

[a] TSP grade phosphoric acid input: 1.299 mt/mt of MAP (Mudahar and Hignett, 1987a). For example, the total energy consumption of 1.55 GJ in the form of PA for MAP is obtained by multiplying 1.299 mt of PA by 2.85 GJ/mt of PA times 0.42.

[b] Ammonia input: 0.166 mt/mt of MAP (Mudahar and Hignett, 1987a).

[c] TSP grade phosphoric acid input: 1.106 mt/mt of DAP (Mudahar and Hignett, 1987a). For example, the total energy consumption of 1.32 GJ in the form of PA for MAP is obtained by multiplying 1.106 mt of PA by 2.85 GJ/mt of PA times 0.42.

[d] Ammonia input: 0.222 mt/mt of DAP (Mudahar and Hignett, 1987a).

Compound Fertilizers

Compound fertilizers are obtained by direct mixing of two or more straight fertilizers at the desired proportion. These fertilizers are available as granular mixtures, bulk blends or fluid mixtures. However, granular and mixed fluid forms are more common. From the TFI survey report, it is observed that energy required for granular and fluid mixtures over and above the energy required for the constituent fertilizers are 1.29 GJ/mt and 0.15 GJ/mt, respectively. The U.S. consumption figures for these fertilizers are not available. Thus the additional energy required of compound fertilizers is not considered in the final analysis.

Energy Consumption of Primary Plant Nutrients

After estimating the energy requirements of individual fertilizers supplying the primary plant nutrients, an estimate of the weighted average energy requirements of constituent nutrients is derived. While nitrogen and phosphorous are available in different fertilizers types, potash is mainly supplied in the form of muriate of potash. In order to compute the unit energy requirements of nitrogen and phosphorous, the annual average of U.S. consumption of different fertilizers from 1981 to 1987 are used as weights.

The energy consumptions of two major mixed fertilizers, DAP and MAP, are apportioned between nitrogen and phosphorous. The energy consumptions of DAP and MAP in the form of phosphoric acids are charged to phosphorous, and that in the form of ammonia to nitrogen. The nutrient concentration of most DAP fertilizers is 18-46-0, i.e. nitrogen and phosphorous are in the ratio of 28 percent and 72 percent, respectively. Therefore, 28 percent of the process energy consumption of DAP is charged to nitrogen fertilizers and 72 percent to phosphorous fertilizers. Similarly, the nutrient concentration of MAP fertilizers is 11-54-0, and thus, 17 percent of its process energy is charged to nitrogen fertilizers and 83 percent to phosphorous fertilizers. Table 15 provides the estimates of energy apportionments of DAP and MAP between the two major nutrients.

Table 15 **Apportionment of total energy requirements of DAP and MAP fertilizers between nitrogen and phosphorous.**[a]

	Natural Gas	Electricity	Fuel Oil	Imported Steam	Exported Steam[a]	Total
	GJ/mt					
MAP:	5.84	3.09	0.12	2.64	(3.76)	7.93
Nitrogen	5.57	0.21		0.04	(0.05)	5.77
Phosphorous	0.28	2.88	0.12	2.60	(3.71)	2.17
DAP:	9.35	2.83	0.17	2.32	(3.24)	11.43
Nitrogen	9.10	0.35	0.02	0.08	(0.08)	9.46
Phosphorous	0.25	2.48	0.15	2.24	(3.16)	1.97

[a] The entire energy consumed of DAP and MAP in the form of ammonia is charged to nitrogen and that in the form of PA to phosphorous. The process energy of both the fertilizers is apportioned between the two nutrients based on their respective proportions in the parent fertilizers.

Weighted average energy requirements of nitrogen and phosphorous nutrients are estimated in Table 16. First, the unit energy requirements of all the individual fertilizers are multiplied with the quantities of respective fertilizers consumed which gives the total energy invested in the production of each fertilizers. For example, total energy requirements of all the fertilizers are summed to obtain the gross energy consumption (4.976×10^8 GJ) in supply of nitrogen. Then, the gross quantity of nitrogen supplied by all the nitrogenous fertilizers under study is calculated as 8969 thousand mt. The gross energy requirement is divided by the gross nutrient supply to obtain unit energy requirement of a nutrient. The same procedure is followed to calculate the unit energy requirements by source (i.e., natural gas, electricity, etc.) of individual nutrients.

Table 16 The unit energy requirements of nitrogen, phosphorous and potash nutrients in 1987.

