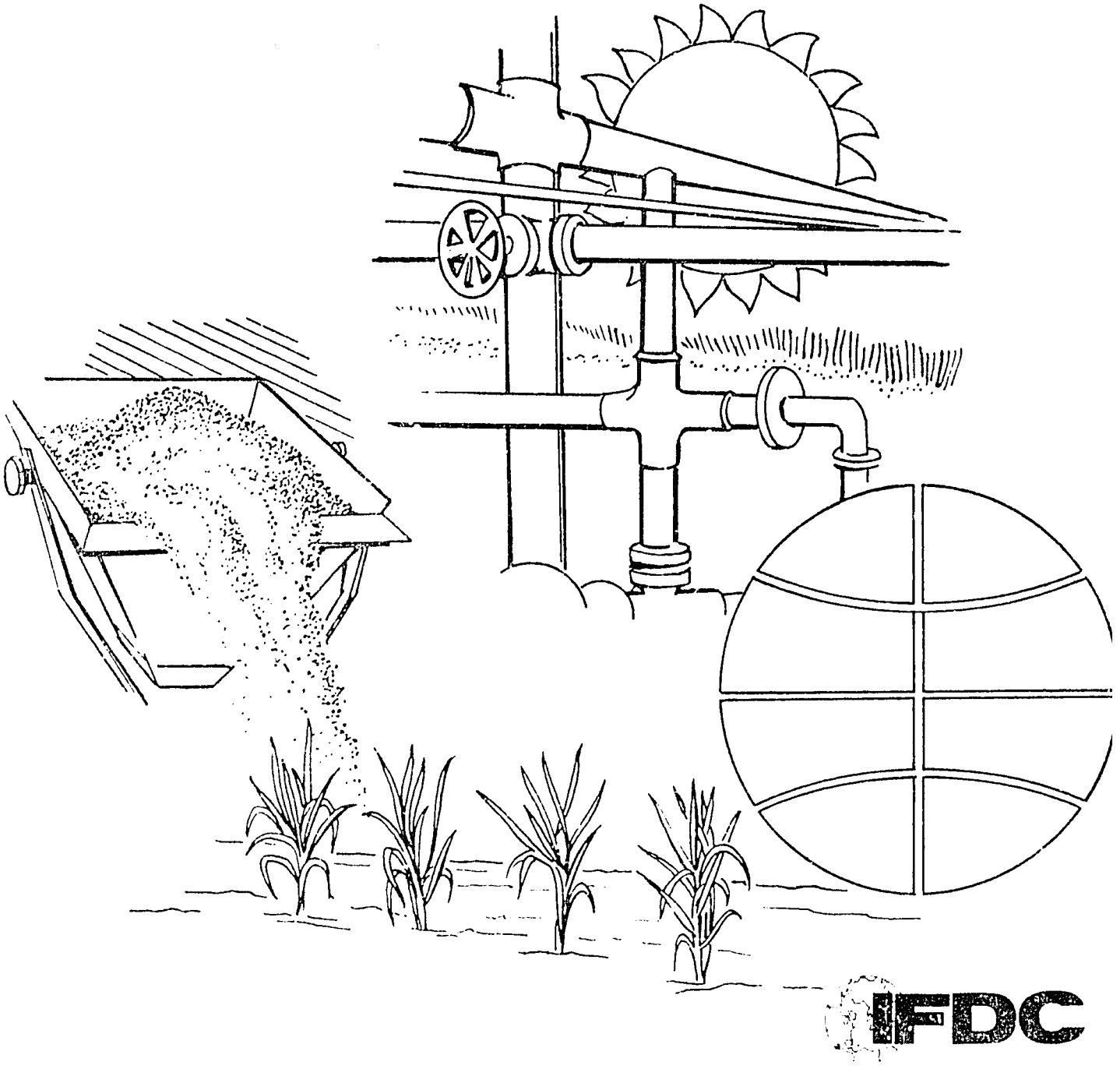
ENERGY AND FERTILIZER

POLICY IMPLICATIONS AND OPTIONS FOR DEVELOPING COUNTRIES



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ABSTRACT

This study deals with economic and technical analysis of the linkages among energy, fertilizer, and agricultural sectors. The main objectives of the study are to estimate energy requirements for fertilizer manufacturing, packaging, transportation, and application; to evaluate the policy implications of energy supply and prices on fertilizer production, distribution, and prices; and to evaluate policy options to reduce the adverse impact of energy supply and prices on fertilizer and agricultural sectors.

Even though the focus of the study is developing countries, policymakers, planners, and researchers dealing with different aspects of fertilizer sector planning around the world will find it useful. The major emphasis of the study is on nitrogen fertilizers which are not only highly energy intensive but are the most popular among developing countries. However, the fertilizer sector accounts for only a small percentage of total energy use. Technical Bulletin No. 19, which was issued as the "Executive Brief," provides highlights of the study.

The most promising means for saving fertilizer energy is more efficient use of fertilizer at the farm level. In fertilizer manufacturing, the greatest energy saving is likely to come from operating existing plants more efficiently. Many energy-efficient innovations are available which together promise potentially large savings in fertilizer manufacture. The potential for energy saving in fertilizer distribution is likely to be small in the short run and should be approached with caution.

The national governments must take the lead in promoting energy-efficient manufacture, distribution, and use of fertilizer. The international organizations can play a crucial role in facilitating the formulation and successful implementation of such national programs.

Keywords: energy, fertilizer, agriculture, developing countries, public policy

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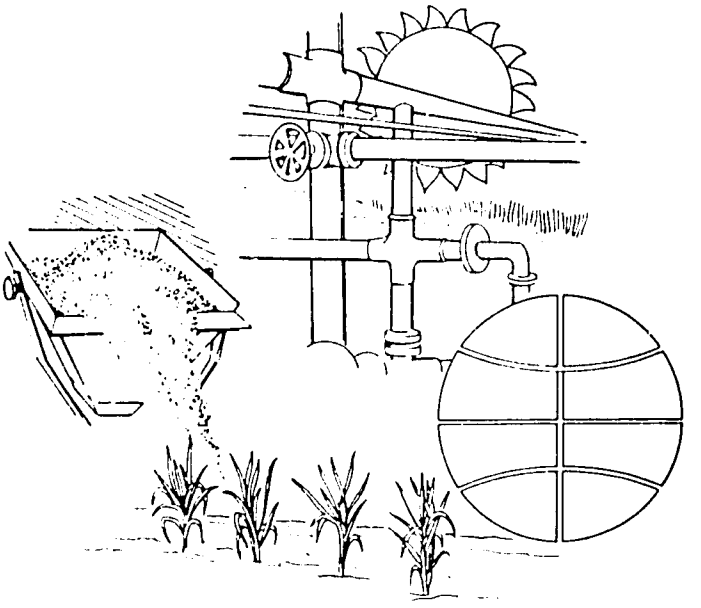

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TABLE OF CONTENTS

Page

Foreword ix
Preface xi
Symbols, Acronyms, and Abbreviations xii
Conversion Units xiv
Equivalent Energy Units xv

Chapter 1. Introduction 1
Statement of the Problem 1
Energy Consumption and Gross National Product 2
Objectives and Plan of the Study 4

Chapter 2. Food, Fertilizer, and Energy Linkages--A Conceptualization 5
Population Dynamics 5
Food and Nutrition Status 7
Fertilizer Sector Dynamics 8
Demand for Commercial Energy 9
Nitrogen and Energy: A Country Perspective 10

Chapter 3. Fertilizer--Key for Agriculture and Food Production 15
Agriculture--Basis for Economic Development 15
Sources of Agricultural Productivity 16
Contribution of Fertilizer to Food Production 18
Share of Fertilizer Energy in Agricultural Production 20
Energy Input/Output Ratios for Crop Production 21

Chapter 4. Changing Structure and Outlook for Fertilizer Sector 25
Historical Antecedents 25
Average Fertilizer Use 26
Aggregate Fertilizer Consumption 28
Aggregate Fertilizer Production and Trade 30
Regional Shift in Fertilizer Consumption 32

Chapter 5. Energy--Vital Input Into the Fertilizer Sector 35
Types of Energy Used in the Fertilizer Sector 35
Energy Consumption Estimates for the Fertilizer Sector 37
Energy Requirements for Individual Fertilizers 39
Energy Requirements for Individual Nutrients 41

Chapter 6. Energy and Growth in Nitrogen Fertilizer Industry 43
Dominance of Nitrogen Fertilizer 43
Urea as the Dominant Nitrogen Fertilizer 44
Ammonia as a Basis of Nitrogen Fertilizers 47
Regional Shift and Outlook for Ammonia Production 47
Sources of Feedstock for Ammonia Production 50
Preference for Natural Gas as Ammonia Feedstock 53
Market Outlook for Ammonia Feedstocks 55

TABLE OF CONTENTS
(Continued)

Page

Chapter 7. Impact of Energy Prices on Fertilizer Prices 61
Trend in Oil, Urea, and Wheat Prices 61
Historical Fertilizer Price Behavior 62
Natural Gas Prices and Ammonia Production Costs 64
Natural Gas Prices and Urea Production Costs 66
Outlook for Fertilizer Prices 69
Fertilizer Prices and Food Production Costs 70
Alternatives to Reduce Energy Costs 75

Chapter 8. Energy Requirements for Fertilizer Manufacturing 77
Assumptions Regarding Energy Use Estimates 77
Ammonia and Nitrogen Fertilizers 78
Phosphate Fertilizers and Intermediates 84
Potash Fertilizers 95
Nitrophosphates and Mixed Fertilizers 97
Secondary Elements and Micronutrients 100

Chapter 9. Energy Requirements for Fertilizer Distribution and Application 103
Energy for Transportation of Nitrogen 103
Energy for Transportation of Phosphates 104
Energy for Transportation of Potash 107
Considerations on Energy Use for Transportation 107
Energy for Packaging of Fertilizers 110
Energy for Application of Fertilizers 110

Chapter 10. Energy Savings in Fertilizer Manufacturing 111
Energy Savings Through Improvements in Technology 111
Energy Savings Through Operational Efficiency 123
Energy Substitution Possibilities 125
Energy Use and Economies of Scale 130
Economics of Energy Savings and Substitution 133

Chapter 11. Energy Savings Through Supplementary Sources of Nitrogen 135
Alternative Sources of Nitrogen Supply 135
Organic Sources of Energy and Nitrogen 138
Biological Fixation of Nitrogen 146

Chapter 12. Energy Savings Through Efficient Fertilizer Marketing 153
Magnitude and Components of Fertilizer Marketing Costs 153
Approaches to Reduction of Energy and Marketing Costs 154
Energy and Cost Implications of Fertilizer Transportation 156

Chapter 13. Energy Savings Through Efficient Fertilizer Use 159
Fertilizer Use Efficiency Levels 159
Efficiency Improvement Through Fertilizer Management 161
Efficiency Improvement Through Fertilizer Technology 167
Energy Savings Through Efficiency Improvements 169

TABLE OF CONTENTS
(Continued)

Page

Chapter 14. Summary, Conclusions, and Recommendations 171
Energy and Fertilizer: Policy Problem 171
Energy for Fertilizer Sector in Perspective 172
Changing Structure and Outlook for the Fertilizer Sector 175
Energy and Growth in the Nitrogen Fertilizer Sector 175
Impact of Energy Prices on Fertilizer Production Cost 177
Energy Requirements for Fertilizer Manufacturing. 178
Energy Requirements for Fertilizer Distribution 179
Prospects for Saving Energy in Fertilizer Manufacturing 180
Energy Savings by Supplementing Chemical Nitrogen Sources 181
Energy Savings Through Efficient Fertilizer Marketing 182
Energy Savings Through Efficient Fertilizer Use 183
Energy and Fertilizer: Policy Recommendations. 184

References 188
Appendixes 201
Glossary 230

LIST OF TABLES

Page

1. Food, Fertilizer, and Energy Indicators in Selected Countries 12
2. Use of Commercial Energy in Agricultural and Fertilizer Sectors of World Regions, 1972/73 22
3. Share of Fertilizer in Total Farm Energy Consumption and Energy Output/Input Ratio for Crop Production 23
4. Consumption of Fertilizer Per Hectare of Arable Land and Permanent Crops in 1979. 26
5. Growth in Fertilizer Consumption per Hectare of Arable Land and Permanent Crops From 1969 to 1979 27
6. Current and Projected Levels of Fertilizer Consumption in the World 29
7. Current and Projected Fertilizer Trade Balance in the World 31
8. Estimated Consumption of Energy by the World Fertilizer Sector. 38
9. Average Energy Requirements for Fertilizer Production, Packaging, Transportation, and Application: Summary of Various Studies 42
10. Estimated Share of Nitrogen in Fertilizer Consumption and Production. 43
11. Role of Urea in Nitrogen Fertilizer Sector in 1979. 46
12. Growth in Total Ammonia Capacity Among Leading World Producers. 48
13. Percentage Change in Ammonia Capacity in the World by Sources of Feedstock 51
14. Energy Consumption and Relative Investment Cost for 1,000 mtpd Ammonia Plants Using Various Feedstocks 54
15. Regional Share in the Estimated Proven Gas Reserves in the World Over Time. 57
16. Estimated Potential for Ammonia Production From Flared Natural Gas in OAPEC Countries During 1979 58
17. Liquefied Natural Gas World Trade. 59
18. Impact of Natural Gas Prices on Ammonia Production Costs in the United States 65
19. Economic Impact of an Increase in Natural Gas Prices on Urea Production Costs. 67
20. Economic Impact of Natural Gas Prices, Capital Costs, and Capacity Utilization Rate on Urea Production Costs. 68
21. Capital Requirements for 1,000-mtpd Ammonia and 1,700-mtpd Urea Facilities Using Natural Gas in the United States 69
22. Price Relatives for International (f.o.b.) Nutrient and Crop Prices. 72
23. Price Relatives for Nutrient and Crop Prices in the United States 74
24. Energy Use for Phosphoric Acid Production 88
25. Energy Use in Production of Granular TSP. 90
26. Energy Use in Production of Granular DAP and MAP. 91
27. Comparison of Energy Use for Phosphate Products 94
28. Energy Use for Nitrophosphate Processes and Comparison With DAP and AN. 98
29. Typical Energy Requirements for Fertilizer Transportation 104
30. Reduction in Energy Use in Ammonia Synthesis Over Time. 112
31. Technological Developments and Energy Use for Ammonia Synthesis Based on Natural Gas. 113
32. Probable Maximum Savings in Energy Use for Selected Nitrogen Fertilizers 121
33. Probable Maximum Savings in Energy Use for Selected Phosphate Fertilizers 123
34. Order of Substitutability of Ammonia Feedstocks. 127
35. Energy Use and Variation in Ammonia Production Costs by Plant Size 131
36. Estimated Cost Overruns for Building Fertilizer Plants in India. 132
37. Economic Implications of Energy Saving and Energy Substitution Innovations in Fertilizer Manufacturing: Alternative Scenarios 134
38. Sources of Nitrogen for Crop Production in the World During 1975 136
39. Sources of Nitrogen for Crop Production in the United States During 1970 136

LIST OF TABLES
(Continued)

Page

40. Alternative Natural Nitrogen Supply Sources in Temperate Zone 137
41. Sources of Nitrogen Supply in Mid-Europe Agriculture During Early 1970s 137
42. Economic and Technological Characteristics for Chemical and Organic Fertilizers 140
43. Average Nutrient Contents in Organic Manures and Plant Residues in India 141
44. Estimated Annual Supply of Primary Plant Nutrients From Organic Fertilizers in China, 1977 142
45. Estimated Nutrient Supply From Compost and Chemical Fertilizers in India 144
46. Economic Value of Cow Dung as a Source of Nitrogen and Biogas 145
47. Selected Nitrogen-Fixing Rhizobial Species of Significance in Food Production. 148
48. Nitrogen Fixed by Selected Legume Crops 148
49. Area Under Selected Legume Crops in Developing Countries During 1979 150
50. Yields of Nitrogen From Various Methods of Application of Azolla Pinnata in China 151
51. Average Freight Rates for Fertilizer Shipments in the International Market 154
52. Energy Intensity Estimates for Different Transportation Modes 157
53. Percentage Share of Different Transportation Modes in the Movement of Fertilizer in Selected Asian Countries 158
54. Paddy Response to Nitrogen From Alternative Sources, Differing Forms, and Various Methods of Application in the Philippines. 162
55. Effects of NPK Fertilization on Grain Yield of Flooded Rice in the Philippines. 163
56. Efficiency of Plant Nutrient Utilization Applied Annually on an Oat-Ryegrass Mixture, Louisiana, United States 163
57. Share of Nutrients Supplied by Compound Fertilizers During 1978/79 166
58. Estimated Potential Savings in Energy and Nitrogen Through Improved Nitrogen Use Efficiency During 1978/79 168
59. Share of Total Commercial Energy Used in the Fertilizer and Agricultural Sectors. 173
60. Average Energy Requirements for Fertilizer Nutrients 174
61. Share of Energy Consumption in the World Fertilizer Sector by Activities and Nutrients, 1978/79 174
62. Average Energy Use for Manufacturing Selected Nitrogen, Phosphate, and Potash Fertilizers 178
63. Probable Maximum Saving in Energy Use for New Fertilizer Plants Using Available Technology for Selected Fertilizers. 180
64. Approximate Share of Freight Costs in c.i.f. Fertilizer Prices in India During 1980. 183
65. Potential Economic Benefits of Doubling Nitrogen Use Efficiency During 1978/79 184

LIST OF FIGURES

Page

1. Relationship Between Commercial Energy Consumption and GNP for Selected Countries During 1978 3
2. Conceptualization of Linkages Between Energy, Fertilizer, and Agricultural Sectors. 5
3. Dynamics of World Population. 6
4. Energy and Nitrogen Self-Sufficiency: Two-Way Country Classification 10
5. Conceptualization of Factors Determining Crop Yield, Agricultural Modernization, and Food Production 17
6. Sources of Nutrient Supply and Plant Growth. 19
7. Evolution of Total Nutrient ($N + P_2O_5 + K_2O$) Consumption 28
8. Regional Shift in Incremental N, P_2O_5, and K_2O Consumption in the World Over Time 33
9. Types of Energy Used in the Fertilizer Sector 36
10. Average Energy Requirements for Manufacturing Selected Nitrogen, Phosphate, and Potash Fertilizers 40
11. Proportion of Fertilizer Ammonia Capacity Allocated to Produce Urea 44
12. Ammonia Capacity in the World by Sources of Feedstock. 52
13. Historical Trends in International Annual Average Prices for Crude Oil, Urea Fertilizer, and Wheat. 61
14. Historical Trend in International Semiannual Average Fertilizer Prices. 64
15. Annual Average Index of Prices Received and Paid by Farmers in the United States (1971 = 100) 75
16. Energy Requirements for Manufacturing Fertilizers at Different Capacity Utilization Rates 124
17. Fuel Costs by Different Vessel Sizes for Fertilizer Shipment 156

FOREWORD

At the expected rates of increase, the world population is projected to reach 6.3 billion by the year 2000. Approximately 78% of this population will reside in developing countries. This increase in population represents an addition of about 2 billion people to this spaceship earth. The major challenge faced by all of us in the remainder of the 20th century is to find ways of expanding the production of food, feed, and fiber in order to provide the basic human needs for the rapidly expanding population. Fertilizer is a major factor in expanding the yields and production of these commodities.

From 1950 to 1971, the world fertilizer prices declined steadily as advances in technology, economies of scale, and improvements in distribution more than offset rising labor and construction costs. Starting in 1971, skyrocketing energy prices, general inflation, and increases in construction costs have reversed the downward trend in fertilizer prices. In 1980 the world prices of some popular fertilizers such as urea were quadruple the 1971 low. Nitrogen fertilizers are energy intensive, hence, most severely affected; they are also the most popular among developing countries.

Higher fertilizer prices slowed the spread of the "green revolution" except where the adverse effect of higher fertilizer prices was cushioned through massive injection of fertilizer subsidies. The recent increase in energy prices and the resultant increase in fertilizer and food prices pose a renewed threat of economic disaster, especially to the low-income developing nations. Obviously, something needs to be done to avoid the catastrophic consequences on humanity of scarce energy supply and rising energy prices in many developing countries.

It is in this context that the International Fertilizer Development Center (IFDC) initiated a major study at the request of the U.S. Agency for International Development (USAID). Dr. Mohinder S. Mudahar, Economist, and Mr. Travis P. Hignett, Chemical Engineer, of IFDC undertook the study to provide a comprehensive analysis of the linkages between the energy and fertilizer sectors. Specifically, the study deals with assessing the implications of energy supply and prices on fertilizer production and prices, determining energy requirements for fertilizer production and distribution, and evaluating policy options and prospects for improving energy efficiency in the fertilizer sector.