Fertilizers	Natural Gas	Electricity	Fuel Oil	Steam	Exported Steam	Total Unit Energy	Nutrient Energy	Total Fertilizer	Total Nutrient	Total Energy
	---------- GJ/mt of fertilizer ----------						GJ/mt of nutrient	000's mt	000's mt	000's GJ
Ammonia	40.79	1.10			(0.38)	41.49	50.60	4921	4035	204182
Urea	26.02	2.55		3.70	(0.81)	31.46	68.41	2431	1118	76481
Ammonium Nitrate	18.50	1.78		2.39	(1.82)	20.85	61.33	2009	683	41888
UAN	16.11	1.02		0.63	(0.37)	17.38	57.94	6582	1975	114425
Ammonium Sulfate	10.48	0.87			(0.10)	11.25	53.65	663	139	7458
Other fertilizers	22.38	1.47		1.34	(0.70)	24.49	51.02	470	225	11503
DAP	9.10	0.35	0.02	0.08	(0.08)	9.46	52.60	3025	544	28615
MAP	5.57	0.21	0.00	0.04	(0.05)	5.77	52.48	2266	249	13068
Total									8969	497620
Weighted Average of N	51.81	2.76	0.01	2.11	(1.20)		55.48			
SSP	0.18	0.90	0.07			1.15	5.27	69	15	79
TSP	0.54	2.51	0.55	1.89	(2.35)	3.14	6.82	721	332	2264
DAP	0.26	2.48	0.15	2.24	(3.16)	1.97	4.28	3025	1391	5949
MAP	0.28	2.88	0.12	2.60	(3.71)	2.17	4.01	2266	1223	4908
Others	0.51	2.39	0.51	1.73	(2.16)	2.98	6.76	204	90	608
Total									3052	13808
Weighted Average of P_2O_5	0.63	5.37	0.40	4.71	(6.58)		4.52			
Muriate of Potash[a]	1.61	1.27	0.00			2.88				
Potash as K_2O[b]	2.69	2.11	0.00				4.80			

[a] Estimates are for 1985.

[b] Potash is assumed to be supplied only in the form of muriate of potash with 60 percent K_2O.

The weighted average energy use for nitrogen is estimated at 55.48 GJ/mt of N. Natural gas is the single largest energy input into nitrogen fertilizers, accounting for 93 percent of the total requirement. Electricity and steam will account for, respectively, 4.97 percent, and 3.80 percent of the total nitrogen's energy requirement. An average steam energy of 1.20 GJ/mt is released mainly in urea and ammonium nitrate synthesis which is available for export to other plants. This surplus energy is credited to nitrogen.

The average energy requirement of phosphorous is estimated to be 4.52 GJ/mt of P_2O_5 (Table 16). The main forms of energy that are consumed in the supply of phosphorous are electricity (5.37 GJ/mt) and imported steam (4.71 GJ/mt). However, more than 50 percent of this energy requirement is compensated for by surplus steam energy released in the production of sulfuric acid (6.58 GJ/mt).

From the latest available TFI survey data on muriate of potash, the unit energy requirement of potash element is estimated at 4.80 GJ/mt of K_2O (Table 16). The main forms of energy used are natural gas (2.69 GJ/mt) and electricity (2.11 GJ/mt).

Energy Consumption in Packaging, Transportation and Application

A significant amount of energy is required to pack, transport and finally apply the fertilizers to plants. The energy required for these purposes will depend upon the physical nature of the fertilizers, bagging operation, distance between production plants and farmlands, and type of technology for fertilizer application. The latest available energy estimates for these operations come from Mudahar and Hignett (1981, 1982), and it is assumed that the technology of packaging, transportation and application has not changed much during the last decade (Table 17).

The energy estimates for transportation include transportation of raw material, intermediate products and final products. The total energy requirements of all the three operations is estimated to be 8.60, 9.80 and 7.30 GJ/mt for nitrogen, phosphorous and potash fertilizers, respectively. The energy requirements of phosphorous and potash fertilizers for the above three post-production operations are relatively high when compared to their respective production energy consumption (4.52 GJ/mt and 4.80 GJ/mt).

Table 17 **The energy consumed for packaging, transportation and application (PTA) of primary plant nutrients, 1981.**

Activity	Energy Consumption		
	Nitrogen (N)	Phosphorous (P_2O_5)	Potash (K_2O)
	------------------------ GJ/mt ------------------------		
Packaging	2.58	2.65	1.75
Transportation	4.47	5.68	4.60
Application	1.55	1.47	0.95
Total PTA	8.60	9.80	7.30

Source: Mudahar and Hignett (1981); Mudahar and Hignett (1982).