Despite its significance, it is ironic that only about 3.5% of total commercial energy is used for agricultural production in the world. However, fertilizer accounts for about 45% of this 3.5%. Clearly there is a need not only to provide priority allocation of energy to these sectors but also to improve energy efficiency in all phases of fertilizer manufacture, distribution, and use. Approximately 81% of the total commercial energy consumed in the fertilizer sector is for fertilizer manufacture, and 90% of this is for nitrogen fertilizer alone. The average energy use for manufacture of nitrogen is about 9 times that of phosphate and 11 times that of potash.

The study analyzes ways to save energy and improve energy efficiency in fertilizer production, distribution, and use. The most promising way to save fertilizer energy is to use fertilizer more efficiently. This is especially true of nitrogen fertilizer use in developing countries where the use efficiency may be substantially lower than 40%. An improvement in fertilizer use efficiency will reduce the amount of fertilizer needed to increase food production, improve the economics of fertilizer use at the farm level, and increase agricultural production at the national level. The best way to improve energy efficiency in manufacturing, especially in developing countries, is through efficient utilization of fertilizer plants. For example, an improvement in the operating rate of fertilizer plants not only saves energy per unit of output but also reduces fertilizer production costs and increases fertilizer supply.

The initial results of the study were discussed at the National Academy of Sciences (NAS) workshop on "Energy and Food Production in Developing Countries." The study is published in two volumes. The highlights of the study are contained in the "Executive Brief," Technical Bulletin No. 19. The study is expected to provide a useful guide to fertilizer manufacturers, distributors, extension agents, and policymakers in their efforts to improve energy efficiency in the fertilizer sector.

There is an all-out need to design and implement programs to improve energy efficiency in the fertilizer sector in order to ensure that more fertilizer will be available at reasonable prices in the decades to come. IFDC is dedicated to developing and disseminating fertilizer technology and know-how that will improve fertilizer use efficiency, especially in the tropics. This will not only save energy but also result in higher food production.

Donald L. McCune
Managing Director
International Fertilizer Development Center

PREFACE

The fertilizer sector provides an important link between the energy and agricultural sectors. Energy resources are used as feedstock and/or fuel to manufacture and distribute fertilizer, which, in turn, is a major factor in expanding agricultural production.

The population pressure, limited availability of new cultivable land, ever increasing energy prices, and scarcity of energy supply further reinforce these linkages. The importance of fertilizer will increase further in order to provide food, feed, and fiber to the expanding population, and to earn foreign exchange.

The purpose of this study is to analyze the implications of energy supply and prices on fertilizer production, distribution, and prices, and to evaluate policy options to reduce the unfavorable impact of energy supply and prices on fertilizer and agricultural sectors.

The "Executive Brief" for the study has been published as IFDC Technical Bulletin No. 19, which is directed mainly at the policymakers and administrators in both developed and developing countries. However, the complete details of the study are available in this companion volume, as Technical Bulletin No. 20.

The study was initiated during 1980 in response to a request from USAID. However, in view of lack of a comprehensive study of this nature and its perceived usefulness to a wider audience, the scope of the study was expanded. The highlights of the study were discussed at a workshop sponsored by NAS on "Energy and Food Production in Developing Countries," Washington, D.C., June 29-July 1, 1981.

The superb research assistance provided by C. David Edwards at different stages of this study is gratefully acknowledged. The authors also wish to thank Mr. Edwin M. Wheeler, President, and Dr. William C. White, Senior Vice-President, of The Fertilizer Institute (TFI) for permission to use their Energy Use Survey for estimating energy requirements in fertilizer manufacture.

We are grateful to USAID for financial assistance at the initial stages of the study and to Ms. Emmy Simmons and Dr. Douglas Caton of USAID for valuable discussions and comments. We also gratefully acknowledge the encouragement, support, and comments received from IFDC management and Board members during the course of the study. Finally, we would like to recognize the assistance provided by IFDC's word processing staff headed by Mrs. Marie Stribling; editorial staff headed by Mrs. Marie Thompson; and communications staff headed by Dr. Vic Sheldon. We are grateful to them for their contributions which greatly improved the final product.

SYMBOLS, ACRONYMS, AND ABBREVIATIONS

Fertilizers

AN . . . . . ammonium nitrate
AS . . . . . ammonium sulfate
B . . . . . boron
Ca . . . . . calcium
CAN . . . . . calcium ammonium nitrate
Cl . . . . . chlorine
CO_2 . . . . . carbon dioxide
Cu . . . . . copper
DAP . . . . . diammonium phosphate
Fe . . . . . iron
H_2 . . . . . hydrogen
K . . . . . potash
KCl . . . . . potassium chloride
K_2O . . . . potash, expressed as potassium oxide
MAP . . . . . monoammonium phosphate
Mg . . . . . magnesium
MgO . . . . . magnesium oxide
Mn . . . . . manganese
Mo . . . . . molybdenum
N . . . . . nitrogen
NH_3 . . . . . anhydrous ammonia
NO . . . . . nitric oxide
NO_x . . . . . oxides of nitrogen (nitric oxide plus nitrogen dioxide)
P . . . . . phosphorus
P_2O_5 . . . . . phosphate, expressed as phosphorus pentoxide
S . . . . . sulfur
SCSG . . . . . sulfur-coated supergranules
SCU . . . . . sulfur-coated urea
SSP . . . . . single superphosphate
TSP . . . . . triple superphosphate
UAN . . . . . urea-ammonium nitrate
Zn . . . . . zinc

Organizations and Countries

CERI . . . . . Chemical Economy Research Institute
EPA . . . . . U.S. Environmental Protection Agency
ESCAP . . . . . Economic and Social Commission for Asia and the Pacific
FAI . . . . . Fertiliser Association of India
FAO . . . . . Food and Agriculture Organization of the United Nations
FIAC . . . . . Fertilizer Industry Advisory Committee
Germany, D.R. . . . . German Democratic Republic
Germany, F.R. . . . . Federal Republic of Germany
IBRD . . . . . International Bank for Reconstruction and Development–The World Bank
ICAR . . . . . Indian Council of Agricultural Research
ICI . . . . . Imperial Chemical Industries
IFDC . . . . . International Fertilizer Development Center
IFPRI . . . . . International Food Policy Research Institute
IRRI . . . . . International Rice Research Institute
NAS . . . . . National Academy of Sciences
NFDC . . . . . National Fertilizer Development Center of the Tennessee Valley Authority
OAPEC . . . . . Organization of Arab Petroleum Exporting Countries
OPEC . . . . . Organization of Petroleum Exporting Countries
SIDA . . . . . Swedish International Development Authority
TFI . . . . . The Fertilizer Institute
TVA . . . . . Tennessee Valley Authority
U.S. . . . . United States of America
U.S.S.R. . . . . Union of Soviet Socialist Republics
UN . . . . . United Nations
UNEP . . . . . United Nations Environmental Programme
UNIDO . . . . . United Nations Industrial Development Organization
USAID . . . . . U.S. Agency for International Development
USDA . . . . . U.S. Department of Agriculture
WFC . . . . . World Food Council

Measuring Units

atm. . . . . atmosphere
bbl . . . . . barrel
Btu. . . . . British thermal unit
dwt. . . . . deadweight
EJ . . . . . exajoule
ft^3 . . . . . cubic feet
g . . . . . gram
gal . . . . . gallon
Gcal . . . . . gigacalorie
GJ . . . . . gigajoule
ha. . . . . hectare
hp . . . . . horsepower
J . . . . . joule
kcal . . . . . kilocalorie
kg. . . . . kilogram
kJ. . . . . kilojoule
km . . . . . kilometer
kW . . . . . kilowatt
kWh . . . . . kilowatthour
lb . . . . . pound
Mcf. . . . . thousand cubic feet
MJ . . . . . megajoule
m . . . . . meter
mm. . . . . millimeter
mt . . . . . metric ton
mtpd. . . . . metric tons per day
mtpy. . . . . metric tons per year
m^3 . . . . . cubic meter
PJ. . . . . petajoule
ppm . . . . . parts per million
psig. . . . . pounds per square inch gauge
scf . . . . . standard cubic feet
TJ . . . . . terajoule

Miscellaneous

c.i.f. . . . . cost, insurance, and freight
CPE . . . . . centrally planned economies
DgME . . . . . developing market economies
DME. . . . . developed market economies
f.o.b.. . . . . free on board
GNP . . . . . gross national product
HHV. . . . . high heating value
IDR . . . . . isobaric double recycle
LHV . . . . . low heating value
LNG . . . . . liquefied natural gas
LPG . . . . . liquefied petroleum gas
OTEC . . . . . Ocean Thermal Energy Conversion
PARC . . . . . Pressure swing adsorption purification, Ammonia synthesis, Rankine Cycle
PSA . . . . . Pressure Swing Adsorption
Rs . . . . . Indian rupee (unless otherwise indicated)
$ . . . . . U.S. dollar (unless otherwise indicated)

CONVERSION UNITS

Linear Measurement

mm. . . . . millimeter = 0.001 meter
cm . . . . . centimeter = 0.01 meter = 0.3937 inch
m . . . . . meter = 3.28 feet = 39.37 inches
km . . . . . kilometer = 0.62 mile

Area Measure

cm^2 . . . . . square centimeter = 0.155 square inch
m^2 . . . . . square meter = 10.76 square feet
km^2 . . . . . square kilometer = 0.386 square mile
ha. . . . . hectare = 10,000 square meters = 2.471 acres

Weight

g . . . . . gram = 0.032 troy ounce
kg. . . . . kilogram = 1,000 grams = 2.205 pounds
mt . . . . . metric ton = 1,000 kilograms = 2,205 pounds = 1.102 short tons
g-mole. . . . . gram mole = the molecular weight of a compound multiplied by 1 gram

Volume

cm^3 . . . . . cubic centimeter = 0.061 cubic inch
m^3 . . . . . cubic meter = 35.34 cubic feet = 1,000 liters
l. . . . . liter = 0.264 U.S. gallons = 1.057 quart
bbl . . . . . barrel (of petroleum) = 42 gallons = 159 liters

Weight per Unit of Volume (Density)

sp gr . . . specific gravity = the ratio of the weight of a substance to the weight of an equal volume of water at 4°C; no dimensions; numerically equal to density in grams per cubic centimeter
g/cm^3 . . . . . grams per cubic centimeter = 62.43 pounds per cubic foot
kg/m^3 . . . . . kilograms per cubic meter = 0.0624 pounds per cubic foot
mt/m^3. . . . . metric tons per cubic meter = grams per cubic centimeter

Power

W. . . . . watt = 1 joule per second
kW . . . . . kilowatt = 1,000 watts = 1.34 horsepower
kWh . . . . . kilowatt-hour = 3,413 Btu

Pressure

kg/cm^2 . . . . . kilograms per square centimeter = 14.7 pounds per square inch
atm. . . . . atmosphere = 14.7 pounds per square inch = 1 kilogram per square centimeter (approximately)
psig. . . . . pounds per square inch gauge

Temperature

°C . . . . . degrees Celsius or centigrade; °C x 1.8 + 32 = °F
°F . . . . . degrees Fahrenheit (°F - 32)5/9 = °C

EQUIVALENT ENERGY UNITS

Energy can be measured in different units, the most common of which are described below. With few exceptions, the energy units used in this study are based on the joule.

Joule

Joule (abbreviated as "J") is the fundamental metric system unit for measuring energy. The most common unit is gigajoule (one billion joules), abbreviated as GJ. Other multiples of the joule are:

1 Kilojoule (kJ) = 10^3 J = 10^{-6} GJ
1 Megajoule (MJ) = 10^6 J = 10^{-3} GJ
1 Gigajoule (GJ) = 10^9 J = 1 GJ
1 Terajoule (TJ) = 10^{12} J = 10^3 GJ
1 Petajoule (PJ) = 10^{15} J = 10^6 GJ
1 Exajoule (EJ) = 10^{18} J = 10^9 GJ

Btu

One British thermal unit (Btu) refers to the heat (energy) required to raise the temperature of 1 lb of water by 1°F, where 1°F = 0.556°C. The approximate Btu equivalents (conversion factors) of the joule are:

1 J = 0.000948 Btu = 10^{-3} x 0.948 Btu
1 kJ = 0.948 Btu = 1 x 0.948 Btu
1 MJ = 0.948 thousand Btu = 10^3 x 0.948 Btu
1 GJ = 0.948 million Btu = 10^6 x 0.948 Btu

1 Btu = 1055 J
1 million Btu = 1.055 GJ = 10 Therm

kcal

One calorie refers to the heat (energy) required to raise the temperature of 1 g of water by 1°C, where 1°C = 1.8°F. One kilocalorie, commonly referred to as kcal, or Calorie, is equivalent to 1,000 calories. The approximate kcal equivalents of joule and Btu are:

1 J = 0.000239 kcal = 10^{-3} x 0.239 kcal
1 kJ = 0.239 kcal = 1 x 0.239 kcal
1 MJ = 0.239 thousand kcal = 10^3 x 0.239 kcal
1 GJ = 0.239 million kcal = 10^6 x 0.239 kcal

1 calorie = 4.184 J = 0.003968 Btu
1 kcal = 4,184 J = 3.968 Btu
1 Btu = 252 calories = 0.252 kcal
1 kWh = 864 kcal = 3,620 kJ = 3,413 Btu[1]
1 kW = 1.34 hp

1. In this study, 1 kWh is equated to 10,000 Btu or 0.01055 GJ or 2,520 kcal because conversion of fuel energy to electrical energy typically is 34% efficient.

The approximate equivalents of energy contained in a unit of common fuels are developed below. All of these fuels vary in composition and, hence, heating value. Coal is highly variable.

Crude Oil

1 U.S. bbl of crude oil = 42 U.S. gal
= 35 Imperial gal
= 159 liters
= 6.12 GJ
= 5.80 million Btu
= 1.46 million kcal

1 U.S. gallon of crude oil = 138,000 Btu = 0.1457 GJ
1 U.S. gallon of gasoline = 126,000 Btu = 0.1329 GJ
1 U.S. gallon of diesel oil = 142,000 Btu = 0.1498 GJ
1 U.S. gallon of No. 4 fuel oil = 144,000 Btu = 0.1519 GJ
1 mt (295 U.S. gal) of No. 4 fuel oil = 42.4 million Btu = 44.7 GJ

Bituminous Coal

1 mt of coal = 26.5 GJ
= 25.1 million Btu
= 6.3 million kcal
= 1.102 short tons of coal

Naphtha

1 mt of naphtha = 47.3 GJ
= 44.8 million Btu

Natural Gas

1,000 scf of natural gas[2] = 1.08 GJ
= 1.02 million Btu

Gross Versus Net Heating Value

The heating values of fuels shown above are "gross" heating values, also referred to as high heating value (HHV). This is the basis on which fuels are generally sold.

However, ammonia plant design engineers often quote fuel and feedstock requirements on the basis of "net" heating values or low heating value (LHV). The difference is the amount of heat that would be released if all of the water vapor that is formed when the fuel is burned were condensed to liquid water. This heat cannot be recovered economically in most cases.

2. One standard cubic foot of gas (scf) refers to the volume measured at 60°F and atmospheric pressure at sea level.

In the case of typical natural gas, the net heating value is about 10% less than the gross; for example,

1,000 scf = 1.08 GJ (gross) = 0.97 GJ (net)
= 1.02 million Btu (gross) = 0.92 million Btu (net)

On the other hand, the difference is about 7% with crude oil and 3%-4% with coal. Most of the fuel energy requirement estimates in this study are based on gross heating values unless otherwise stated.

Equivalent Fuel Requirements

All energy estimates will be expressed in terms of equivalent fuel requirements. Electrical and mechanical power and steam will be converted to the amount of fuel required to generate them. The approximate values used in this study are: 1 lb of steam = 1,000 Btu, and 1 kWh = 10,000 Btu. These values are only a rough approximation. In the case of electricity, the factor assumes an efficiency of 34% in converting fuel to electric power, including transmission losses. In the case of steam, actual values vary widely depending on efficiency of steam generation and the pressure and temperature at which it is generated.

CHAPTER 1

INTRODUCTION

Statement of the Problem

The economies of most developing countries have still not recovered from the adverse economic impact of the energy, fertilizer, and food crises of the mid-1970s. The recent increase in energy prices and the concomitant increase in fertilizer and food prices pose a renewed threat of economic disaster to the low-income developing nations in their endeavor to achieve a better standard of living. The situation is further aggravated by a rapid increase in population, an increase in the absolute number below the poverty line, a widening of the gap between the rich and the poor, and the prevalence of traditional, outdated methods of food production. Clearly, there is an urgent need to expand food production, increase agricultural productivity, and improve efficiency in the energy and fertilizer sectors.

Fertilizer is a major factor in expanding food output; its production, however, is highly energy intensive. This is especially the case with nitrogen fertilizer, which is the most popular type in developing countries. It is estimated that of the total commercial energy consumption in the world, the production and distribution of fertilizer account for approximately 1.5% and agriculture (including fertilizer) accounts for about 3.5%. Despite this small fraction, however, the cost of fertilizer is very sensitive to changes in energy supply and energy prices.

The linkage between the fertilizer and energy sectors is extremely crucial for several reasons. First, fertilizer production depends mainly on nonrenewable energy resources, especially fossil fuels. Second, the supply of nonrenewable energy resources is localized, unevenly distributed, and influenced by the decisions of a few oil-exporting countries. Third, the fertilizer sector is a "price taker" rather than a determinant of energy prices. Because fertilizer accounts for approximately 45% of the commercial energy used in agricultural production for the world as a whole, an increase in energy prices influences prices of both fertilizer and food.

Energy Consumption and Gross National Product

The relationship between per capita commercial energy consumption and per capita gross national product (GNP) for selected countries during 1978 is reported in Figure 1. The scatter of energy consumption and income pairs indicates that (1) per capita commercial energy consumption increases as per capita GNP increases, implying a positive relationship and (2) the rate of growth in per capita commercial energy consumption declines with an increase in per capita GNP, especially at higher income levels.

The commercial energy consumption in developing countries is very low.[1] During 1978 only 20% of the world's commercial energy was consumed in developing countries, although those countries had approximately 80% of the world's known oil reserves and 73% of the world's population. The low consumption of commercial energy in developing countries can be attributed to (1) low per capita income levels, (2) heavy dependence on noncommercial energy sources, and (3) relatively small wastage of commercial energy.

The direct and indirect demand for commercial energy will increase as the developing countries experience structural change, move into higher stages of economic development, and replace noncommercial energy with commercial energy sources. This will happen as a result of shifts in at least three areas over time. First is the nutritional effect; i.e., the demand for energy will increase as the nutritional patterns shift from plant to animal sources. Second is the agricultural modernization effect; i.e., the demand for energy in the form of fertilizer, fuel, irrigation, and insecticides will increase as the agricultural sector is transformed from traditional agricultural practices to more modern ones. Third is the industrialization effect; i.e., the demand for energy will expand as the developing countries expand their industrial and service sectors.

However, the rate of increase in energy consumption in developing countries may not be the same as it was in the now so-called developed countries. This is mainly because energy was cheap in the past and improving energy efficiency was not the priority objective of research and public policy. Furthermore, the components of commercial energy consumption are likely to shift in favor of renewable energy resources.

1. However, noncommercial energy sources are extremely important in most developing countries. For example, according to Revelle (1980), the share of noncommercial energy (excluding human and animal labor) in energy use per capita is approximately 27% in China, 84% in Bangladesh, 57% in India, 64% in Sri Lanka, and 54% in Thailand.