Temporal Comparison of Fertilizer Energy Consumption

The comparison of total energy utilization in the production of the primary plant nutrients over the period 1979-87 is presented in Table 18. The unit nutrient energy requirements for 1979 and 1983 also are reestimated using TFI survey data for these earlier years, and used in this comparison. Mudahar and Hignett (1987a, 1987b) also reported energy requirements of major fertilizers and their constituent nutrients for 1979 and 1983, but these estimates appeared to be either overestimated or underestimated for two reasons. First, their estimates were based on the

Table 18 The energy consumed in the production, and packaging, transportation and application (PTA) of primary plant nutrients in years 1979, 1983 and 1987.

Fertilizers Nutrients	1979			1983			1987		
	Production[a]	PTA[b]	Total	Production[a]	PTA[b]	Total	Production	PTA[b]	Total
	----------	----------	----------	----------	GJ/mt	----------	----------	----------	----------
Nitrogen (N)	63.48	8.60	72.08	60.96	8.60	69.56	55.48	8.60	64.08
Phosphorous (P_2O_5)	9.81	9.80	19.61	4.83	9.80	14.63	4.52	9.80	14.32
Potash (K_2O_5)	4.24	7.30	11.54	4.94	7.30	12.24	4.80	7.30	12.10

[a] Energy estimates of nitrogen and phosphorous production for 1979 and 1983 were developed using the TFI survey data of the respective years, and the same procedure followed in this study for developing 1987 energy estimates was used in developing these estimates, except the following difference:

> For 1979, 69% of the phosphoric acid was assumed to be produced through dihydrate dry-rock-feed method, and 31% through dihydrate wet-rock-feed method. For 1983, 25% of the phosphoric acid was assumed to be produced through dihydrate dry-rock-feed method, 67.5% through dihydrate wet-rock-feed method and 7.5% through hemihydrate wet-rock-feed method.

[b] Energy consumption for PTA is assumed constant during the study period.

assumption that all phosphoric acids were manufactured through the dry-rock-fed dihydrate method (Mudahar and Hignett, 1987b, p. 147) which was not actually true. The TFI survey indicated that 31 percent of the sample manufacturers in 1979 and 75 percent in 1984 (the breakup for 1983 was not available) used wet-rock-feed methods. Second; they may not have properly apportioned the energy requirements of mixed fertilizers between the constituent nutrients.

The energy consumed for packaging, transporting and application is assumed unchanged over this period. The total energy consumed for nitrogen fertilizers declined substantially -- from 72.08 GJ/mt to 64.08 GJ/mt, or a reduction of 11.11 percent from 1979 to 1987. Similarly, the energy requirements of phosphorous fertilizers decreased substantially over the same period -- 19.61 to 14.32 GJ/mt, or a reduction of 27.04 percent. However, energy requirement of potash fertilizers slightly increased over the years -- 11.54 to 12.10 GJ/mt, or an increase of 4.84 percent from 1979 to 1985. During the period 1983-87, nitrogen energy use declined steadily, but that for phosphorous fertilizers stayed almost the same. This supports the view that the technological advancement and adoption of energy-efficient production practices during the 80s resulted in a substantial energy saving especially in the production of nitrogenous and phosphorous fertilizers. Since the average energy requirement of nitrogen fertilizers are significantly higher than that of phosphorous and potash fertilizers, even a small percent change in its energy use will significantly reduce the total energy consumed by the fertilizer industries.

III. ENERGY CONSUMPTION IN MANUFACTURING PESTICIDES

Pesticides include herbicides, insecticides, and fungicides. Most modern pesticides are manufactured entirely from intermediates derived from fossil fuels (petroleum or natural gas). The manufacturing process involves a series of chemical reactions such as heating, stirring, distilling, filtering, drying and similar processes. Pesticides are formulated as active ingredients before finally being packed for commercial release. Three are three common formulations of pesticides: emulsifiable oils, wettable powders and granules.

Pesticide production requires both indirect and direct energy. Indirect energy is the sum of energies embodied in all the intermediates derived from natural sources which will go into production of pesticides. The direct energy requirement is the energy consumed in all the operations involved in processing final product of a given pesticide. The procedure for estimating energy requirements of pesticides is outlined by Green (1987). From an extensive literature search, it appears that Green's estimates of pesticide energy uses are the most recent and reliable.

Green's estimates of energy consumption are based on the procedure that follows. First, the amounts of intermediate products like ethylene, propylene or methane required to produce a tonne of a certain chemical are calculated. Then the amounts of raw material such as natural gas and crude oil to produce these amounts of ethylene, propylene or methane are determined. Finally, energy equivalents of these raw materials are calculated using routine conversion standards to determine the indirect energy requirements of end product. Direct energy inputs in the manufacture of pesticides are estimated from the amounts of fuel oil, electricity and steam used in the various manufacturing operations. Precise estimates can be attained only if the material and operations flow charts for all the pesticides are available. Much of this information is under patent and hence, is not readily available. In these circumstances, a best estimate for certain pesticides will have to be made based on other pesticides of similar chemical structure for which information is published.

For the purpose of this analysis, we concentrate on those pesticides which are most commonly used in the major US field crops for the purpose of this analysis. Table 17 presents quantities of various pesticides consumed the in US in 1990. The energy requirements of all these pesticides are not readily available. The weed scientist at the Department of Plant and Soil Sciences, University of Tennessee was consulted to identify the pesticides and group them based on their chemical structure.[3] The pesticides of similar chemical structure and for which energy use estimates were available in Green (1987) were used as proxy for those pesticides for which energy use estimates were not available.

Given the energy requirements of all the individual pesticides and their quantities consumed, the weighted average energy consumptions of herbicides, insecticides and fungicides are estimated by dividing the gross sum of energy consumed by all the pesticides by gross total active ingredients consumed. Thus, the unit energy consumed in producing active ingredients of herbicides, insecticides and fungicides are calculated as in GJ/mt 214.93, 245.06 and 356.39, respectively (see Table 19). Note that over 90 percent of the energy used to produce pesticides is for herbicides.

The above active ingredients will be formulated into usable forms before releasing into market. Pesticides are formulated into three common types: emulsifiable oils, wettable powders and granules. Green estimated that formulation into emulsifiable oil, wettable powder and granules requires an additional energy of 20, 30 and 10 GJ/mt, respectively. Further, additional energy is required for packaging and distribution. Green also estimated that packaging formulated pesticides into cans or bags requires an amount of 2 GJ/mt of energy whereas transportation energy depends on the distance pesticides are distributed. If the pesticides are domestically produced and used, distribution energy is estimated to 1 GJ/mt (Green, 1987). On the other hand, if the same is imported from other countries, distribution energy could add up to 5 GJ/mt.

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[3] Dr. W. A. Krueger, Associate Professor, Plant and Soil Science Department, The University of Tennessee, Knoxville, TN.

Table 19 Energy requirements of active ingredients (a.i.) of commonly used pesticides for major US field crops, 1990.

Pesticide	Unit Energy	Total Pesticide	Total Energy
	GJ/mt of a.i.	mt of a.i.	GJ
Herbicides:			
Metolachlor	276	16298	4498216
Norflurazon[a]	150	503	75508
Glyphosate	454	1208	548282
Bromoxynil[a]	150	704	105643
Propanil	220	29718	6538028
Bentazon	434	2808	1218506
Dicamba	295	2235	659414
2,4-D	85	4390	373178
MCPA	130	934	121388
Trifluralin	150	9966	1494917
Cyanazine	201	11174	2246022
Methazole[a]	150	133	19931
EPTC	160	13868	2218957
Molinate[a]	150	1095	164280
Pendimethalin[a]	150	3763	564403
Butylate	141	6431	906783
Alachlor	278	22999	6393792
Isopropalin[a]	150	477	71494
Fluazifop-Methyl	518	215	111349
Chlorsulfuron	365	33	119178
Metribuzin[a]	200	1619	323708
Atrazine	190	26360	5008341
Prometryn[a]	200	668	133601
Diuron	200	259	51880
Linuron	290	922	267239
Total		158780	34126781
Average herbicide energy (GJ/mt) of a.i.			214.93

[a] Unit energy requirements of these pesticides are developed based on our consultation with the weed scientist at The University of Tennessee's Plant and Soil Science Department, and energy requirements of pesticides of similar chemical structure reported in Green (1987).

Table 19, cont. **Energy requirements of active ingredients (a.i.) of commonly used pesticides for major US field crops, 1990.**

Pesticide	Unit Energy Requirement	Total Pesticide	Total Energy
	GJ/mt of a.i.	mt of a.i.	GJ
Insecticides:			
Chlofpyrifos[a]	250	2559	639662
Fonofos[a]	200	1280	256046
Fensulfothion[a]	200	10	1995
Terbufos[a]	200	4640	928042
Carbofuran	454	1219	553224
Total		9708	2378969
Average insecticide energy (GJ/mt) of a.i.			**245.06**
Fungicides:			
Benomyl	397	37	14583
Fluometuron	355	1075	381552
Total		1112	396135
Average fungicide energy (GJ/mt) of a.i.			**356.39**

[a] Unit energy requirements of these pesticides are developed based on our consultation with the weed scientist at The University of Tennessee's Plant and Soil Science Department, and energy requirements of pesticides of similar chemical structure reported in Green (1987).