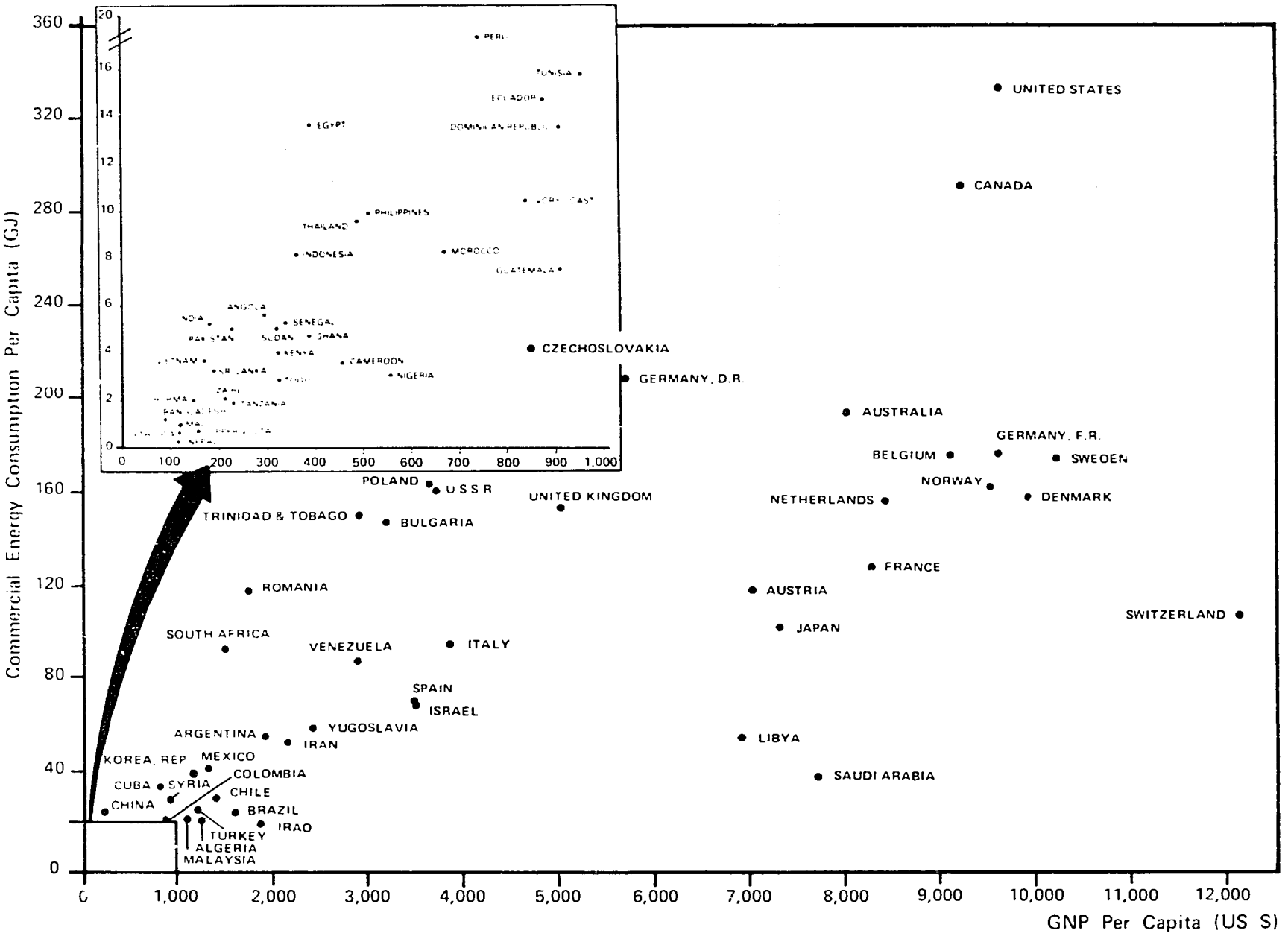

Figure 1. Relationship Between Commercial Energy Consumption and GNP for Selected Countries During 1978.

Objectives and Plan of the Study

The objectives of this study are fourfold: (1) to examine the linkages among energy, fertilizer, and agricultural sectors; (2) to assess the implications of energy supply and prices on fertilizer production and prices; (3) to estimate energy requirements for fertilizer manufacturing, packaging, transportation, and application; and (4) to evaluate policy options and prospects for saving energy in fertilizer manufacturing, marketing, and use. The underlying objective is to find ways to reduce the unfavorable impact of scarce energy supply and high energy prices on the fertilizer sector in developing countries, without significantly jeopardizing their stated national goals of improving the standards of living and eliminating hunger.

The main purpose of the study is to analyze the impact of scarce energy supply and high energy prices on fertilizer (especially nitrogen) production, distribution, and use in developing countries. The prospects for saving energy in fertilizer manufacturing and distribution, the potential for supplying nutrients from noncommercial fertilizer sources, and the prospects for saving energy through efficient fertilizer use are examined in detail. The study is designed to generate and provide information on alternative options to improve energy efficiency in the fertilizer sector of developing countries.

It is expected that this information would provide national and international organizations with the guidelines for making decisions with respect to research, technical assistance, financial assistance, training, and policy formulation in the areas of food, fertilizer, and energy. This information is especially crucial for low-income developing countries. As discussed above, the demand for commercial energy in these countries will increase over time.

CHAPTER 2

FOOD, FERTILIZER, AND ENERGY LINKAGES: A CONCEPTUALIZATION

The conceptualization of the linkages between energy, fertilizer, and agricultural sectors is provided in Figure 2. The demand for food, fertilizer, and energy is a derived demand that depends on population and income growth. To provide a realistic economic perspective of the implications of the energy prices on fertilizer and food prices and supply, each of these components, linkages among them, and their significance need to be carefully understood.

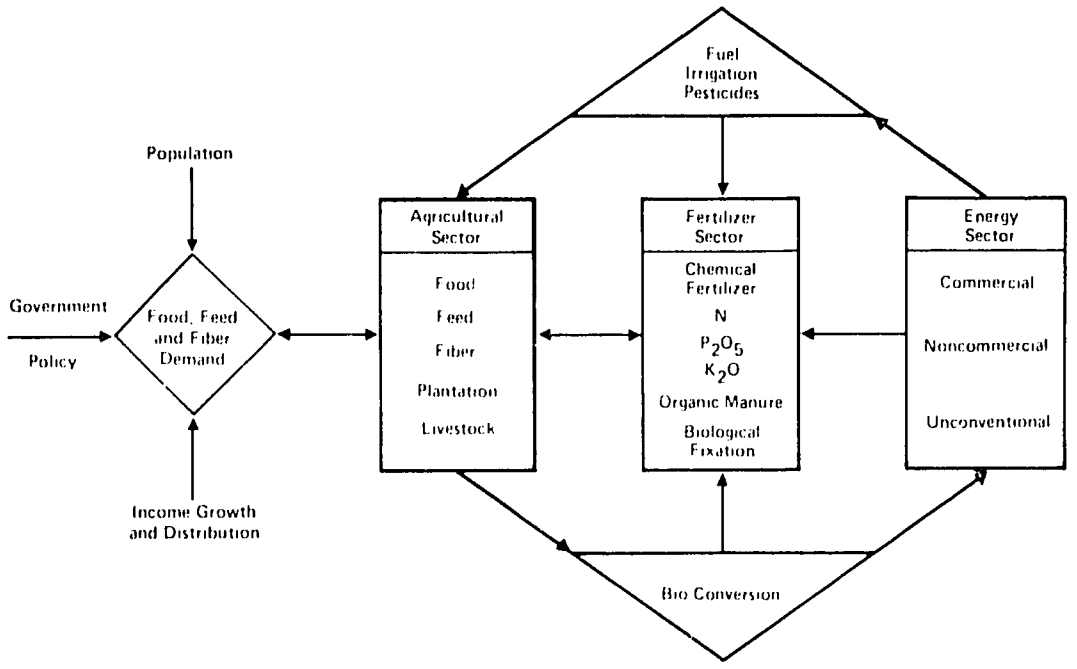

Figure 2. Conceptualization of Linkages Between Energy, Fertilizer, and Agricultural Sectors.

Population Dynamics

The dynamics of world population is reported in Figure 3. The world population was estimated to be about 4.4 billion during 1980 and is projected to be 6.3 billion by the year 2000; this represents an increase of approximately 1.9 billion in 20 years. This exponential growth in population with a large base is the core of the economic problem since providing for basic needs alone means a substantial drain on resources away from their other productive uses.

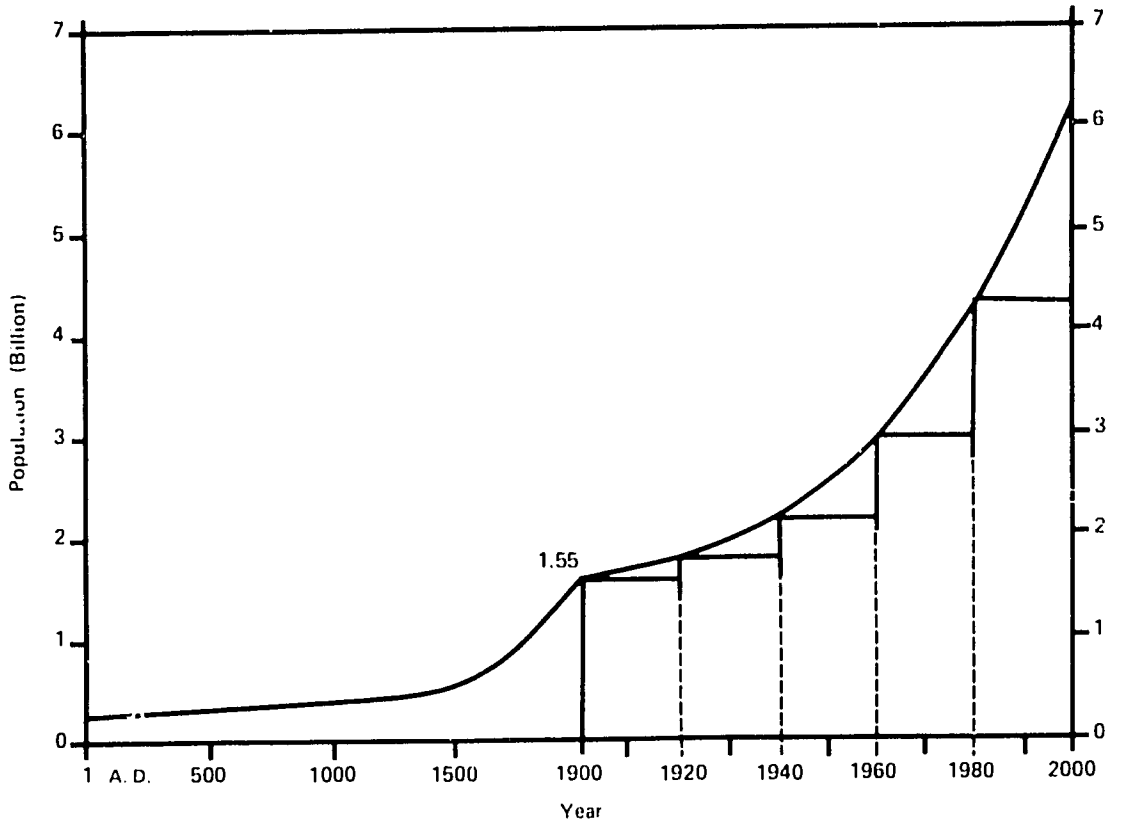

Figure 3. Dynamics of World Population.

Two other significant structural changes taking place over time have an important bearing on the problem, especially for the developing countries. First, the share of developing countries in world population has increased from 66% in 1950 to 73% in 1980 and is expected to be 78% in the year 2000. At present 51% of the world population is in developing market economies alone, with about 18%, 16%, 10%, and 55% of this in Africa, Latin America, the Near East, and the Far East, respectively.[2] Second, infant mortality rate is gradually declining and life expectancy has increased. According

2. In this study we have adopted FAO's classification of countries. According to this classification, the world is divided into three broad categories. These are (a) developed market economies, (b) developing market economies, and (c) centrally planned economies. Developed countries consist of developed market economies, Eastern Europe, and Union of Soviet Socialist Republics (U.S.S.R.); whereas, developing countries consist of developing market economies and centrally planned countries from Asia. The list of countries included in each of these categories is given in Appendix A.

to the World Bank (1980), the life expectancy at birth in low-income countries has increased from 35.2 years in 1950 to 49.9 years in 1978, representing a 42% increase in life expectancy.

Food and Nutrition Status

The demand for food is rapidly increasing in response to population growth, income growth, and the efforts of various governments to reduce the incidence of hunger and malnutrition. A most urgent economic problem is to provide adequate food for the world's hungry and malnourished people. Projections made by various international organizations, including the World Food Council (WFC), Food and Agriculture Organization of the United Nations (FAO), World Bank (IBRD), and International Food Policy Research Institute (IFPRI) indicate potentially large food deficits in the next 10-20 years.

Based on past trends, IFPRI (1977) projects that production of staple food crops in developing market economies alone will fall short of meeting demands in 1990 by 120-145 million mt. On a regional basis, Asia accounts for 40% of the total projected food deficit; North Africa/Middle East, about 25%; sub-Sahara Africa, over 20%; and Latin America, over 10%. The countries in Asia and sub-Sahara Africa face the most serious food problem. A large share of the population in developing countries faces serious nutrition problems; furthermore, the nutrition gap between high- and low-income groups in a particular developing country and between poor and rich nations is also very large.

The average caloric intake per capita per day in developing countries is 2,282 calories, which is about 68% of the intake in developed countries. On the other hand, the average protein intake in developing countries is 57 g/day, which is about 58% of that in the developed countries. Over time there have been only marginal improvements in nutritional standards. One of the major features of nutrition in developing countries is that plant sources contribute about 91% of the caloric intake and 79% of the protein intake. On the other hand, the corresponding figures for developed countries are 69% and 44%, respectively. Calories and protein derived from animal sources are, however, far more expensive and energy intensive.

The average caloric and protein figures do not convey a realistic picture of the nutrition problem. The low-income segment of the population has limited purchasing power and allocates a large proportion of their income on food expenditure. A major proportion of the world's malnourished people reside in those countries facing serious food deficits. According to FAO (1979), the number of people with food intake below the minimum critical limit (1.2 times the Basal Metabolic Rate) is estimated to be 415 million during 1974/76 in the developing market economies, which is about 21% of

their population. Out of this total, 68 million are in Africa, 41 million in Latin America, 19 million in the Near East, and 286 million in the Far East. This amounts to approximately 22%, 13%, 11%, and 27% of the total population in each of these respective regions.

The incidence of malnutrition depends to a great extent on the degree of unevenness of food supplies and food distribution and the degree of inequality in the purchasing power. The main reason for hunger is poverty. Consequently, there is a need to design public policies that not only expand food production but also eradicate poverty.

Fertilizer Sector Dynamics

There are 16 essential plant nutrients. Of these 16 elements, three (carbon, hydrogen, and oxygen) are obtained from air and water. Six elements are called "macronutrients"; these include nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur. The first three have traditionally been the main concern of the fertilizer industry and are known as "primary nutrients." However, increasing frequency of deficiencies of the other three has forced attention to be given to supplying one or more of the "secondary nutrients" in fertilizers. The other seven essential elements (boron, chlorine, copper, iron, manganese, molybdenum, and zinc) are called "micronutrients" because plants require them in small quantities, less than 1 kg/ha. Soil supplies usually are adequate, but increasing incidence of deficiencies of some of them, such as zinc, has been noted in some developing countries.

To expand food production to feed the expanding population adequately, there is a need to increase the supply and efficient use of plant nutrients. The plant nutrients that are removed from the soil by crops are replenished mainly through the use of chemical fertilizers, organic manures, and biological fixation of nitrogen. The fertilizer sector requires energy to produce and distribute fertilizers for eventual application on agricultural lands. The importance of chemical fertilizers in economic development derives mainly from the importance of agriculture and the degree of its modernization.

Fertilizer use in most developing market economies is rather low. However, agronomic research indicates a substantial potential for expansion. According to FAO (1981) during 1979, the fertilizer use per hectare in the developing market economies was about 24% of that in the developed market economies, 29% of that in the centrally planned economies, and 40% of the world average. From an aggregate point of view, during 1979/80 the developing countries accounted for approximately 31% of the world consumption and 20% of the world fertilizer production. The corresponding shares of the developing market economies were 18% and 10%, respectively. Among

the nutrients supplied by chemical fertilizers, nitrogen is used in the greatest quantities. During 1979/80, nitrogen as a proportion of total nutrient consumption was 51% for the world, 45% for the developed countries, and 66% for the developing countries.

Any disruptions in energy supply or an increase in energy prices is bound to increase nitrogen prices proportionately more than the prices for phosphate and potash fertilizers, primarily because nitrogen production is relatively more energy intensive. An increase in retail fertilizer prices and its impact on fertilizer use depend, of course, on many other factors, including crop prices, fertilizer marketing efficiency, fertilizer response, and fertilizer policies. The fertilizer crisis of 1973/74 was partly the result of a sudden increase in oil prices by the Organization of Petroleum Exporting Countries (OPEC) countries and the unstable international fertilizer market. The result was an increase in fertilizer prices, an increase in investment for fertilizer capacity expansion, and even a decline in fertilizer consumption, as well as a decline in food production in some countries.

Demand for Commercial Energy

The commercial energy sector is linked with the agricultural sector both directly (through fuel and irrigation) and indirectly (through the manufacture and distribution of fertilizer and pesticides). The use of commercial energy through these modern farm inputs applied to fertilizer-responsive crop varieties has been mainly responsible for the so-called "green revolution." However, an increase in energy prices or prices of energy-derived inputs may slow down the growth in agricultural production, especially in energy-importing, fertilizer-importing, food-deficit countries. On the other hand, the agricultural sector is a major producer of energy, including food energy, noncommercial energy, and now even alcohol through bioconversion for producing what is popularly known as "gasohol."

Historically, as discussed in the previous chapter, growth in GNP and commercial energy consumption are positively correlated. However, the share of the world's commercial energy consumed in the developing countries is rather small (about 20%). Clearly, if these countries wish to achieve higher economic growth, they must increase their use of energy. This expanding demand must be met through an expansion in domestic production and/or imports. Given current oil prices, however, many oil-importing countries do not have the financial capability and are experiencing serious balance-of-payment problems.

Since the main focus of this study is on analyzing the relationship between fertilizer and energy sectors in developing countries, the self-sufficiency of selected countries with respect to energy and nitrogen is reported in Figure 4.[3] The countries are divided into four categories, including (1) deficits in both energy

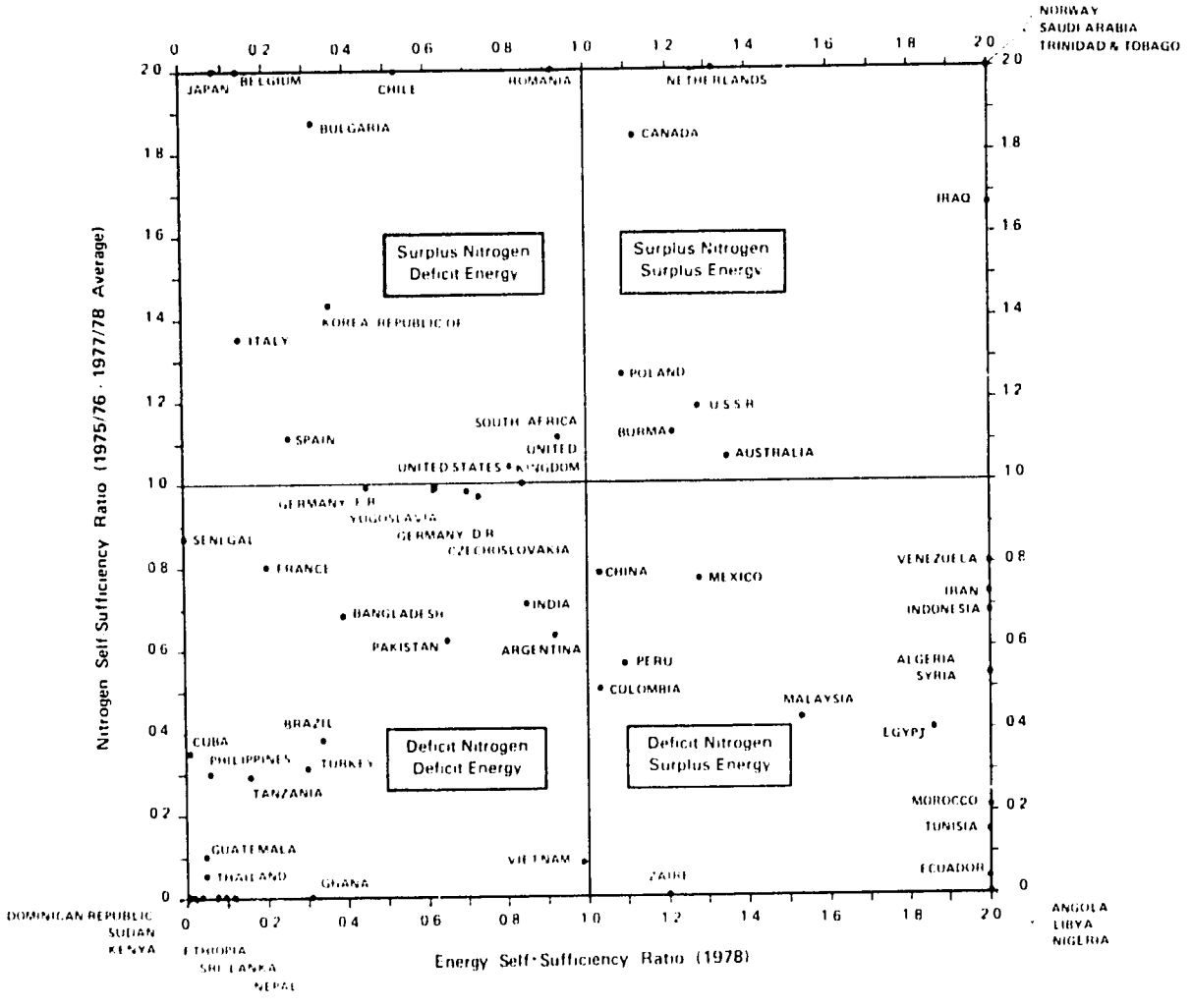

Figure 4. Energy and Nitrogen Self-Sufficiency: Two-Way Country Classification.