IV. ENERGY-SAVING INNOVATION IN FERTILIZER SECTOR: CONTRIBUTION TO U.S. CROP SECTOR

As mentioned earlier, energy-saving technology adopted by the fertilizer industry has resulted in substantial reductions in energy requirements of several fertilizers. An interesting question that arises is how individual crops have gained over years from the energy-innovation that occurred in the fertilizer industry. Fertilizer energy use of an individual crop depends on two factors: energy inputs for fertilizer production and fertilizer use rates, which itself is governed by a host of technological and economic forces within the agricultural industry. Without getting into the details of techno-economic changes in the agricultural sector, estimates of the overall benefit that the fertilizer industry contributed to the crop sector over a period of time can be attained.

Define fertilizer energy consumption per unit area of a given crop as Z [GJ/hectare (ha)], which is fertilizer use rate F (mt/ha) times unit fertilizer energy use rate E (GJ/mt). Symbolically,

$$Z = F \cdot E.$$

Taking the total derivative of the above expression, we have:

$$dZ = E \cdot dF + F \cdot dE.$$

Further, expressing the total derivatives on both sides by their respective total differences, we can approximate the above expression by

$$\Delta Z = E \cdot \Delta F + F \cdot \Delta E.$$

The term on the left hand side ΔZ is the actual change in per unit area energy consumption. The first term on the right hand side can be interpreted as the change in fertilizer energy requirement due to a change in fertilizer use rate ΔF. The second term represents the savings in energy requirement attributed to technological change in the fertilizer sector. The three total difference terms, ΔZ, ΔF, and ΔE, can be computed by subtracting the quantities of respective variables for a given second period from the quantities of respective variables for a given first period. The second term on the right hand side $F \cdot \Delta E$ when positive can be interpreted as the total benefit contributed by the fertilizer sector to a given crop sector. Thus, the change in actual fertilizer energy consumption by crop is decomposed into two sources: techno-economic changes in the crop sector and innovation in the fertilizer sector. Re-arranging the above expression, we can approximately compute the real innovation-related change in crop's fertilizer energy requirement ($F \cdot \Delta E$) as:

$$F \cdot \Delta E \approx \Delta Z - E \cdot \Delta F.$$

When there is a reduction in energy consumption rate E, depending on the sign of ΔF, the real energy saving $F \cdot \Delta E$ can be greater or less than the actual energy saving ΔZ. For instance, there is an increase in F over two points in time (ΔF is negative), then the real energy-saving benefit enjoyed by crop farmers will be more than the actual energy saving.

The above analysis is conducted for four major U.S. crops at three time points 1979, 1983 and 1987. The changes in per hectare real and actual energy consumed for these crops in the form of three major nutrients over the period between 1979 and 1983, and the period between 1979 and 1987 are computed. The per hectare total energy consumption on all the three nutrients (as a direct sum of energy consumptions of three individual nutrients), and its change over time also are computed for all the study crops. The results of this analysis are presented in Table 20 and Figure 2.

Producers of all the four crops have gained real energy-saving benefits in terms of nitrogen and phosphorous individually, and all the three nutrients together during the study periods. Only in the case of potash has there been an increase in real energy consumed, in percent of 6.45, 7.91, 5.21, and 8.18 during 1979-83, and 4.44, 5.77, 3.90, and 4.16 during 1979-87 for corn, cotton, soybean, and wheat, respectively.

Table 20 The contribution of energy-efficient technical change in fertilizer industry to major US crops during 1979-83 and 1979-87.

	Units	Nitrogen (N)				Phosphorous (P_2O_5)			
		Corn	Cotton	Soybean	Wheat	Corn	Cotton	Soybean	Wheat
1979									
Nutrient application rate (*F*)	mt/ha	0.163	0.062	0.005	0.045	0.077	0.029	0.020	0.021
Nutrient energy (*E*)	GJ/mt	72.08	72.08	72.08	72.08	19.61	19.61	19.61	19.61
Crop Nutrient Energy (*Z*)	GJ/ha	11.76	4.44	0.34	3.24	1.51	0.57	0.39	0.42
1983									
Nutrient application rate (*F*)	mt/ha	0.172	0.067	0.004	0.060	0.074	0.024	0.015	0.026
Nutrient energy (*E*)	GJ/mt	69.56	69.56	69.56	69.56	14.63	14.63	14.63	14.63
Crop nutrient Energy (*Z*)	GJ/ha	11.98	4.66	0.29	4.19	1.08	0.35	0.22	0.38
Actual savings in crop nutrient energy[a] (ΔZ)	GJ/ha	-0.22 (-1.86)	-0.22 (-4.85)	0.05 (16.10)	-0.95 (-29.36)	0.44 (28.90)	0.22 (38.85)	0.16 (42.17)	0.04 (9.11)
Real savings in crop nutrient energy[a] ($F \cdot \Delta E$)	GJ/ha	0.43 (3.69)	0.17 (3.80)	0.01 (3.04)	0.15 (4.69)	0.37 (24.29)	0.12 (20.89)	0.08 (19.75)	0.13 (31.05)
1987									
Nutrient application rate (*F*)	mt/ha	0.157	0.073	0.003	0.065	0.063	0.023	0.013	0.023
Nutrient energy (*E*)	GJ/mt	64.08	64.08	64.08	64.08	14.32	14.32	14.32	14.32
Crop nutrient Energy (*Z*)	GJ/ha	10.12	4.65	0.22	4.19	0.90	0.32	0.19	0.33
Actual savings in crop nutrient energy[a] (ΔZ)	GJ/ha	1.64 (13.97)	-0.21 (-4.64)	0.12 (35.81)	-0.95 (-29.45)	0.61 (40.47)	0.25 (43.97)	0.20 (50.90)	0.09 (21.31)
Real savings in crop nutrient energy[a] ($F \cdot \Delta E$)	GJ/ha	1.26 (10.74)	0.58 (13.07)	0.03 (8.02)	0.52 (16.16)	0.33 (22.07)	0.12 (20.77)	0.07 (18.20)	0.12 (29.17)

[a] Numbers in parentheses indicate percent values. Changes are calculated with respect to 1979 values.
[b] The total figures may not add up to sum of individual nutrients due to rounding.

Table 20, cont. The contribution of energy-efficient technical change in fertilizer industry to major US crops during 1979-83 and 1979-87.

	Units	Potash (K_2O)				Total[b]			
		Corn	Cotton	Soybean	Wheat	Corn	Cotton	Soybean	Wheat
1979									
Nutrient application rate (*F*)	mt/ha	0.087	0.015	0.030	0.010				
Nutrient energy (*E*)	GJ/mt	11.54	11.54	11.54	11.54				
Crop Nutrient Energy (*Z*)	GJ/ha	1.00	0.17	0.34	0.11	14.28	5.19	1.07	3.77
1983									
Nutrient application rate (*F*)	mt/ha	0.092	0.019	0.026	0.013				
Nutrient energy (*E*)	GJ/mt	12.24	12.24	12.24	12.24				
Crop nutrient Energy (*Z*)	GJ/ha	1.13	0.23	0.31	0.16	14.19	5.24	0.85	4.73
Actual savings in crop nutrient energy[a] (ΔZ)	GJ/ha	-0.13 (-12.98)	-0.06 (-38.47)	0.03 (8.67)	-0.05 (-43.26)	0.09 (0.62)	-0.06 (-1.10)	0.25 (23.17)	0.96 (25.51)
Real savings in crop nutrient energy[a] ($F \cdot \Delta E$)	GJ/ha	-0.06 (-6.45)	-0.01 (-7.91)	-0.02 (-5.21)	-0.01 (-8.18)	0.74 (5.16)	0.28 (5.31)	0.07 (6.45)	0.27 (7.22)
1987									
Nutrient application rate (*F*)	mt/ha	0.079	0.017	0.024	0.009				
Nutrient energy (*E*)	GJ/mt	12.10	12.10	12.10	12.10				
Crop nutrient Energy (*Z*)	GJ/ha	0.96	0.21	0.29	0.10	11.98	5.18	0.70	4.62
Actual savings in crop nutrient energy[a] (ΔZ)	GJ/ha	0.04 (3.97)	-0.04 (-24.78)	0.05 (15.63)	0.01 (9.97)	2.20 (16.08)	0.005 (0.09)	0.37 (34.81)	-0.85 (-22.62)
Real savings in crop nutrient energy[a] ($F \cdot \Delta E$)	GJ/ha	-0.04 (-4.44)	-0.01 (-5.77)	-0.01 (-3.90)	-0.005 (-4.16)	1.55 (10.88)	0.69 (13.31)	0.08 (7.89)	0.64 (16.99)

[a] Numbers in parentheses indicate percent values. Changes are calculated with respect to 1979 values.
[b] The total figures may not add up to sum of individual nutrients due to rounding.