3. The data on energy and nitrogen self-sufficiency as reported in Table 1 were used to draw the figure. However there are two differences that are worth mentioning. First, the self-sufficiency in the figure is represented by ratio rather than percentage. Second, the points on the line represented by the value 2.00 indicate that the self-sufficiency was equal to or greater than 200%.

and nitrogen, (2) surplus in both energy and nitrogen, (3) surplus in energy but deficit in nitrogen, and (4) deficit in energy but surplus in nitrogen. The countries that have a surplus of nitrogen but based on imported feedstocks (e.g., Japan) would be slowly phasing out much of their nitrogen industry. On the other hand, countries with plentiful domestic feedstocks but limited nitrogen industry (e.g., Mexico) would be emerging as major nitrogen producers in the world. Further details on food, fertilizer, and energy indicators in selected countries are provided in Table 1. Countries that depend on imports to meet a major part of their domestic requirements for food, fertilizer, and energy may face serious economic upheavals in the next 20 years.

It should be noted, however, that some countries listed as having an energy deficit in Table 1 have adequate supplies of natural gas, which can be used to produce nitrogen fertilizers (e.g., Pakistan and Bangladesh). Others have undeveloped energy resources, and still others are likely to discover energy resources. One should also realize that different energy resources usually cannot be technologically and/or economically substituted for each other. One country, for example, could possess abundant supplies of coal yet be a major importer of oil.

Table 1. Food, Fertilizer, and Energy Indicators in Selected Countries[a]

Region/Country	Self-Sufficiency, % in: Food 1974-76 Average	Fertilizer 1977/78-1979/80 Average: N	Fertilizer 1977/78-1979/80 Average: NPK	Commercial Energy, 1978	Population, 1979 (millions)	Arable Land, % of Potential in Use	Fertilizer Use, kg/ha of Arable Land and Permanent Crops, 1979	Per Capita Consumption of Commercial Energy, kg of Oil Equivalents, 1978
Developed market economies								
North America								
Canada	119	210	515	112	24	48	41	6,755
United States	111	106	104	81	220	49	111	7,737
Western Europe								
Belgium	98	363	286	14	10	72	540	4,134
France	110	85	88	20	53	67	312	2,971
Germany, F.R.	81	98	133	45	61	80	479	4,092
Italy	83	135	95	14	57	65	189	2,197
Netherlands	121	333	289	132	14	73	805	3,624
Norway	79	381	215	228	4	42	320	3,790
Spain	96	108	130	26	36	58	82	1,636
United Kingdom	72	99	88	84	56	63	324	3,546
Yugoslavia	99	95	76	62	22	73	110	1,384
Oceania								
Australia	170	95	88	135	14	29	29	4,505
Other DME								
Japan	73	198	98	8	116	81	478	2,602
South Africa	112	116	94	93	28	66	64	2,162
Developing market economies								
Africa								
Algeria	70	54	64	779	18	83	23	468
Angola	95	0	0	935	7	8	4	131
Ethiopia	104	0	0	8	32	57	6	13
Ghana	139	0	0	31	11	46	7	112
Kenya	102	0	0	4	16	59	17	95
Morocco	94	25	211	19	20	87	29	194
Nigeria	102	0	6	1,811	75	80	3	72
Senegal	109	80	92	0	6	58	6	123
Tanzania	96	33	47	16	17	25	6	44
Tunisia	92	27	511	202	6	95	12	369
Zaire	97	0	0	120	28	6	1	47
Latin America								
Cuba	139	30	19	1	10	99	156	794
Dominican Republic	124	0	0	1	6	89	59	316
Guatemala	117	9	9	5	7	72	59	177
Mexico	98	78	79	128	68	67	49	941
Trinidad and Tobago	68	951	550	372	1	63	54	3,377
Argentina	124	54	27	92	27	66	4	1,274

(Continued)

Table 1. Food, Fertilizer, and Energy Indicators in Selected Countries[a] (Continued)

Region/Country	Self-Sufficiency, % in: Food 1974-76 Average	Fertilizer 1977/78-1979/80 Average: N	Fertilizer 1977/78-1979/80 Average: NPK	Commercial Energy, 1978	Population, 1979 (millions)	Arable Land, % of Potential in Use	Fertilizer Use, kg/ha of Arable Land and Permanent Crops, 1979	Per Capita Consumption of Commercial Energy, kg of Oil Equivalents, 1978
Brazil	108	36	44	34	123	19	58	540
Chile	84	198	89	53	11	96	25	678
Colombia	104	43	39	103	29	17	53	476
Ecuador	114	4	10	371	8	61	36	344
Peru	89	71	57	109	17	24	32	442
Venezuela	77	87	47	471	14	17	60	2,033
Near East								
Egypt	87	47	55	186	41	99	212	315
Libya	52	0	0	3,113	3	83	24	1,285
Sudan	104	0	0	2	18	27	4	117
Iran	84	36	47	672	37	99	24	1,230
Iraq	76	203	314	2,458	13	101	19	430
Saudi Arabia	50	1,290	836	4,818	8	87	19	888
Syria	89	36	23	200	8	86	21	659
Turkey	100	37	38	35	44	98	53	539
Far East								
Bangladesh	93	57	44	39	86	100	45	29
Burma	104	89	67	121	34	24	11	43
India	98	69	64	85	678	93	30	121
Indonesia	98	120	90	344	148	55	44	189
Korea, Republic	87	173	138	36	37	107	384	925
Malaysia	137	34	18	153	13	54	103	487
Nepal	100	0	0	12	14	85	9	7
Pakistan	98	51	43	65	80	72	52	117
Philippines	122	20	24	6	49	66	35	231
Sri Lanka	82	0	0	10	15	83	72	74
Thailand	129	3	1	5	46	57	17	222
Other DgME								
Centrally planned economies								
Asian CPE								
China	102	85	84	103	945	131	129	569
Vietnam	92	19	41	99	51	77	30	85
Eastern Europe and U.S.S.R.								
Bulgaria	106	178	126	32	8	73	193	3,415
Czechoslovakia	94	101	58	73	15	65	335	5,123
Germany, D.R.	91	113	277	70	17	73	325	4,844
Poland	98	77	70	109	35	79	218	3,806
Romania	105	222	167	92	22	88	137	2,749
U.S.S.R.	97	121	126	128	264	66	75	3,742

a. Derived from UN (1979), FAO (1980), Rask (1980), and FAO (1981a).

CHAPTER 3

FERTILIZER—KEY FOR AGRICULTURE AND FOOD PRODUCTION

The main objectives of this chapter are to discuss briefly (1) the role of agriculture in economic development, (2) the contribution of fertilizer to food production, and (3) the share of total commercial energy used in fertilizer and agricultural sectors. This will provide a proper perspective of the problem, the nature of the policy issues involved, and the urgency of the search for the solutions.

Agriculture—Basis for Economic Development

The leading role of agriculture in the economic development of low-income countries is well documented in the literature.[4] In addition to providing food, labor, and capital for the expanding industrial sector, agriculture contributes a major source of foreign exchange earnings and provides a significant market for industrial goods. Many countries derive a high percentage of their scarce foreign exchange from export of agricultural products such as sugar, coffee, tea, rubber, fiber crops, and products made from these agricultural commodities. In this respect, the use of fertilizer further expands the role of agriculture in economic development by improving both land and labor productivity, as well as alleviating foreign exchange problems.

The modernization of the agricultural sector plays a dual role in helping the poor and landless to participate in the growth process and share in its benefits. First, it is instrumental in creating jobs both within and outside the agricultural sector through its linkage effects, and thus increasing the purchasing power of the poor whose only source of income is their jobs. Second, through expanded food production it makes more food available to the poor, who spend a major portion of their income for food.

The agricultural sector in most developing countries, however, must absorb more labor in absolute terms in the future, even though its proportional share in the total population may be declining over time. For example, according to FAO (1977a), the population of India is projected to increase from 712 million in 1981 to 1,077 million by the year 2001. Out of the additional 365 million people, 120 million will be workers (assuming current proportions).

4. See, for example, Johnston and Mellor (1961), Mellor (1965, 1976), Johnston and Kilby (1975), and Hayami and Ruttan (1971).

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Out of these workers, 52 million will be cultivators, 36 million will be nonagricultural workers, and 32 million will be agricultural (landless) laborers. Clearly, in the next 20 years, the agricultural sector must produce food for an additional 365 million people, must absorb 52 million additional cultivators, and create jobs for an additional 32 million landless laborers. The situation in many other developing countries is not much different. Furthermore, the large food deficits noted earlier cannot be eliminated, in the long run, unless the deficit countries make a concerted effort to raise their own food production.

Sources of Agricultural Productivity

Increasing food production involves (1) an extensive cultivation through land development, (2) an intensive cultivation to increase crop yields, and (3) multiple cropping. The African and Latin American countries still have substantial scope for land development (see Table 1); the Asian countries, however, are facing serious constraints with respect to bringing more land under cultivation. Moreover, despite the potential in the African and Latin American countries, land development in remote areas involves large investments which are often beyond the reach of individual farmers and even many governments. Regardless of the agricultural development strategy followed by a particular country, however, the use of fertilizer will play a major role in building and maintaining soil fertility for crop production.

Despite the likely potential for new land development for agricultural purposes in certain countries, the choice agricultural land may also be going out of production. First of all, the demand for agricultural land for nonagricultural purposes is increasing rapidly. This is due to the structural change inherent in the process of economic growth. The nonagricultural uses of land include urbanization, industrialization, waste disposal, housing, and other infrastructure. This loss of agricultural land may not be easily overcome, mainly because the market value of land for nonagricultural purposes is often much higher than for agricultural purposes. Secondly, a large amount of good agricultural land is lost every year because of soil erosion, deforestation, and desertification. These are very serious problems especially in tropical (humid tropical and subtropical) and arid (arid and semiarid) regions of the world.

Obviously, a large part of the additional food required to feed the growing population must come from an increase in crop yields or an improvement in land productivity.[5] A conceptual framework identifying factors determine agricultural modernization and food production is developed in Figure 5. The development and supply of modern farm inputs are required but they are not the only conditions necessary for transforming the traditional agricultural

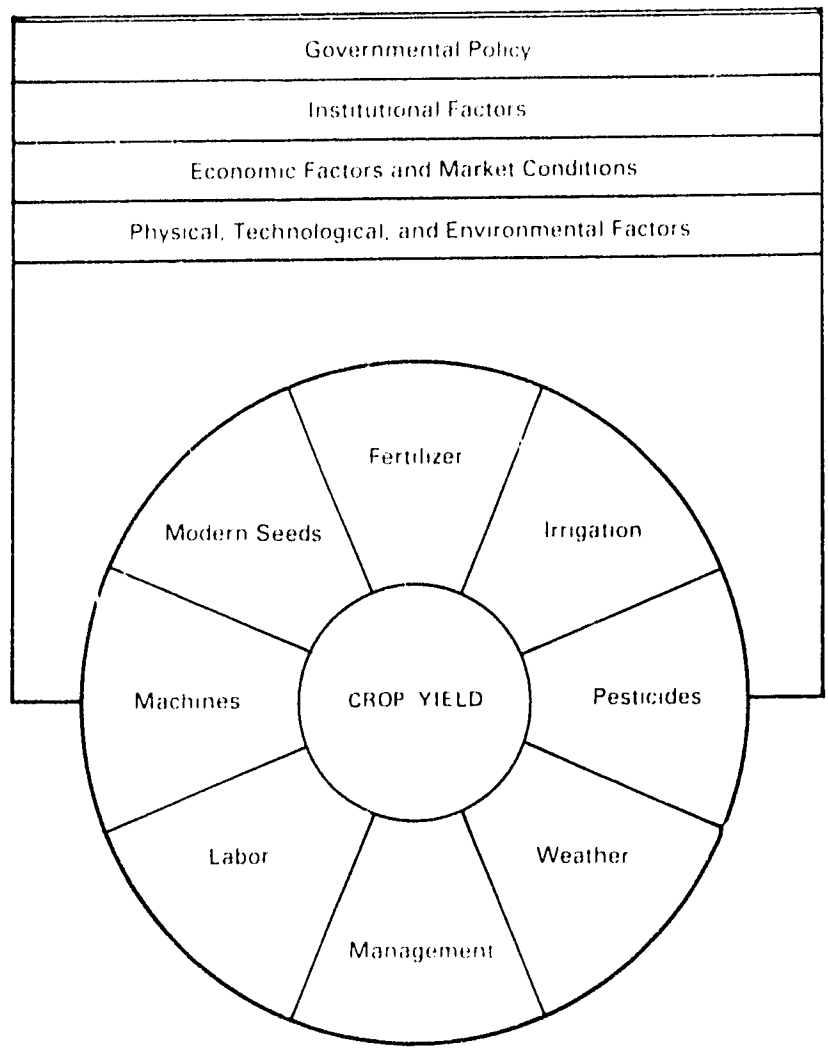

Figure 5. Conceptualization of Factors Determining Crop Yield, Agricultural Modernization, and Food Production.

5. The evolution of agricultural strategy for a particular country would depend on resource endowments, factor prices, and government policy. For example, Japan pursued land-saving type of technological change (chemical and biological) as opposed to labor-saving type of technological change (mechanical) pursued by the United States. The theoretical framework and empirical evidence for induced technological change, in response to factor prices and factor scarcities, is provided in Hayami and Ruttan (1971).

sector into a modern sector. The decisions to use and substitute various farm inputs, if available, are made by individual farmers in most countries. However, these decisions are greatly influenced by the economic institutions, government policies, and other factors which modify the farmer's decision environment.

Contribution of Fertilizer to Food Production

There have been studies in both developed and developing countries which attempt to estimate the contribution of fertilizer use to crop production. These estimates, however, should be assumed only as first-order approximations with respect to the contribution of fertilizer. It is very difficult, if not impossible, to isolate the quantitative magnitudes of crop production which can be realistically attributed to chemical fertilizer use at the farm, regional, and national levels. First, as illustrated in Figure 6, chemical fertilizers are only one of the several nutrient supply sources and factors which determine plant growth. Second, the productivity of chemical fertilizers depends on the nature and amount of applications of other complementary farm inputs and management practices. Third, there are long-term effects of fertilizer use on soil fertility that are seldom taken into account; most fertilizer nutrients other than nitrogen have a positive long-term effect while nitrogen has a negative effect unless supplemented by other nutrients.

The available empirical estimates, however, indicate that fertilizer has contributed significantly over time to expanding food production (Bishop and Mudahar, 1979). The preliminary estimates made by Pinstrup-Andersen (1976) indicate that, during the 1948-52 to 1972/73 period, about 15% of total cereal production, 30% of incremental cereal production, and 56% of incremental cereal yield in developing market economies can be attributed to fertilizer use. The contribution to incremental cereal production is estimated to be 20% in Africa, 27% in Latin America, 32% in the Near East, and 28% in the Far East. According to Mellor (1976), 53% of incremental foodgrain production in India during 1973/74 was attributable to fertilizer use, and its contribution is expected to increase to 79% during 1983/84. The estimates developed by Herdt and Barker (1975) indicate that during 1971/72 the total cereal production attributed to fertilizer use was 13.5%-20.2% in Asia.

Furthermore, on the basis of empirical evidence, Herdt and Barker (1975) conclude that the average yield response to fertilizer (mainly nitrogen) applied to modern varieties of rice in Asia is between 10 and 15 kg of grain per kilogram of fertilizer applied. More recently the empirical estimates made by Mudahar (1979a) indicate that 37% of the expansion in rice output and 62% of the expansion in rice yields in Asia from 1965 to 1975 are attributable to fertilizer use. From results of a large cross-country project on farm-level constraints to high rice yields in Asia, the International Rice

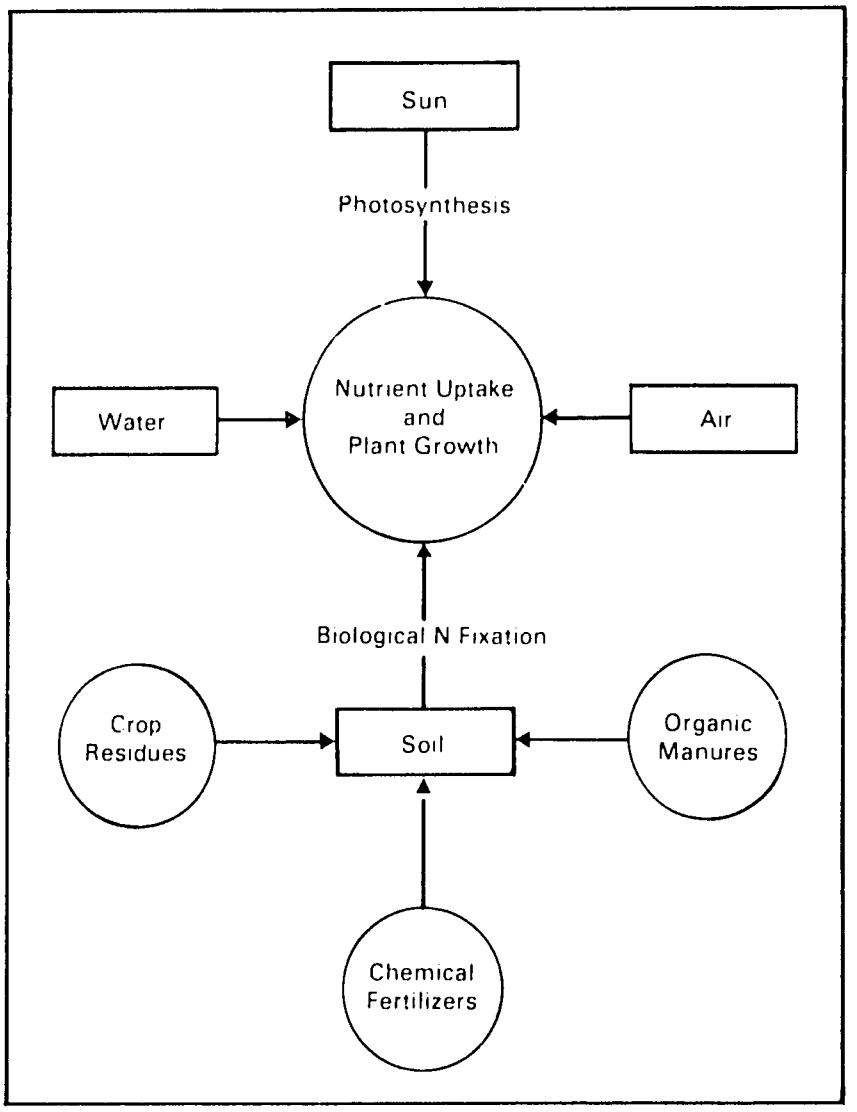

Figure 6. Sources of Nutrient Supply and Plant Growth.

Research Institute (IRRI) (1979) concluded that on the average fertilizer accounted for 44% of the rice yield gap in wet season and 53% of the yield gap in dry season.[6]

The large contribution of fertilizer to cereal production in developing countries is further corroborated by similar studies in developed countries. Christensen, Hendrix, and Stevens (1964) estimated that about 55% of the U.S. grain yield increase from 1940 to 1955 was due to fertilizer use. The Council of Agricultural Science and Technology (1974) estimated that about one-third of the U.S. grain production was due to the use of fertilizer, while Free, Bond, and Nevins (1976) estimated that the contribution of

6. The "yield gap" is defined as the difference between average yield using farmers' inputs and average yield using high inputs.

fertilizer to total U.S. crop output was approximately 37%. More recently Dean (1981) indicated that the use of chemical fertilizers accounts for about 40% of all U.S. crop production.

However, with the exception of areas experiencing "green revolution," the crop yields in developing countries are still very low. This is due to several interrelated factors including distortions in economic incentives resulting from poorly conceived government policies.[7] The available information indicates that fertilizer use is still very low and only a small proportion of crop area is planted to high-yielding crop varieties (HYV). Plant protection methods are not yet very common, and a large portion of the cultivated area depends on uncertain rains for water supply. Clearly there is large potential for increasing crop yields, but it will not be realized apart from large capital investments and appropriate government policies. Furthermore, the productivity of each of these factors, including fertilizer, can be substantially improved through better management.

In addition to contributing directly to food production, fertilizer use contributes indirectly to employment, to increases in foreign exchange through export expansion or import substitution, to growth linkages through industrialization, to improved photosynthetic efficiency of cereal plants, and even to energy supply through expanded production of energy crops.

Share of Fertilizer Energy in Agricultural Production

The share of energy in the form of fertilizer in agriculture's total commercial energy requirements varies across countries, crops, and level of agricultural technology. A smaller share, however, does not necessarily mean that the absolute amount of commercial energy used to produce fertilizer was small, since the share depends on the total commercial energy used in the agricultural sector.

7. The distortions in economic incentives resulting from various government programs and actions in the developing countries are discussed in Schultz (1978). Hopper (1978) has discussed the implications of government prohibitions on agricultural development. Furthermore, the major fertilizer policy issues and their economic implications for developing countries are discussed in Mudahar and Pinstrup-Andersen (1977) and IFDC (1978); the needed information and economic analysis for fertilizer policy formulation in order to accelerate the contribution of fertilizer to economic development is discussed in Mudahar (1978).

As reported in Table 2, the commercial energy used in agricultural production for the world as a whole was 7.6×10^{18} J during 1972/73, and projected to be about 13.5×10^{18} J during 1985/86. This amounts to only 3.5% of total commercial energy use during 1972/73 for the world. The percentage varies from 2.8% in North America to 6.4% in Near East. Agricultural production in most developing countries is still dominated by farming methods that are less dependent on commercial energy. Even in developed countries, like the United States where the use of commercial energy in agricultural production is relatively high, the share of energy used in the agricultural production sector is rather small.

The commercial energy in agricultural production is mainly used in the form of fertilizer, pesticides, irrigation, and fuel to operate various farm machines. According to FAO (1977b), as reported in Table 2, fertilizer alone accounted for 45% of total commercial energy used in agricultural production in the world during 1972/73. The share of fertilizer is projected to increase to 57% during 1985/86. However, the share varied significantly from region to region, with fertilizer accounting for almost one-third in developed market economies, and more than one-half in the rest of the world. On the average it ranged from 35% in developed market economies to 64% in developing market economies. It was even higher for Asian centrally planned economies (mainly China), where it was estimated to be approximately 76%. This clearly demonstrates the dependence of the agricultural production sector on an energy supply in the form of fertilizer and its vulnerability to any interruption of that supply.[8]

Energy Input/Output Ratios for Crop Production

Following the pioneering work of Pimentel et al. (1973), there have been several studies estimating energy requirements for individual crop production. According to Pimentel, the share of fertilizer in total energy input for corn production in the United States has increased from 8% (0.76 GJ/ha out of 9.56 GJ/ha) in 1945 to 36% (10.78 GJ/ha out of 29.94 GJ/ha) during 1970, indicating an almost fourteenfold increase. On the other hand, average corn yield has also increased from 2,133 kg/ha (35.4 GJ/ha) in 1945 to 5,082 kg/ha (84.4 GJ/ha) in 1970, implying a 140% increase over 1945. The resulting total energy output/input ratios were 3.7 in 1945 and 2.8 in 1970.

8. Similar estimates for individual countries are available in Steinhart and Steinhart (1974) for the United States, Leach (1975) and White (1981) for the United Kingdom, and Jurgens-Gschwind (1980) for the Federal Republic of Germany.

Table 2. Use of Commercial Energy in Agricultural and Fertilizer Sectors of World Regions, 1972/73[a]

Region	Total Energy Consumption, 10^{18} x J	Energy Used in Agricultural Sector		Energy Used in Fertilizer Sector			% Share by Region of Energy Used in Agricultural Production During	
		10^{18} x J	% of Total	10^{18} x J	% of Agriculture	% of Total	1972/73	1985/86
Developed market economies[b]	135.7	4.6	3.4	1.635	35.3	1.2	61.0	47.0
North America	76.9	2.1	2.8	0.750	35.0	1.0	28.2	22.0
Western Europe	42.9	2.1	4.9	0.724	34.2	1.7	27.8	21.1
Oceania	2.4	0.1	5.6	0.035	25.5	1.5	1.8	1.4
Developing market economies[b]	19.3	0.9	4.8	0.586	63.6	3.0	12.1	21.1
Africa	1.6	0.1	4.5	0.038	54.3	2.4	0.9	1.4
Latin America	8.1	0.3	3.8	0.153	48.9	1.9	4.1	6.3
Far East	7.0	0.4	5.3	0.309	83.5	4.4	4.9	9.1
Near East	2.6	0.2	6.4	0.086	51.2	3.3	2.2	4.3
Centrally planned economies	64.1	2.0	3.1	1.160	58.0	1.8	26.9	31.9
Asian CPE	14.3	0.4	2.9	0.317	76.4	2.2	5.5	6.4
Eastern Europe and U.S.S.R.	49.8	1.6	3.3	0.843	51.6	1.7	21.4	25.5
Developed Countries	185.5	6.3	3.4	2.478	39.5	1.3	82.4	72.5
Developing Countries	33.6	1.3	4.0	0.903	67.6	2.7	17.6	27.5
World	219.1	7.6[c]	3.5	3.381[c]	44.5[c]	1.5	100	100[c]

a. Derived from FAO (1977b).
b. Including countries in other regions not specified.
c. During 1985/86, the commercial energy used in agricultural production is projected to be 13.5 J x 10^{18}, out of which 56.5% is estimated to be used in fertilizer sector.

Furthermore, the additional fertilizer energy use of 4.9 GJ/ha from 1964 to 1970 resulted in 816 kg/ha of corn. This amounts to at least 6 GJ/mt of incremental corn yield from additional fertilizer use, since many other factors have also contributed to increased corn yield from 1964 to 1970. On the other hand, the average fertilizer energy use was 2.1 GJ/mt of corn yield during 1970. In other words, the incremental energy output/input ratio from 1964 to 1970 was 2.76 as compared with 7.8, the average energy output/input ratio during 1970. Similar energy output/input estimates have also been reported in Pimentel (1980) for other U.S. crops; and in Lovering and McIsaac (1976) for major crops in Canada.

Similar energy estimates for major crops in the developing countries are almost nonexistent. Whatever limited comparative information is available was developed by Pimentel et al. (1973), FAO (1977b), and Leach (1975), and is summarized in Table 3. The amount of energy used in the form of fertilizer in developing countries (in this case Nigeria and Philippines) is rather small as compared with that used in developed countries (in this case, United Kingdom and United States). However, the productivity of fertilizer energy (as expressed by average output/input ratio) is much higher in the case of developing countries than in the developed countries. Since the average energy output/input ratio is not a very good index to measure productivity of fertilizer energy, one should be cautious in drawing any policy conclusions based on this index alone.

Table 3. Share of Fertilizer in Total Farm Energy Consumption and Energy Output/Input Ratio for Crop Production

Crop	Country	Energy Input: Fertilizer	Energy Input: Total[a]	Fertilizer as % of Total	Average Crop Yield	Average Fertilizer Energy Input
		- - (GJ/ha/year) - -			(mt/ha)	(GJ/mt)
Maize	United Kingdom	5.51	26.37	21	5.02	1.10
	United States	11.12	29.85	37	5.06	2.20
	Nigeria	0.90	1.44	63	0.99	0.91
	Philippines	0.38	2.79	13	0.93	0.41
Rice	United States	11.66	65.46	18	5.68	2.08
	Philippines	0.45	4.16	11	1.55	0.29
Wheat	United Kingdom	9.05	15.01	57	3.96	2.29

a. Includes labor (human + draft, animal) energy.

On the basis of this index, it has been generally argued in the literature that energy efficiency in developing countries is greater than in developed countries. This may be so, but the available empirical evidence is rather fragmentary. The crop yields in developing countries are about one-fourth to one-fifth of the corresponding yields in developed countries. The low energy output/input ratio is partly explained by the prevalence of classical law of diminishing returns to fertilizer use because farmers in developed countries are operating at a much higher level of technology. Yet, reverting to traditional agriculture in order to save commercial energy is neither feasible nor advisable.

One could conclude without reservation, however, that fertilizer has played an important role and will play an even greater role in transforming the traditional agricultural sector and in expanding food production. Furthermore, we must remember that intensive farming through higher fertilizer use does produce more energy output, whether as food, feed, fiber, or fuel.

CHAPTER 4

CHANGING STRUCTURE AND OUTLOOK FOR FERTILIZER SECTOR

The location of manufacturing facilities, production, consumption, and trade patterns in the world fertilizer sector are expected to change in response to the location, supply, and price of energy. The purpose of this chapter is to examine the past growth, the present status, and the future outlook of different aspects of the fertilizer sector, especially with an emphasis on the economic implications of these changes for developing countries.

Historical Antecedents

The development of the chemical fertilizer industry has rather a short history.[9] The function of plant nutrients in plant growth began to be understood in the early 19th century. De Saussure and Liebig laid the foundation of the modern fertilizer industry by recommending that fertilizers be added to soil. The commercial fertilizer industry began around the middle of the 19th century when Lawes produced superphosphate in England. The use of commercial fertilizers in most countries was introduced around the year 1900. The fertilizer products which were introduced as commercial fertilizers included Chilean nitrate, Peruvian guano, potash, basic slag, superphosphate, and ammonium sulfate.

Ammonia was recognized as the basis for producing nitrogen fertilizers. However, the synthetic ammonia process was not discovered until the early 20th century. Haber and Bosch from Germany laid the foundation of the modern nitrogen fertilizer industry by synthesizing ammonia from hydrogen and nitrogen using coke as feedstock. Ironically, it was World Wars I and II which provided the needed impetus to the research and development of the fertilizer industry, especially nitrogen. However, the fertilizer use remained rather small until the middle of the 20th century. It was used mainly in developed countries and on plantation crops in developing countries.

9. The details of historical development in the fertilizer industry, with respect to individual fertilizers and production processes, are available in Hignett (1981), IFDC (1979), Lamer (1957), and Slack (1970).

Average Fertilizer Use

Average fertilizer use has been increasing over time but at quite different rates of growth in developed and developing countries. The average fertilizer use levels for world regions are reported in Table 4. Two aspects of fertilizer use stand out.

Table 4. Consumption of Fertilizer Per Hectare of Arable Land and Permanent Crops in 1979[a]

Region	N	P_2O_5	K_2O	Total[b]
	(kg/ha)			
Developed market economies	58	36	33	127
North America	48	24	26	97
Western Europe	105	64	60	229
Oceania	6	30	5	41
Other DME	61	63	44	169
Developing market economies	17	9	5	31
Africa	4	3	2	8
Latin America	17	16	10	42
Near East	21	13	1	34
Far East	23	8	5	36
Other DgME	16	2	2	20
Centrally planned economies	60	28	20	107
Asian CPE	100	19	4	123
Eastern Europe and U.S.S.R.	43	31	26	100
Developed all	52	34	30	116
Developing all	29	11	5	44
World	40	22	16	77

a. Derived from FAO (1981a).
b. Totals may not be exact because of rounding off numbers.

First, the use in developing market economies is among the lowest in the world. During 1979, the average fertilizer use in developing market economies was 24% of that in developed market economies, 29% of that in centrally planned economies, and 40% of that in the world. Whereas, during 1979, the developing market economies accounted for about 50% of world population which was 2.8 times the population of developed market economies and 1.5 times the population of centrally planned economies. Relevant questions which arise are (1) whether the developing market economies can and/or should bridge this large gap, and (2) if not, what other technologically and economically feasible alternatives are

available to the developing countries which would enable them to meet their growing demand for plant nutrients.

Second, the average NPK ratio reveals that the fertilizer use in developing countries is dominated by nitrogen. During 1979, the NPK ratios in the average fertilizer use were 1.7:1.1:1.0 and 5.8:2.2:1.0 for developed and developing countries, respectively. This reflects a certain degree of imbalance in fertilizer use in developing countries. The question of nutrient imbalance is specific to crops, soils, technology, and agroclimatic variables. However, the areas with intensive agriculture are experiencing deficiency symptoms of various nutrients. Furthermore, the average nutrient uptake ratio for commonly fertilized crops is different from the prevailing nutrient supply ratio in most developing countries.

The growth in fertilizer consumption per hectare of arable land and permanent crops is reported in Table 5 for all the world regions. First, the overall annual average growth in nutrient use is 4.1% for developed countries and 10.0% for developing countries. The difference in these growth rates is explained by (1) the fertilizer use in developed countries had more or less stabilized at

Table 5. Growth in Fertilizer Consumption Per Hectare of Arable Land and Permanent Crops From 1969 to 1979[a]

Region	Average Annual Compound Growth Rate for			
	N	P_2O_5	K_2O	Total
	(%)			
Developed market economies	4.7	2.0	3.5	3.5
North America	4.8	2.2	4.6	4.0
Western Europe	5.4	1.9	3.0	3.6
Oceania	3.6	1.5	1.9	1.8
Other DME	1.4	2.7	1.5	1.9
Developing market economies	9.1	10.7	9.8	9.8
Africa	10.7	9.8	7.9	10.2
Latin America	6.4	10.3	9.0	8.3
Near East	8.7	12.1	7.2	9.8
Far East	9.2	8.8	9.6	9.2
Other DgME	12.5	7.7	13.3	12.2
Centrally planned economies	10.0	9.1	4.8	8.6
Asian CPE	16.4	11.4	3.2	14.7
Eastern Europe and U.S.S.R.	6.3	8.5	4.5	6.4
Developed all[b]	5.1	3.0	3.7	4.1
Developing all[b]	10.5	9.7	8.2	10.0
World	7.3	5.3	4.4	6.1

a. Calculated from data reported in FAO (1981a) and previous issues.
b. The base year refers to 1968 rather than 1969.

high levels and (2) the fertilizer use levels in the base year in the developing countries was rather low and the use is rapidly expanding. Second, the use of nitrogen fertilizer is growing faster than that of phosphate or potash in both developed and developing countries. The developed countries have been able to build up high levels of phosphate and to a lesser extent potash in the soil, with resulting residual effects. This is not possible with nitrogen because it does not remain in the soil very long. Nitrogen is also more energy intensive fertilizer than phosphate or potash.

Aggregate Fertilizer Consumption

The evolution of fertilizer consumption from 1950/51 (i.e., 1950) to 1985/86 (i.e., 1985) is reported in Figure 7. The common use of fertilizer in developing countries began around 1950. During 1950/51, the total nutrient consumption in the world was 13.65 million mt, out of which 92% was in developed and 8% was in developing countries. In developing countries most of the fertilizer

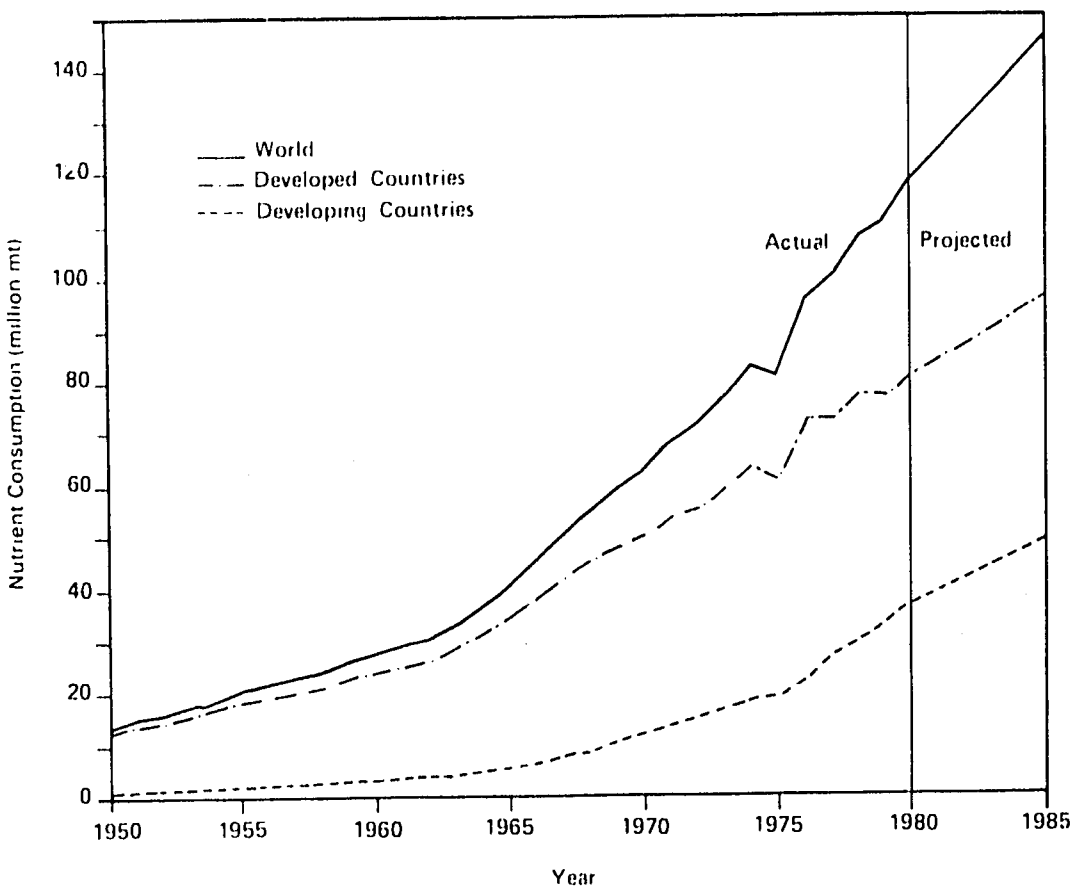

Figure 7. Evolution of Total Nutrient ($N + P_2O_5 + K_2O$) Consumption.

was used on plantation and cash crops, rather than food crops. Furthermore, the share of individual plant nutrients during 1950/51 was 28%, 42%, and 30% for nitrogen, phosphate, and potash, respectively. During 1979/80, the world nutrient consumption was approximately 111.73 million mt, indicating an eightfold increase over 1950/51. The share of developing countries increased from 8% in 1950/51 to 31% in 1979/80. Furthermore, the share of individual plant nutrients also changed to 51% for nitrogen, 28% for phosphate, and 21% for potash during 1979/80.

The current and projected levels of aggregate fertilizer consumption are summarized in Table 6. For the world as a whole the nutrient consumption is projected to increase from 112 million mt in 1979/80 to 141 million mt during 1984/85, representing an almost 26% increase. During 1979/80, the share in aggregate consumption was 41% for developed market economies, 37% for centrally planned

Table 6. Current and Projected Levels of Fertilizer Consumption in the World[a,b]

Regions	1979/80 (Actual)				1984/85 (Projected)			
	N	P_2O_5	K_2O	Total[b]	N	P_2O_5	K_2O	Total[b]
	(million mt)							
Developed market economies	22.6	14.2	12.8	49.7	26.1	15.4	14.5	56.0
North America	11.1	5.5	6.0	22.6	13.3	6.3	6.9	26.5
Western Europe	10.0	6.1	5.7	21.8	11.1	6.4	6.4	23.9
Oceania	0.3	1.4	0.2	1.8	0.3	1.5	0.3	2.1
Other DME	1.2	1.3	0.9	3.4	1.4	1.3	0.9	3.6
Developing market economies	11.3	6.1	3.1	20.5	15.5	9.0	4.3	28.8
Africa	0.5	0.4	0.2	1.2	0.8	0.7	0.3	1.8
Latin America	2.7	2.5	1.6	6.8	3.8	3.7	2.3	9.8
Near East	1.8	1.1	0.1	3.0	2.4	1.5	0.1	4.0
Far East	6.3	2.1	1.2	9.5	8.6	3.1	1.6	13.3
Other DgME	c	c	c	c	0	0	0	0
Centrally planned economies	23.2	10.8	7.6	41.6	29.8	14.6	11.8	56.2
Asian CPE	11.2	2.1	0.4	13.7	14.9	3.1	0.8	18.8
Eastern Europe and U.S.S.R.	12.0	8.6	7.2	27.8	14.9	11.5	11.0	37.4
Developed all	34.7	22.9	20.0	77.5	41.0	26.9	25.5	93.4
Developing all	22.5	8.2	3.5	34.2	30.4	12.1	5.1	47.6
World	57.2	31.1	23.5	111.7	71.4	39.0	30.7	141.1
% nutrient share in total	51	28	21	100	50	28	22	100

a. Derived from FAO (1981a) and FAO (1981b).
b. Totals may not be exact because of rounding off numbers.
c. Represents a unit of less than 0.5.

economies, and about 18% for developing market economies. During 1984/85, these proportions are expected to be 40%, 40%, and 20%, respectively. However, one must be very cautious in interpreting these projections since they are based on simple trends and do not account for changes in agricultural technology and fertilizer prices. Other gradual changes taking place in developing countries include preferences for compound (NPK) and high-analysis fertilizers.

Among the developing market economies, the Far East is by far the largest fertilizer-consuming region, with India accounting for the largest share. During 1979/80, out of 20.5 million mt of nutrient consumption, the shares of Africa, Latin America, the Near East, and the Far East were approximately 6%, 33%, 15%, and 46%, respectively. During 1984/85, the corresponding shares are not projected to change very much. This is quite a contrast in relation to the population distribution. During 1980, 51% of the world's population was estimated to be in developing market economies. Out of this, approximately 18%, 16%, 10%, and 55% were estimated to be in Africa, Latin America, the Near East, and the Far East, respectively.