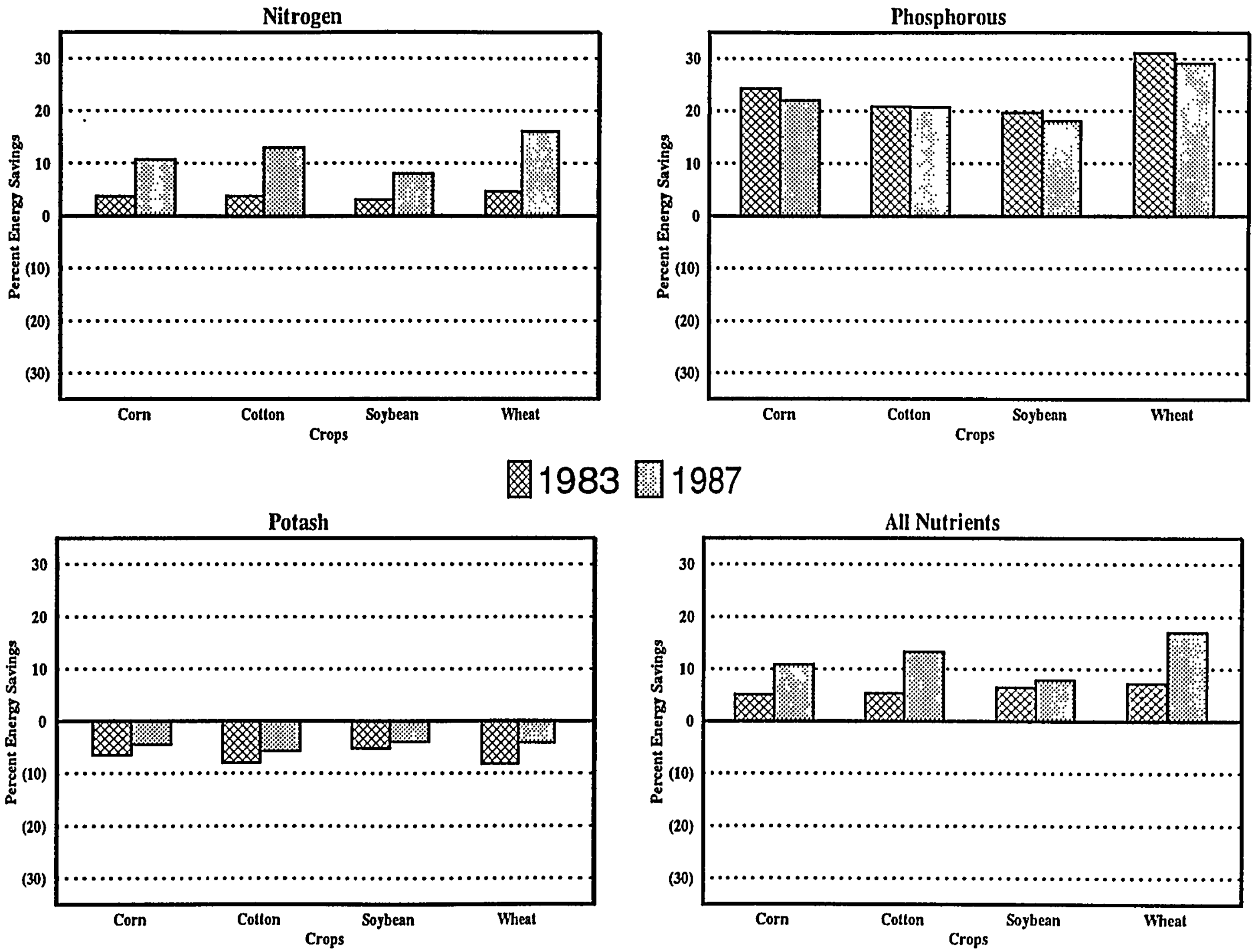

Figure 2 The real savings in nutrient energy requirements of major U.S. crops during 1979-83 and 1979-87.

For nitrogen, real energy savings exceeded the actual energy savings in most cases during the 1979-83 period and for cotton and wheat during the 1979-87 period. As mentioned earlier, this occurred because of a simultaneous increase in fertilizer use rate and decrease in unit nitrogen energy coefficient. For phosphorous, real energy savings are estimated to be less than the actual energy savings in all crops except wheat as fertilizer use rates also have decreased over the study period for these crops. In the case of potash a mixed result can be seen. Overall, the totals of real energy savings on all the three nutrients have been less than the total actual savings in the cases of corn and soybean.