Aggregate Fertilizer Production and Trade

With few exceptions, the developing countries have been and still are net importers of chemical fertilizers. During 1979/80, the developing market economies were estimated to run a deficit equivalent to 8.1 million mt of nutrients.[10] The other region with a net deficit is Asian centrally planned economies. Countries with serious balance-of-payment and foreign exchange problems, especially those which import food and energy, are finding it exceedingly difficult to finance fertilizer imports. The foreign exchange scarcity coupled with their desire to reduce dependence on a rather unstable world fertilizer market have led many developing countries to create or expand their domestic fertilizer capacity. In response to new production plans, however, the net deficit in developing market economies as a group is projected to remain about the same at 8.0 million mt of nutrients during 1984/85. The fertilizer trade balance for N, P_2O_5, and K_2O for world regions is summarized in Table 7.

At the global level, the location of fertilizer industry is determined in part by comparative economic advantage as reflected

10. For the world as a whole the production is estimated to exceed consumption by about 7.2 million mt of nutrients during 1979/80. This does not represent production surplus but rather the amount which is lost, unaccounted for, or in the pipeline.

Table 7. Current and Projected Fertilizer Trade Balance in the World[a]

Regions	1979/80 (Actual) N	P_2O_5	K_2O	Total[b]	1984/85 (Projected) N	P_2O_5	K_2O	Total[b]
	(million mt)							
Developed market economies	4.3	4.1	2.8	11.0	1.6	6.0	5.1	12.7
North America	1.8	4.3	3.2	9.2	-0.5	5.2	5.7	10.4
Western Europe	1.8	-0.2	0	1.6	1.5	0.2	-0.6	1.1
Oceania	-0.1	-0.1	-0.2	-0.3	0	0	-0.3	-0.3
Other DME	0.8	-0.1	-0.1	0.6	0.6	0.6	0.3	1.5
Developing market economies	-3.2	-1.8	-3.1	-8.1	-2.7	-1.5	-3.8	-8.0
Africa	-0.4	0.2	-0.2	-0.5	-0.3	1.8	-0.3	1.2
Latin America	-1.2	-0.8	-1.6	-3.6	-1.0	-1.6	-2.1	-4.9
Near East	0	-0.6	-0.1	-0.6	0.3	-0.2	0.2	0.3
Far East	-1.7	-0.6	-1.2	-3.4	-1.6	-1.5	-1.6	-4.7
Other DgME	c	c	c	c	0	0	0	0
Centrally planned economies	1.6	0.1	2.4	4.1	0.8	-1.1	4.6	4.3
Asian CPE	-1.5	-0.1	-0.4	-2.0	-1.7	-0.3	-0.8	-2.8
Eastern Europe and U.S.S.R.	3.1	0.3	2.8	6.2	2.5	-0.8	5.4	7.1
Developed all	7.3	4.2	5.6	17.2	4.1	5.2	10.5	19.8
Developing all	-4.7	-1.9	-3.5	-10.0	-4.4	-1.8	-4.6	-10.8
World	2.6	2.4	2.2	7.2	-0.3	3.3	5.9	8.9

a. Derived from FAO (1981a) and FAO (1981b).
b. Totals may not be exact due to rounding off numbers.
c. Deficit of 0-0.5 million mt.

by fertilizer production costs on a unit basis. The location, availability, and price of fertilizer raw materials are, among others, major determinants of fertilizer production costs and, hence, comparative economic advantage. Since the potash deposits are found only in a few countries, the world location and trade patterns are not expected to change very much. Canada and the U.S.S.R. have been and will continue to be major sources of fertilizer potash for the world market. The major raw material for phosphate fertilizers is phosphate rock which is relatively more widely distributed around the world. Morocco and the United States will continue to dominate the world market for phosphate rock in the near future. Many other developing countries do have phosphate rock reserves but some are of low quality and may not be suitable for the existing phosphate rock processing technology. However, these countries are actively seeking ways to utilize their indigenous rock to meet domestic phosphate fertilizer requirements. Major changes in cost of production and location are taking place in the case of nitrogen fertilizer industry, the details of which will be discussed in Chapter 6. Despite the strategic role in fertilizer production, the supply of raw materials, however, is not expected to be a barrier to growth in fertilizer industry in the near future.

Unlike fertilizer demand which grows continuously and gradually, fertilizer supply expands in spurts following a typical "cobweb" pattern. Long gestation periods, large investments, indivisibilities, and large risks characterize most of the fertilizer industry and make planning for investment in fertilizer production extremely difficult. The decision to invest in fertilizer industry is further complicated by worldwide inflation, high interest rates, difficulties in making financing arrangements, and uncertain returns to investments. These demand and supply characteristics result in cyclical fertilizer shortages and surpluses and a cyclical patterns in fertilizer prices. The implications for fertilizer consumption and food production could be very serious during tight supply years. These factors also affect farmers' decisions about whether to use fertilizers as well as the government's policies with respect to investment, subsidies, and imports.

Regional Shift in Fertilizer Consumption

Widespread use of chemical fertilizers began later in developing countries than in developed countries. As was pointed out earlier, the share of developing market economies in world fertilizer production and consumption is relatively small, but it is increasing with time. The shares of the different world regions in the incremental (actual and projected) world consumption of fertilizer are reported in Figure 8. The share of the developed market economies declined from more than 60% during the 1950s to about 20% in the 1970s. On the other hand, the share of the developing market economies has increased from less than 10% to almost 30% in the corresponding years. In the case of the Asian centrally planned economies, most of the increase occurred in the late 1960s and early 1970s, with China playing a dominant role. The share of Eastern Europe and the U.S.S.R. has also been gradually increasing.

The gradual shift in favor of the developing countries is occurring for several reasons. First, the developing countries started with a very low base in fertilizer consumption and had nowhere to go but up. Second, the development and adoption of fertilizer responsive wheat and rice varieties, falling real price of fertilizers, and specific government policies directed at expanding food production through modern input use, served as major "demand pull" factors to expand fertilizer consumption during the 1970s. Third, expansion in fertilizer production capacity, mainly in response to the "fertilizer crisis" of 1973/74, created a significant "supply push" factor toward expanded fertilizer consumption during the latter part of the 1970s. In many countries, often the major constraint to expanded fertilizer use is the lack of fertilizer supply. As a result, the creation of domestic fertilizer capacity in many developing countries gave the badly needed boost to fertilizer consumption at both farm and national levels.

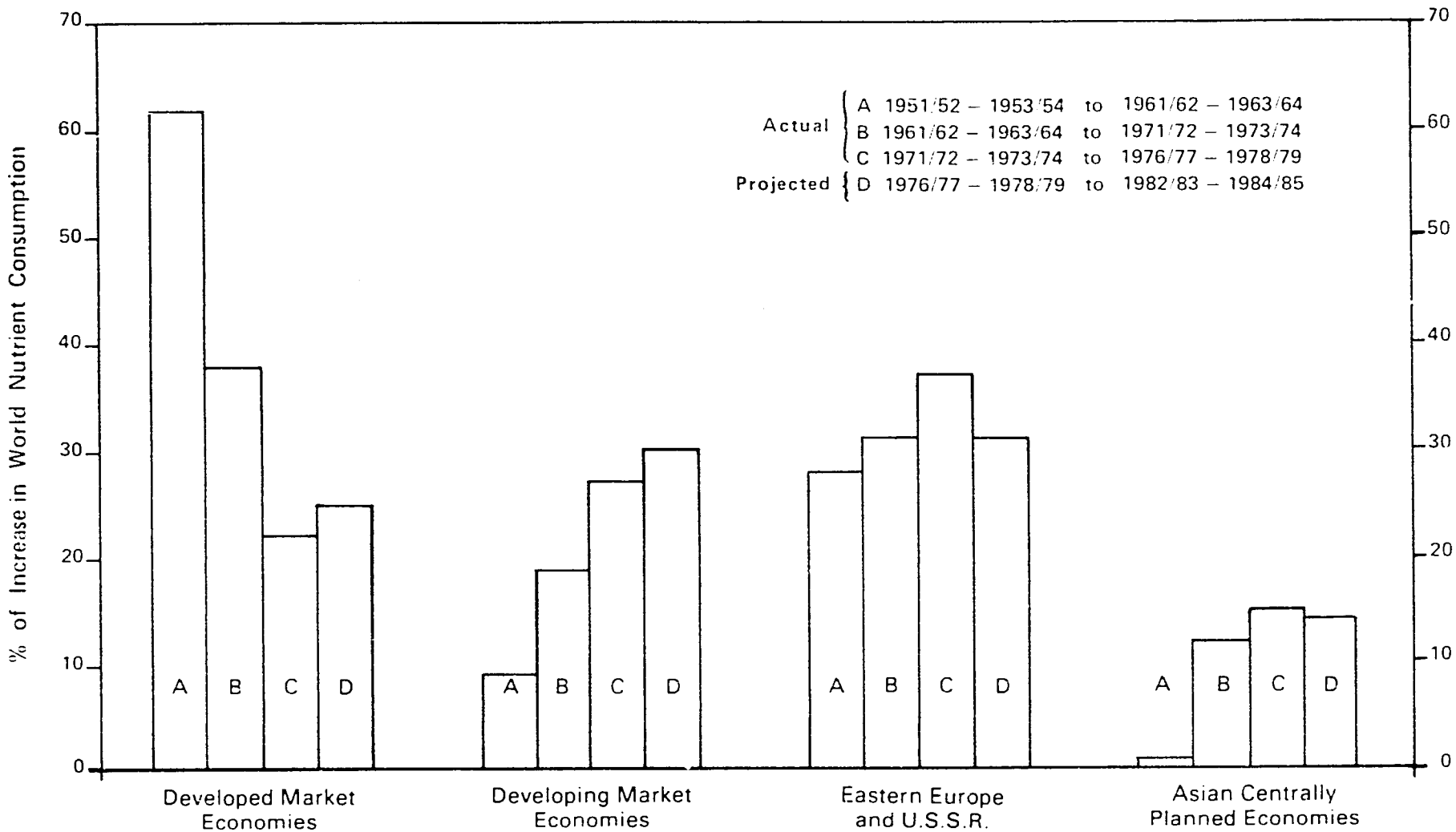

Figure 8. Regional Shift in Incremental N, P_2O_5, K_2O Consumption in the World Over Time.

CHAPTER 5

ENERGY—VITAL INPUT INTO THE FERTILIZER SECTOR

Energy input, and hence energy cost, is a major component of fertilizer production costs. Among the chemical fertilizers, however, the production of nitrogen is not only highly energy intensive but also dependent mainly on hydrocarbon fuels as a source of energy. During 1979/80, the total amount of nitrogen fertilizer consumed in the world was approximately 57.2 million mt. Assuming that 1 mt of N produces 10 mt of grain, 572 million mt of grain was the direct result of using nitrogen fertilizers alone.[11] Out of this, 225 million mt was produced in the developing countries. Another energy crisis that might disrupt the existing nitrogen fertilizer industry in the world can create a "food crisis," which will have far more serious economic repercussions than any energy crisis simply because food, not commercial energy, is the basis of human survival.

Types of Energy Used in the Fertilizer Sector

The types of energy used in the fertilizer sector are illustrated in Figure 9. Three points are worth noting. First, nitrogen fertilizer production uses energy sources both for feedstock and for processing; whereas, phosphate and potash production uses energy only for processing.[12] Second, the main sources of energy for ammonia production are hydrocarbons such as natural gas, naphtha, or fuel oil; whereas, energy sources for phosphate and potash are steam and electricity, which can be generated from any convenient fuel (a small percentage of the total fuel may be used directly for drying raw materials and products). Likewise, conversion of ammonia to urea or other solid nitrogen products uses energy mainly as steam and electricity. The process diagrams developed in Appendix C identify the form of energy needed to manufacture various finished fertilizers and intermediates. Third, fertilizer transportation and application depend mainly on hydrocarbons for motor fuel. As an exception, transportation by rail depends on electricity in some countries.

11. The appropriateness of using 1:10 ratio, to estimate grain output that can be attributed to fertilizer use, is discussed in Mudahar (1978). For most developing countries this may underestimate foodgrain output due to fertilizer use.
12. Energy, in the form of some hydrocarbon derivative, is also used as a feedstock to produce packaging material, but the amount involved is rather small.

FERTILIZER TYPE	FERTILIZER ACTIVITY			
	PRODUCTION (Pr)	PACKAGING (P)	TRANSPORTATION (T)	APPLICATION (A)
N	FEEDSTOCK (H) FUEL (E)	FEEDSTOCK (H) FUEL (E)	FUEL (H)	FUEL (H)
P_2O_5	FUEL (E)	FEEDSTOCK (H) FUEL (E)	FUEL (H)	FUEL (H)
K_2O	FUEL (E)	FEEDSTOCK (H) FUEL (E)	FUEL (H)	FUEL (H)
NPK	FEEDSTOCK (H) FUEL (E)	FEEDSTOCK (H) FUEL (E)	FUEL (H)	FUEL (H)

Where H All or major share from hydrocarbons (solid, liquid, and gas)
E All or major share from electricity and steam

Figure 9. Types of Energy Used in the Fertilizer Sector.

This division of types implies that the costs for nitrogen production, fertilizer transportation, and application are relatively more sensitive to an increase in oil and gas prices. On the other hand, phosphate and potash production costs may be relatively more sensitive to an increase in price of other types of energy such as coal, lignite, or electricity. In some countries a great part of the electricity can be generated from hydropower, a renewable resource. If electricity is generated from hydrocarbon fuels, however, phosphate and potash costs would also increase as oil prices go up. When coal, lignite, or nuclear energy are the main sources of electricity, the rates are not directly affected by oil prices.[13]

13. According to a report in Chemical Engineering (May 4, 1981, p. 17), the share of electricity generated from different sources in the United States during 1980 was: coal = 50.8%, natural gas = 15.1%, hydro = 12.1%, nuclear = 11.0%, and oil = 10.8%. The remaining 1.2% was generated by other resources, including geothermal, wood, and waste recovery.

Energy Consumption Estimates for the Fertilizer Sector

Despite the crucial role of energy, only a small part of total commercial energy consumed is used in the fertilizer sector. Preliminary estimates of energy consumption in the form of fertilizers are developed in Table 8. Energy consumption for the fertilizer sector in the world during 1978/79 was approximately 4.89 x 10^{18} J and is projected to increase to 6.44 x 10^{18} J during 1984/85, implying an almost 32% increase. The share of developing countries is expected to increase from 32% in 1978/79 to 36% during 1984/85. During 1978/79, of the total fertilizer energy, almost 81% was used for fertilizer production. The proportion is slightly higher (84%) for the developing countries. The remaining proportion is used for packaging, transportation, and application.

Furthermore, for the world as a whole, the proportion of energy used for fertilizer production is approximately 90%, 6%, and 4% for N, P_2O_5, and K_2O, respectively.[14] Similar estimates were also made by FAO (1977b) for 1972/73; these were summarized earlier in Table 2. According to these estimates, the energy used for fertilizer production in the world was approximately 3.38 x 10^{18} J, and 27% of that was in the developing countries. Furthermore, the energy used in fertilizer production and distribution during 1972/73 amounted to only 1.5% of the total commercial energy consumed in the world. The corresponding shares for the developed and developing countries were 1.3% and 2.7%, respectively.[15]

Clearly, any effort to reduce fertilizer energy should be concentrated primarily on nitrogen fertilizer manufacture and secondly on transportation of products, intermediates, and raw material. Probably the greatest opportunity for reducing future energy needs for nitrogen fertilizers is to use them more efficiently so

14. According to Blouin and Davis (1975), during 1974/75 the total energy used in the U.S. fertilizer sector was approximately 552 x 10^{12} Btu. Out of this 12% was required for fertilizer transportation and distribution and 88% for fertilizer production (out of which 85% was for N, 13% for P_2O_5, and 2% for K_2O).

15. It should be pointed out, however, that much of the energy for fertilizers that are consumed in developing countries is not actually used within the country; rather, the energy for imported fertilizers or intermediates is consumed in the exporting country. Thus, the source of energy may be natural gas that would otherwise be wasted by flaring. According to Honti (1981), the amount of natural gas that is flared (worldwide) is three times as much as would be required to produce the world nitrogen supply.

Table 8. Estimated Consumption of Energy by the World Fertilizer Sector[a]

Region	Energy Consumption for Fertilizer Production and PTA[b]			Share in Energy Consumption During 1978/79 for			Share in Fertilizer Production During 1978/79				Regional Share in the World During	
	1978/79	1984/85	% Growth	Fertilizer Production	Fertilizer PTA	Total	N	P_2O_5	K_2O	Total	1978/79	1984/85
	(million GJ)			(%)								
Developed market economies	2,085	2,479	19	80	20	100	89	6	5	100	43	38
North America	1,001	1,231	23	81	19	100	90	5	5	100	20	19
Western Europe	917	1,052	15	80	20	100	89	6	5	100	19	16
Oceania	47	55	17	62	38	100	55	38	7	100	1	1
Other DME	120	139	16	77	23	100	84	10	6	100	2	2
Developing market economies	930	1,454	56	83	17	100	92	6	2	100	19	23
Africa	48	77	60	79	21	100	89	8	3	100	1	1
Latin America	254	393	55	79	21	100	87	9	5	100	5	6
Near East	147	234	59	84	16	100	93	7	0	100	3	4
Far East	479	749	56	85	15	100	94	4	2	100	10	12
Other DgME	1	0	0	100	0	100	100	0	0	100	c	0
Centrally planned economies	1,875	2,507	34	82	18	100	91	5	4	100	38	39
Asian CPE	653	847	30	86	14	100	96	3	1	100	13	13
Eastern Europe and U.S.S.R.	1,222	1,662	36	79	21	100	87	7	6	100	25	26
Developed all	3,307	4,142	25	80	20	100	88	7	5	100	68	64
Developing all	1,583	2,301	45	84	16	100	94	4	2	100	32	36
World	4,890	6,442	32	81	19	100	90	6	4	100	100	100

a. Totals may not be exact because the numbers are rounded off.
b. PTA = packaging, transportation of raw material and product, and application.
c. Represents a unit of less than 0.5.

that less nitrogen per metric ton of food production will be required. Use of increased proportions of less energy-intensive fertilizers should help ensure more energy-efficient crop production. Clearly, there is a need to allocate more energy to the fertilizer sector in order to produce more food to feed the expanding population. However, every effort must be made to improve energy efficiency in all phases of fertilizer production, distribution, and use.

Energy Requirements for Individual Fertilizers

As far as production of individual fertilizers is concerned, the energy requirements for products and corresponding nutrients are reported in Figure 10. There is a substantial variation in energy requirements for different fertilizers, ranging from 79.5 GJ/mt of nutrients for prilled urea (highest) to 2.2 GJ/mt for granular monoammonium phosphate (MAP) (not including energy for nitrogen input) using the hemihydrate process. The production of urea requires 8.5 times as much commercial energy as triple superphosphate (TSP) does and 18.5 times as much as potassium chloride (KCl) in North America. For precisely this reason, many oil-importing countries find it difficult to continue operating the existing nitrogen fertilizer facilities and plan to close some plants. The result is a trend away from traditional sources of fertilizer supply (e.g., Japan, Western Europe) to countries with large feedstock reserves.

As indicated in the preceding discussion, urea is the most popular nitrogen fertilizer, especially in the developing countries. However, urea is the most energy-intensive nitrogen fertilizer and also the most difficult to use efficiently. Consequently, there is a need to reexamine the present trend to concentrate on the manufacture of urea to the virtual exclusion of other nitrogen fertilizers in developing countries.

The total amount of commercial energy used in the fertilizer sector may be rather small, but without it fertilizer (especially nitrogen) cannot be produced and cannot be transported across continents and within countries. Therefore, energy prices have a substantial impact on fertilizer prices. In the absence of power (e.g., during power outage), the large fertilizer plants cannot be run, and this results in low operating rates, higher energy use, and higher per-unit fertilizer costs. Power disruption is one of the primary reasons for the low utilization rate of existing fertilizer plants in most developing countries.

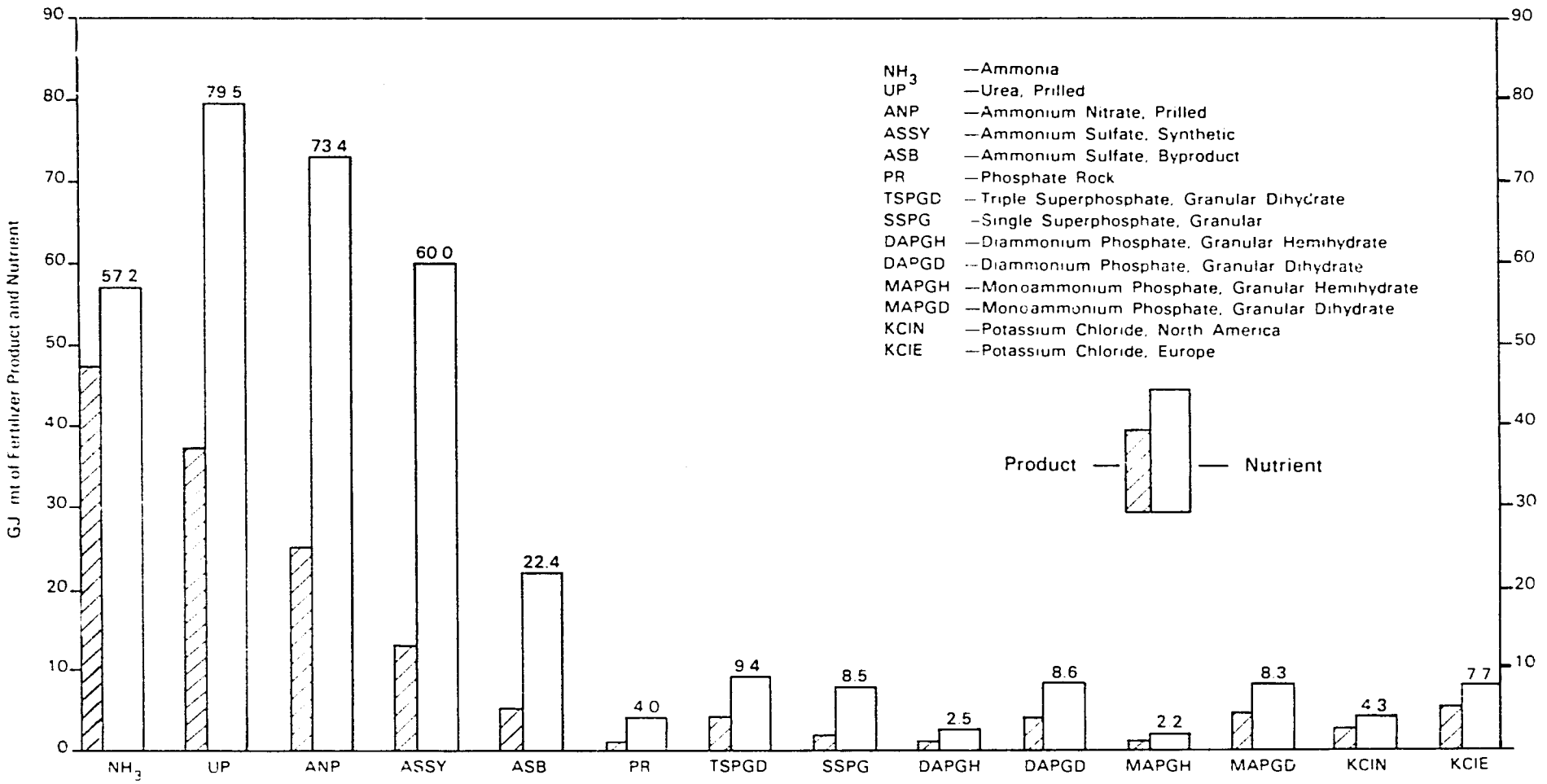

Figure 10. Average Energy Requirements for Manufacturing Selected Nitrogen, Phosphate, and Potash Fertilizers.

Energy Requirements for Individual Nutrients

There are a number of factors that determine commercial energy requirements for individual fertilizer products:

1. Use of energy source as feedstock.
2. Type of feedstock and raw material.
3. The degree of nutrient concentration.
4. The amount of processing required to obtain the final product.
5. Whether the process is exothermic or endothermic.
6. The nature and level of the fertilizer production technology.
7. The degree of automation in the operating fertilizer plants.

Since these factors vary across fertilizers, fertilizer plants, and countries, the commercial energy requirements also vary.

In addition to fertilizer products, it is useful to obtain the commercial energy requirements for individual plant nutrients (N, P_2O_5, and K_2O). Such information not only provides a broad overview of commercial energy requirements on a nutrient basis but also is used to obtain energy requirements for the entire fertilizer sector. The average energy requirements for individual nutrients depend on the share of the individual fertilizers providing a particular nutrient and on certain other assumptions. In this sense, one must interpret these estimates as good first-order approximations. These estimates may vary from one country to another, depending on the major source of the primary nutrient.

Estimates of average energy requirements for N, P_2O_5, and K_2O production and distribution are given in Table 9 and compared with other available estimates there. According to these estimates, the energy requirements for fertilizer production are 69.5, 7.7, and 6.4 GJ/mt for N, P_2O_5, and K_2O, respectively. On the other hand, typical energy requirements for fertilizer packaging, transportation, and application are 8.6, 9.8, and 7.3 GJ/mt for N, P_2O_5, and K_2O, respectively. In case of N, approximately 90% of the energy requirement is for production alone. But in the case of P_2O_5 and K_2O slightly less than 50% of the energy requirements is expended for production, and the remaining energy is used for packaging, distribution, and application.

These energy requirement estimates reported in Table 9 vary across different studies. However, these differences can be explained. First, some studies do not account for energy requirements for distribution at all, others lump distribution with production, and still others include energy for transportation of imported raw materials. Second, most studies use individual fertilizers as a basis for the estimates rather than a weighted average of all nutrient supply sources. Third, some studies are for specific countries where conditions may not be typical of world averages. Fourth, the underlying assumptions also vary across different studies.

Table 9. Average Energy Requirements for Fertilizer Production, Packaging, Transportation, and Application: Summary of Various Studies

Source	GJ/mt for Production of			GJ/mt for PTA[a] of			GJ/mt, Total		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
Mudahar and Hignett	69.54	7.70	6.38	8.59	9.75	7.32	78.13	17.45	13.70
Leach (1975)[b]	c	c	c	c	c	c	80.00	14.00	9.00
White (1978)	65.13	11.64	9.30	c	c	c	c	c	c
Tatchell and Lewis (1977)[d]	79.60	14.00	8.07	c	c	c	c	c	c
Blouin (1974)[e]	51.69	12.45	5.60	c	c	c	c	c	c
Jurgens-Gschwind (1980)	54.00	13.70	6.00	6.00	13.7	3.6	60.00	27.4	9.6
FAO (1977b)[f]	c	c	c	c	c	c	80.00	14.00	9.00
Pimentel et al. (1973)[g]	c	c	c	c	c	c	77.55	14.03	9.69
Lovering and McIsaac (1976)[h]	c	c	c	c	c	c	90.64	20.27	14.73
Revelle (1980)	62.80	c	c	c	c	c	c	c	c

a. PTA stands for packaging, transportation of raw material and product, and application.
b. Bagged fertilizer delivered to farm.
c. Represents not available.
d. Includes fertilizer packaging. N is from urea, and P_2O_5 and K_2O are from complex fertilizers.
e. N, P_2O_5, and K_2O are from urea, DAP, and KCl, respectively.
f. Originally from Leach (1975). Refers to bagged fertilizers delivered to farm.
g. For fertilizer manufacture and processing.
h. For fertilizer manufacture and transportation. The N, P_2O_5, and K_2O are from AN, TSP, and KCl, respectively.

The present estimates are a weighted world average based on estimates of the proportions of each major type of fertilizer produced. Energy requirements for manufacturing each product are based on the average North American practice (see Appendix B) when available, supplemented by other information. Energy for transportation is based on rough estimates of the average distance for each type of transport for each nutrient and includes transportation of raw materials for those countries that import them. Further details on the energy estimates and the underlying assumptions are given in Chapters 8 and 9.

CHAPTER 6

ENERGY AND GROWTH IN NITROGEN FERTILIZER INDUSTRY

The preceding analysis indicates that (1) production of nitrogen accounts for approximately three-fourths of the total commercial energy used in the fertilizer sector and (2) the major source of energy used in nitrogen production is nonrenewable hydrocarbons. It is in this context that the growth in nitrogen fertilizer industry is directly dependent on energy supply and prices.

Dominance of Nitrogen Fertilizer

Nitrogen often is regarded as the most important fertilizer nutrient because its supply often limits crop yields, although phosphorus is the limiting factor in many of the developing countries. However, nitrogen fertilizer is used in much larger quantities in developing countries, and its manufacture is by far the most energy intensive. Although elemental nitrogen is abundant in the earth's atmosphere, plants cannot use it until it is "fixed" in chemical compounds. Nitrogen fixation requires energy, whether by natural or manmade processes.

As reported in Table 10, nitrogen dominates the fertilizer scene at all levels, including both fertilizer use at the farm level and aggregate fertilizer consumption, production, and trade. The degree of dependence on nitrogen fertilizers is relatively greater in developing and Asian centrally planned economies than in developed

Table 10. Estimated Share of Nitrogen in Fertilizer Consumption and Production[a]

Region	% Share of Nitrogen in Fertilizer			
	Average Use Per Hectare 1979	Aggregate Consumption 1979/80	Aggregate Production 1979/80	Aggregate Trade 1979/80
Developed market economies	46	46	44	39
Developing market economies	55	55	65	(40)[b]
Asian centrally planned economies	82	82	83	(75)[b]
Eastern Europe and U.S.S.R.	43	43	44	50
World	51	51	50	36

a. Derived from FAO (1981a).
b. Parenthesis implies a deficit.

economies. It is this dependence on nitrogen fertilizer, much of which is imported, that makes the developing countries relatively more vulnerable to energy shortages and price hikes in the international market.

The main reason for nitrogen's dominant role in the fertilizer scene is its demand at the farm level. This demand is, of course, influenced by the fact that the immediate economic returns from nitrogen use are often higher (or perceived to be higher) than the returns from the use of phosphate and potash. The available evidence indicates that the share of nitrogen in the fertilizer scene will not really change in the near future. However, the location of the nitrogen industry and its trade patterns are expected to change substantially with time.

Urea as the Dominant Nitrogen Fertilizer

The developments with respect to the share of urea in nitrogen fertilizer production capacity are illustrated in Figure 11. The most common sources of nitrogen supply are urea, ammonium nitrate

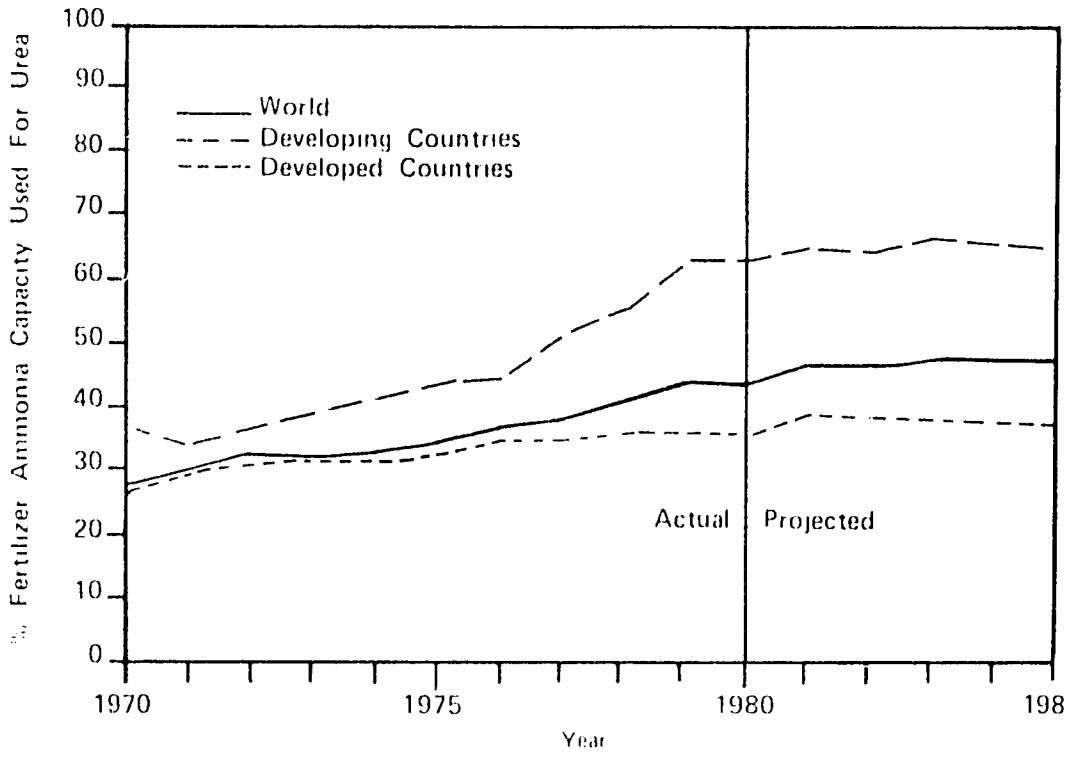

Figure 11. Proportion of Fertilizer Ammonia Capacity Allocated to Produce Urea.

(AN), and ammonium sulfate (AS). Until 1970, ammonium nitrate accounted for the highest percentage of the world nitrogen fertilizer capacity. During 1970, ammonium nitrate accounted for 31% of the capacity as opposed to 29% for urea. However, from 1971 onward urea has been occupying a larger and larger share in the nitrogen fertilizer capacity. The share of urea in world nitrogen fertilizer capacity has increased from 31% in 1971 to 45% in 1979 and is projected to be 49% during 1985. The proportionate share of urea capacity in nitrogen fertilizer capacity for developing countries is higher than for the developed countries. In developing countries the share has increased from 34% in 1971 to 64% in 1979 and is projected to be 67% during 1985. The share of ammonium nitrate and ammonium sulfate is declining over time.[16]

The share of urea in nitrogen fertilizer consumption is reported in Table 11. During 1979, 30% of the total nitrogen in the world was consumed in the form of straight urea, which is approximately three-fourths of total urea production. The rest of the urea was consumed as components in compound fertilizers, especially in developed countries. The share of straight urea in the total nitrogen consumption varies significantly from one region to another. For example, this share of urea in Asia during 1979 was estimated to be 62% (the highest) and only 8% in Western Europe (the lowest). Furthermore, 68% of total urea was consumed in developing countries, with Asia as the leader, accounting for approximately 61% of the world total and 90% of that consumed in the developing countries.

There are several reasons for urea becoming the leading source of nitrogen. Among others are its high nutrient content (46%), the low handling and distribution charges on a nutrient basis, and the possibilities of economies of scale from large urea plants made possible through innovations in nitrogen production technology. In the light of these factors, urea probably will continue to be the dominant source of nitrogen supply in most developing countries.

Urea may be a good fertilizer but it also has serious drawbacks. First, the efficiency of urea, in terms of uptake by plants, is comparatively low. The available evidence indicates that nitrogen losses from urea applied to rice can be as high as 80%. Second, urea poses problems in handling, storage, and use in hot and humid conditions, and is not chemically suitable for bulk blends with TSP. Third, on a nutrient basis, urea uses more energy than any other

16. The share of individual nitrogen fertilizers (urea, AN, and AS) in total fertilizer ammonia capacity is estimated after making appropriate allowances for ammonia used for industrial purposes. The share of ammonia used for industrial purposes is approximately 20% in developed and 10% in developing countries.

Table 11. Role of Urea in Nitrogen Fertilizer Sector[a] in 1979

Region[b]	Urea N Capacity	Urea N Production	Urea N Consumption[c]	Total Nitrogen Consumption	Straight Urea N Consumption as % of Total N Consumption	Regional Share in World Urea N (Straight) Consumption
	(million mt)					(%)
North America	4.0	3.6	1.0	10.4	10	6
Western Europe	3.6	2.7	0.8	9.8	8	5
Eastern Europe and U.S.S.R.	6.4	4.9	3.2	13.1	24	20
Oceania	0.1	0.1	0.1	0.3	33	1
Africa	0.3	0.2	0.4	1.5	27	3
Asia[d]	12.3	8.7	9.6	15.4	62	61
Latin America	0.9	0.4	0.7	2.7	26	4
World	27.6	20.6	15.8	53.2	30	100

a. Derived from Pronstad and Louis (1981).
b. The regional classification is slightly different from what is followed in other tables, mainly because the original data were available only in this form.
c. Consumption of urea as straight N fertilizer only. The remainder of the urea was consumed as part of compound fertilizers and nitrogen solutions. The difference in regional urea production and consumption is also due to urea trade.
d. Asia includes the Asian portion of the Middle East and China.

nitrogen fertilizer. Energy requirements of urea are 1.1 times that of ammonium nitrate and 3.5 times that of byproduct ammonium sulfate. Aside from byproduct ammonium sulfate which is in limited supply, the lowest energy forms of fertilizer nitrogen available to farmers are ammonium phosphates and ammonia for direct application.

Ammonia as a Basis of Nitrogen Fertilizers

The atmospheric nitrogen can be fixed as a plant nutrient (1) biologically through aerobic and anaerobic N fixation mechanisms, (2) meteorologically as by lightning, and (3) chemically through ammonia synthesis. Nature's fixation of nitrogen is seen dramatically in high-energy discharge of lightning which cause the nitrogen and oxygen of the air to combine to form nitrogen oxides that react with water and eventually form nitrates in rainwater or soil. Fixed nitrogen brought down by rainfall originates partly from meteorological sources and partly from decaying vegetable matter. The nitrogen fixation through biological processes also requires energy which is supplied indirectly by the sun.

The nitrogen fertilizer industry, however, depends almost exclusively on ammonia as a source of nitrogen. The ammonia synthesis occurs under very high pressure and temperature (see Figure C-1) as follows:

$$3H_2 + N_2 \rightarrow 2NH_3$$

(Hydrogen) + (Nitrogen) → Ammonia

Both gases must be in as pure a form as possible. Nitrogen is obtained from the atmosphere. On the other hand, hydrogen is normally obtained from steam reforming of natural gas or naphtha or the partial oxidation of heavy fuel oil or coal. In this respect, ammonia synthesis and, hence, nitrogen fertilizer industry is primarily dependent on nonrenewable hydrocarbons for its source of hydrogen although some is obtained from water through electrolysis. Ammonia can be used as a fertilizer and very commonly is in North America and some other countries such as Denmark and Mexico. Alternatively, it can be converted into straight or compound solid (prilled or granular) fertilizers to supply nitrogen requirements in most developed and developing countries. Regardless of the feedstock used in its production, ammonia is the key input in the manufacture of nitrogen fertilizers.

Regional Shift and Outlook for Ammonia Production

Even though ammonia is also used for industrial purposes, trends in ammonia production to a great extent reflect trends in

Table 12. Growth in Total Ammonia Capacity Among Leading World Producers[a]

Country/Region	Ammonia Capacity ,'000 mt of N				% Change in Ammonia Capacity		
	1970	1975	1980	1985	1970 to 1975	1975 to 1980	1980 to 1985
Developed market economies[b]	29,710	34,456	37,887	39,512	16	10	4
Canada	1,302	1,233	2,083	3,203	- 5	69	54
France	1,965	2,485	2,840	2,568	26	14	-10
Germany, F.R.	2,473	2,529	2,980	2,545	2	18	-15
Japan	2,420	3,602	2,926	2,926	49	-19	0
Netherlands	1,586	2,133	2,287	2,287	34	7	0
United States	12,556	13,678	15,600	15,570	9	14	0
Developing market economies[b]	4,288	9,147	16,328	26,321	113	79	61
Brazil	35	215	464	1,034	514	116	123
Egypt	125	165	541	867	32	228	60
India	1,483	2,808	4,756	7,607	89	69	60
Indonesia	48	285	1,101	1,823	494	286	66
Korea, Republic of	428	635	1,065	1,065	48	68	0
Mexico	566	812	1,780	3,260	43	119	83
Pakistan	175	344	547	1,408	97	59	157
Trinidad and Tobago	372	272	567	1,111	-27	108	96
Turkey	125	125	397	668	0	218	68
Centrally planned economies[b]	16,713	23,033	39,905	46,331	38	73	16
Bulgaria	1,159	1,159	1,331	1,809	0	15	36
China	3,471	4,833	8,321	8,321	39	72	0
Poland	1,522	2,004	1,950	2,356	32	- 3	21
Romania	1,193	1,736	3,238	3,484	46	87	8
U.S.S.R.	7,073	10,098	20,945	25,755	43	107	23
World	50,711	66,636	94,120	112,164	31	41	19

a. Derived from NFDC (1981).
b. Regional totals are for the entire region and not just the selected countries shown.

nitrogen fertilizer production. The world ammonia production capacity has increased from 50.7 million mt (in terms of N) in 1970 to 94.0 million mt in 1980 and is expected to increase to 112.2 million mt during 1985. The growth in ammonia production capacity by world regions and by the leading ammonia producers is reported in Table 12. The share of developing countries in the total ammonia production capacity was only 17% during 1970. However, the developing countries share increased to 22% during 1975 and to 27% during 1980. It is projected that the share of developing countries will be 32% during 1985. This represents a gradual shift to a more vigorous growth in developing market economies, Eastern Europe and the U.S.S.R., with relatively little growth in developed market economies.