The real energy savings (or the energy savings attributed to innovation in the fertilizer sector) in the form of nitrogen energy for corn, cotton and wheat (in GJ/ha 1.26, 0.58, 0.52 during 1979-87, respectively) could be regarded as a significant achievement particularly from environmental and resource scarcity points of view. Nitrogen energy savings especially of corn and wheat resulted in a substantial energy saving at the national level since these two crops were the leading crops in terms of harvested acres in 1987 (26.8 and 26.6 million ha, respectively). As noted earlier, every metric tonne of fertilizer nitrogen requires 51.81 GJ of energy in the form of natural gas, which is 80.9 percent of nitrogen's total energy requirement (64.08 GJ/mt). Use of natural gas is estimated to release 13.78 kg of carbon/GJ to atmosphere (Marland, 1983). Thus, the above noted energy savings on nitrogen for corn and wheat would translate into total reductions of 0.376 and 0.154 million tonnes of carbon release into the atmosphere. This also means a sizable reduction in dependence on fossil sources.

V. SUMMARY AND CONCLUSION

Agricultural chemicals that are derived from fossil-fuels are major energy intensive inputs in agriculture. Economic pressures on the agricultural sector, the growing scarcity of world's fossil resources and the environmental consequences of agricultural chemical use stimulated research and development of technology in manufacturing, distribution, and application of these chemicals that is more energy efficient. Consequently, the fertilizer industry has undergone a major technological advancement in the last decade. This study revisited the energy requirements of major plant nutrients and pesticides. In the case of fertilizers, the manufacturers' energy survey report supplied by The Fertilizer Institute was the chief source of information. Energy estimates for pesticides are made from consulting previously published literature. The study also estimated the contribution of technical innovation in fertilizer industry to US crop sector in terms of energy-saving.

The weighted average energy uses in production of nitrogen and phosphorous nutrients using 1987 technology were in GJ/mt 55.48 and 4.52, respectively. Using 1985 technology, energy requirement of potash was 4.80 GJ/mt. The total energy needs of nitrogen, phosphorous and potash for production, packaging, transportation and application are estimated to be 64.08, 14.32 and 12.10 GJ/mt, respectively. Energy requirements for nitrogen and phosphorous nutrients have substantially declined over the period from 1979 to 1987. Because the average energy requirement and plant application rate of nitrogen are significantly higher than those of phosphorous and potash, even a small reduction in its energy use will have substantial impact on agriculture's dependence on non-renewable fossil resources. More than 80 percent of nitrogen's energy requirements is in the form of natural gas. Unit energy consumption in producing active ingredients of major US herbicides, insecticides, and fungicides were in GJ/mt 214.93, 245.06 and 356.39, respectively.

As a result of energy-efficient technical change in fertilizer industry, producers of major US crops have gained real energy-saving benefits in terms of nitrogen and phosphorous individually, and all the three nutrients together during the period 1979-87. Only in case of potash, there has been an increase in real energy consumed (in percent of 6.45, 7.91, 5.21, and 8.18 during 1979-83, and 4.44, 5.77, 3.90, and 4.16 during 1979-87 for corn, cotton, soybean, and wheat, respectively).

In an absolute sense, there were significant real energy savings in the form of nitrogen on corn, cotton and wheat (in GJ/ha 1.26, 0.58, 0.52 during 1979-87, respectively). This is a significant achievement particularly from environmental and resource scarcity points of view. Energy saving on nitrogen especially for corn and wheat translated into substantial energy savings at the national level since these two crops topped in terms of hectarage planted in 1987 (26.2 and 25.2 million ha, respectively). These energy savings on nitrogen for corn and wheat have resulted in a substantial reduction in not only dependence on fossil sources but also in greenhouse gas emissions (by an estimated reduction of 0.376 and 0.154 million tonnes of carbon release into the atmosphere, respectively).

Although the results of this study indicate that substantial energy efficiency is achieved in manufacturing agricultural chemicals, further investigation is needed on the economic cost of achieving such efficiency. As Mudahar and Hignett (1987b, p. 154) state, *saving energy for the sake of saving it does not provide a very strong economic justification for large capital investments*. Energy-saving innovations most likely have economic implications on capital investment, level of employment, skilled man-power requirements, and need for viable disposal of excess steam energy released from energy-efficient plants. Marginal costs of capital and labor adjustments associated with such innovations have to be compared with short-term and long-term marginal benefits of energy-saving.

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