The market outlook for ammonia production and supply by year 1985, as reported in Table 12, seems bright. However, the location and trading patterns are shifting away from traditional supply sources.[17] During 1970 the United States and the U.S.S.R. accounted for 25% and 14%, respectively, of the world ammonia capacity. During 1985 the world ammonia production scene is projected to reverse itself with the United States and the U.S.S.R. accounting for 14% and 23%, respectively. The ammonia production capacity in Japan, the Federal Republic of Germany, and France is expected to decline in absolute terms. East European countries, including Bulgaria, Poland, and Romania, are expanding their ammonia production capacity. Among the developing countries, China, India, Mexico, and Indonesia are emerging as major ammonia producers.

In response to high ammonia prices caused partly by the energy crisis of 1973/74, most of the developed countries expanded their ammonia production in order to take advantage of high world prices in the nitrogen fertilizer trade. However, the major part of the expansion in ammonia production occurred in developing countries, leading to a buildup of overcapacity in the world. The excess production resulted in the fall in prices and even the shutdown of some ammonia plants in Japan and North America. In some parts of the United States, for example, it is cheaper to

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17. Stangel (1975) has analyzed the shift in location and trading patterns for fertilizer in the Asian context in response to the 1973/74 energy crisis.

import ammonia than to produce it. On the other hand, Mexico, India, Indonesia, the U.S.S.R., and China are expanding their ammonia production capacity rapidly. This expansion is mainly the result of their having a supply of feedstock available for ammonia production and/or a desire to reduce their dependence on imports for an adequate supply of ammonia. It should be noted, however, that urea cannot be produced economically from imported ammonia because carbon dioxide is a necessary raw material that is available at almost no cost only at ammonia plants.

Sources of Feedstock for Ammonia Production

Man's first effort to fix nitrogen imitated nature's lightning flashes. High-energy electric arc process associated with hydroelectric generators fixed nitrogen derived from the air to form nitrates. However, the process was wasteful of energy and was soon abandoned. Electrolytic production of hydrogen to make ammonia by the Haber-Bosch process is preferable where cheap, abundant hydroelectric power is available. With a given amount of electricity, four times as much nitrogen can be fixed in the Haber-Bosch as in the arc process, and a higher analysis nitrogen fertilizer can be made. Synthesis of ammonia from nitrogen and hydrogen requires very little energy, but the electrolytic production of hydrogen is energy intensive.

Other sources of feedstock to provide hydrogen in ammonia synthesis include natural gas, naphtha, fuel oil, coke oven gas, coal, and refinery gas. The proportionate contributions of different feedstocks to ammonia production capacity are shown in Table 13 and Figure 12. During 1970, 64% of world ammonia capacity was based on natural gas. This share increased to 66% in 1975, 71% in 1980, and is projected to increase to 73% during 1985. More than 80% of the incremental ammonia capacity in the world is based on natural gas. As a result, the relative share of ammonia based on other feedstocks is declining gradually. At the world level, natural gas is clearly the dominant feedstock for ammonia production.

According to Honti (1981), 80% of the world's ammonia is made from natural gas and this percentage is likely to increase. The percentage of ammonia production from natural gas is higher than the percentage of ammonia capacity because many of the naphtha- or coal-based plants are idle or operating at a low percentage of capacity or have been converted to natural gas. These changes

Table 13. Percentage Change in Ammonia Capacity in the World by Sources of Feedstock[a]

Feedstock	Ammonia Capacity, '000 mt of N								% Change in Ammonia Capacity		
	1970		1975		1980		1985				
	Amount	%	Amount	%	Amount	%	Amount	%	1970-75	1975-80	1980-85
Natural gas	32,210	63.5	44,024	66.1	67,241	71.4	81,958	73.1	37	53	22
Naphtha	4,772	9.4	7,277	10.9	9,318	9.9	10,481	9.3	52	28	12
Fuel oil	1,241	2.4	1,629	2.4	3,165	3.4	4,448	4.0	31	94	41
Coal	1,055	2.1	922	1.4	1,817	1.9	1,874	1.7	-13	97	3
Coke oven	6,610	13.0	7,907	11.9	7,733	8.2	7,782	6.9	20	-2	1
Electrolytic hydrogen	1,002	2.0	708	1.1	799	0.8	799	0.7	-29	13	0
Refinery gas	1,866	3.7	2,074	3.1	1,486	1.6	1,486	1.3	11	-28	0
Variable sources	345	0.7	617	0.9	922	1.0	650	0.6	79	49	-30
Other sources	454	0.9	454	0.7	454	0.5	835	0.7	0	0	84
Unknown sources	1,156	2.3	1,024	1.5	1,185	1.3	1,851	1.7	-11	16	56
TOTAL	50,711	100.0	66,636	100.0	94,120	100.0	112,164	100.0	31	41	19

a. Derived from NFDC (1981).

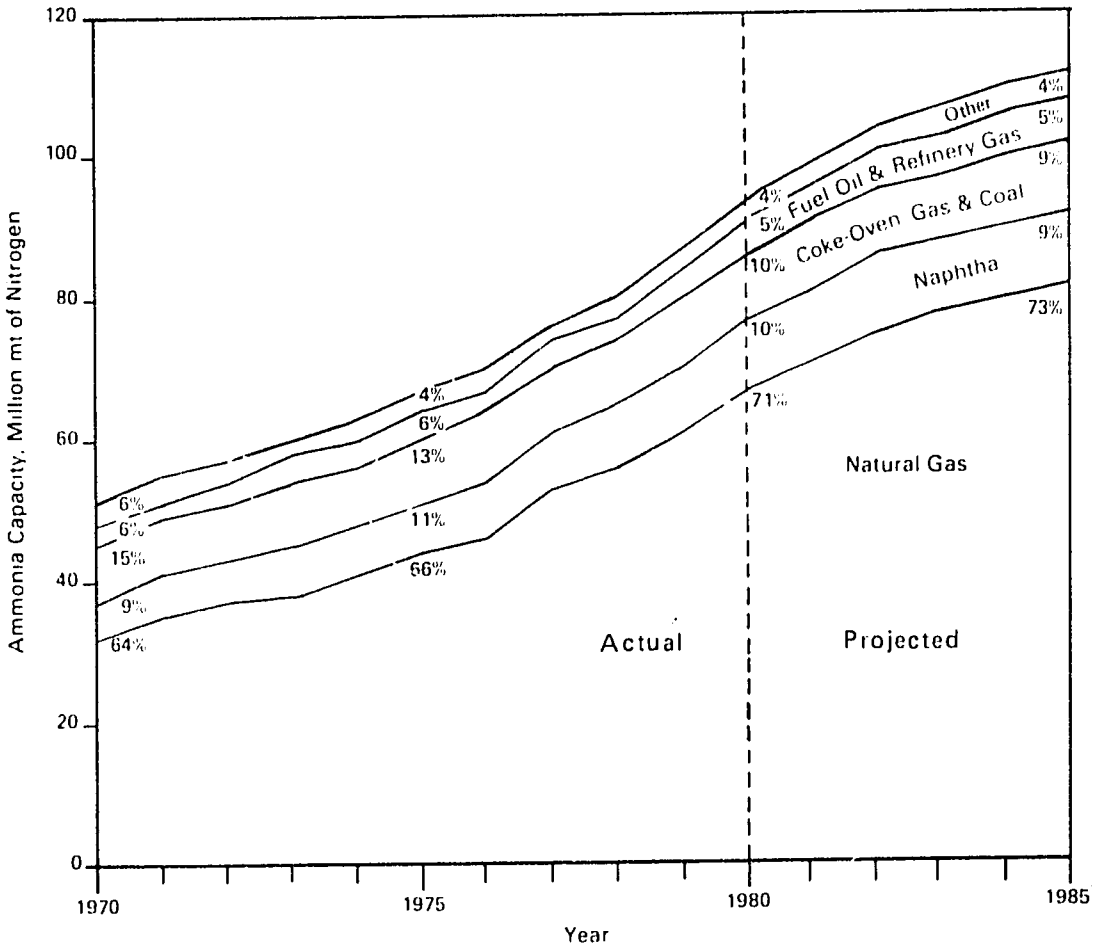

Figure 12. Ammonia Capacity in the World by Sources of Feedstock.

may not be reflected in ammonia capacity data. Naphtha accounts for about 10% of present capacity, but many of the naphtha-based plants have been shut down because the high price of this feedstock makes the ammonia noncompetitive on the world market. Other ammonia feedstocks include liquefied petroleum gas (LPG) which is mainly propane and butane, and liquefied natural gas (LNG).

However, the proportional share of feedstocks in ammonia capacity varies with the world regions and countries. During 1970, the ammonia capacity based on natural gas was 70% in developed market economies, 43% in developing market economies, 73% in Eastern Europe and the U.S.S.R., and only 11% in the Asian centrally planned economies. During 1980, the corresponding shares based on natural gas were 75%, 58%, 87% and 30%, respectively. These shares are projected to increase even further by 1985. The importance of natural gas as a feedstock varies significantly among the leading ammonia-producing countries. The proportionate share of ammonia production capacity based on natural gas during 1980 was 100% in Canada, the Netherlands,

Trinidad, Bulgaria, Poland, and Romania; 95%-100% in the case of the United States, Indonesia, Mexico, and Pakistan; 85% in the case of the U.S.S.R.; and approximately 50% in France, the Federal Republic of Germany, Brazil, and Egypt.

However, there are also countries with large ammonia production capacities that do not depend on natural gas for feedstock. The other feedstock sources include (1) naphtha, contributing 61% in Japan, 48% in India, 100% in South Korea, and 69% in Turkey; (2) fuel oil, contributing 30% in the Federal Republic of Germany and 24% in India; and (3) coke oven gas and coal, contributing 10% in the Federal Republic of Germany, 15% in India, 31% in Turkey, and 51% in China. Only a small share of ammonia production capacity is based on electrolytic hydrogen. This heavy dependence of ammonia production on hydrocarbons, mainly natural gas, naphtha, and fuel oil, makes the nitrogen industry very vulnerable to another energy crisis, especially in some of the developing countries. In order to reduce this dependence, research and development efforts are now directed toward alternative sources of feedstock. Also, there has been increased exploration for natural gas, and numerous new reserves have been found.

Preference for Natural Gas as Ammonia Feedstock

Approximately three-fourths of the world's ammonia capacity is based on natural gas, the preferred feedstock. The selection of feedstock for ammonia/urea complex depends in part on (1) initial capital investment for the plant and (2) energy requirements per metric ton of ammonia. The available estimates with respect to capital investment and energy requirements for ammonia production based on alternative feedstocks are summarized in Table 14. Alternative sources of feedstock reported in the table include electrolytic hydrogen, coal, fuel oil, naphtha, and natural gas.

The magnitude of capital investment and energy estimates do vary across different studies. This is partly due to different sets of assumptions underlying these estimates. However, these studies agree that ammonia plants based on natural gas as feedstock are cheaper than other plants and require less energy to produce a ton of ammonia. The final selection of feedstock would, of course, also depend on regularity in supply and price of feedstock. At this stage, plants based on coal are not yet price competitive with plants based on natural gas. Since the price of natural gas is increasing faster than the price of coal, the ammonia from coal-based plants may soon be preferred over others, especially in countries with large coal reserves. India and South Africa, for example, have already built commercial ammonia plants based on coal.

At the existing gas and naphtha prices, the cost of ammonia production based on naphtha is very expensive. It takes about

Table 14. Energy Consumption and Relative Investment Cost for 1,000-mtpd Ammonia Plants Using Various Feedstocks[a]

Feedstock	Process	Btu x 10^6/mt of NH_3[b]					Relative Investment[c]				
		N-W-W	B	A[d]	B-F-Q	I[e]	N-W-W	B	A[d]	W	I[e]
Electrolytic hydrogen	Electrolysis	135.1	f	111.2	f	102.0	1.50	f	2.20	f	f
Coal	Partial oxidation	46.7	45.0[g]	55.6	49.6	49.6	1.86	1.92	1.80	1.79	2.00
Fuel oil	Partial oxidation	40.3	38.0	37.0	38.6	38.6	1.66	1.30	1.50	1.27	1.60
Naphtha	Steam reforming	37.8	37.0	35.7	37.5	37.4	1.15	1.13	1.15	1.12	1.14
Natural gas[h]	Steam reforming	34.5	34.5	30.9	34.2	34.1	1.00	1.00	1.00	1.00	1.00

a. These energy consumption estimates differ from those reported earlier in several respects: (1) they are battery limit energy requirements, not total; (2) they are based on net heating value of fuel, not gross; and (3) they are based on new plants operated at top efficiency, not existing plants operated at average efficiency.
b. N-W-W = Nichols, Williamson, and Waggoner (1978); B = Blouin (1974); A = Appl (1976); B-F-Q = Buividas, Finneran, and Quartulli (1974); I = IFDC (1979).
c. W = White (1974).
d. Energy export credited. For ammonia based on coal, the energy consumption is 55.6 x 10^6 Btu when coal gasification takes place without pressure, and 46.1 x 10^6 Btu when pressure for coal gasification is 25 bar. The corresponding relative investment is 1.8-2.1.
e. In case of electrolysis, it refers to fuel for generating electricity in a fuel-fired plant.
f. Not available.
g. Minimum energy requirements.
h. Of this, 60% as feedstock and 40% as fuel.

38 Mcf of natural gas to produce a metric ton of ammonia. At $2.50/Mcf of gas, the gas cost alone would be about $95/mt of ammonia. On the other hand, it takes about 0.9 mt of naphtha to produce 1 mt of ammonia. The current price of naphtha is over $250/mt. Clearly naphtha cost alone would be about $225/mt of ammonia. Furthermore, Iran has been a major source of sweet, light crude oil used to produce naphtha. The Japanese nitrogen industry based on naphtha was directly dependent on Iran for its naphtha supply. An Iranian crisis led to disruptions in this supply, so Japan is currently in the process of phasing out its ammonia plants based on naphtha and looking for alternative feedstocks.

Most of the ammonia industry has been normally involved in long-term contracts for the supply and price of gas. Information on the length of the contract and price is difficult to obtain for the whole industry. However, many fertilizer intelligence experts believe that most of the existing gas contracts will soon expire and then come up for renegotiations. The new gas prices will probably be much higher, leading to high cost of ammonia production based on natural gas. This may reduce the substantial competitive edge of gas-based plants over others. Despite an increase in gas prices, however, there is a general feeling that natural gas will continue to be the major feedstock for ammonia production.

It is possible to substitute those feedstocks whose supply is more certain for those which are scarce or uncertain. However, the potential for substitution is limited and depends on a large number of factors, including price and availability of feedstock, capital costs, production costs, and other technical considerations. Retrofitting existing fertilizer plants is technologically possible for alternative feedstocks, but it can result in substantial capital investments and, hence, an increase in capital costs.

Market Outlook for Ammonia Feedstocks

An important question which needs to be answered is whether there are enough feedstock reserves around the world to continue producing nitrogen fertilizers. The answer to this question is positively yes. There are large known reserves of natural gas and other hydrocarbons which, if used for fertilizer production alone, can last for centuries. However, the exploitation of those reserves and their allocation for fertilizer production depends on the price of nitrogen fertilizers and the opportunity cost of gas and other hydrocarbons. Substantial allocation of these feedstocks to nitrogen fertilizer production seems at best uncertain.

The perspective for any individual country with respect to ammonia production can be obtained from information presented

earlier in Figure 4. The countries that may really be in trouble are those which show a deficit in both nitrogen and energy. This includes many of the developing countries that find it difficult to either produce it domestically or pay for imports. Countries with a current surplus of nitrogen but a deficit of energy would soon be phasing out part of their nitrogen industry or retrofitting their plants for use of feedstocks that are relatively abundant. Countries which have surpluses of both energy and nitrogen do not seem to have any serious problems. Finally, countries with a surplus of energy but a deficit of nitrogen supply have a large potential, and some of these have already started developing their ammonia production capacity. This includes most of the oil- or gas-rich countries that are relatively poorly developed. There may be plenty of feedstock to produce ammonia in these countries but the capital investment costs may be high, and this would result in high production costs. The relative production costs, of course, would depend on gas prices, ammonia prices, interest rates, capital investments, and capacity utilization rates.

Countries that have indigenous supplies of natural gas would be relatively less affected by an energy crisis than those that use imported feedstocks. For example, Pakistan and Bangladesh have ample supplies of natural gas even though they are "energy deficient" in the sense that they must import liquid fuels for such uses as transportation. These countries are rapidly increasing their nitrogen fertilizer capacity and should soon become self-sufficient in nitrogen. Furthermore, widespread exploration for natural gas has met with considerable success, and several countries have built or are planning to build nitrogen fertilizer production facilities based on recently discovered deposits. Examples are Malaysia, India, Thailand, Tanzania, Ireland, and New Zealand. Natural gas exploration has been relatively less intensive than oil exploration in the past. However, the prospects of finding new reserves of natural gas are good. Improved technology, for example, has resulted in newly developed better exploration techniques, and the high price of natural gas has improved the economics of those resources that were not economic in the 1960s and 1970s.

Naphtha and heavy fuel oil are the products of oil-refining processes. The estimates on proven oil reserves during 1981 indicate that 78% of the reserves are located in the developing market economies. The Near East countries alone account for 60% of world oil reserves. Other major oil-exporting countries are Venezuela and Mexico in Latin America, Nigeria in Africa, and Indonesia in the Far East. Many other developed countries may be large oil producers but their domestic oil consumption generally exceeds the domestic production.

Estimated proven gas reserves in the world are reported in Table 15.[18] The total gas reserves were estimated to be about 1,588 trillion ft^3 during 1971 and have increased to 2,639 trillion ft^3 in 1981. In 1981, 46% of the world's reserves are estimated to be in developing market economies and 36% in centrally planned

Table 15. Regional Share in the Estimated Proven Gas Reserves in the World Over Time[a,b,c]

Region	Estimated Proven Gas Reserves 1971	Estimated Proven Gas Reserves 1981	Estimated Proven Gas Reserves as a % of the World 1971	Estimated Proven Gas Reserves as a % of the World 1981
	(trillion ft^3)			
Developed market economies	493	474	31	18
North America[d]	325	278	20	11
Western Europe	148	159	9	6
Oceania	19	36	1	1
Other DME	1	1	e	e
Developing market economies	655	1,211	41	46
Africa	156	182	10	7
Latin America	73	160	5	6
Near East	389	779	24	30
Far East	37	90	2	3
Other DgME	0	0	0	0
Centrally planned economies	440	954	28	36
Asian CPE	5	25	e	1
Eastern Europe and U.S.S.R.[f]	435	929	27	35
Developed all	928	1,403	58	53
Developing all	660	1,236	42	47
World	1,588	2,639	100	100

a. Reserves are based on January 1 of the year in which they are listed.
b. Totals may not be exact because the values are rounded off.
c. Derived from International Petroleum Encyclopedia (1981).
d. Includes unproven reserves for Canada.
e. Represents a unit of less than 0.5.
f. Includes reserves for Albania, Bulgaria, Czechoslovakia, German Democratic Republic, Hungary, Mongolia, Democratic People's Republic of Korea, Romania, and Vietnam.

18. There is no shortage of natural gas on a worldwide basis, and known reserves are 60% higher than 10 years ago. According to estimates reported in the International Petroleum Encyclopedia, world natural gas proven reserves (in trillion ft^3) have increased from 1,588.4 in January 1971 to 2,638.5 in January 1981, a 66% increase.

economies. However, North America, the Near East, and Eastern Europe (including the U.S.S.R.) account for 76% of world gas reserves, with 11%, 30%, and 35% as their respective shares. It is these three regions that are expected to be the major producers of ammonia and nitrogen fertilizers in the next 20 years. The current natural gas production is about 57 trillion ft^3, out of which 41% is produced in North America, about 3% in the Near East, 27% in Eastern Europe and the U.S.S.R. According to Laoussine (1980), for the world as a whole, 83% of the total gas production is marketed, 11% is flared, and about 6% is reinjected. On the other hand, for OPEC countries which contribute about 15% of world's gas production, 54% is flared, 31% is marketed, and 15% is reinjected. Out of total gas flared in the world, 70% is in the OPEC countries. Some of the OPEC countries, however, may have no choice but to flare the associated gas since the capital investment costs may be too high to justify capturing it.

The potential for ammonia production from flared natural gas in the member countries of the Organization of Arab Petroleum Exporting Countries (OAPEC) alone is estimated in Table 16. During 1979, 47% of the natural gas (mostly associated gas)

Table 16. Estimated Potential for Ammonia Production from Flared Natural Gas in OAPEC Countries During 1979[a]

Country	Natural Gas[b], $10^9 \times ft^3$ Produced	Utilized	Flared	Flared as % of Production	% Share of Individual Countries in Flared	Equivalent Ammonia Production Potential[c] (million mt)
Algeria	1,540	1,186	354	23	12	8.85
Bahrain	177	143	34	19	1	0.85
United Arab Emirates	539	215	324	60	11	8.10
Saudi Arabia	1,785	444	1,341	75	47	33.55
Syria	19	1	18	94	1	0.45
Qatar	233	157	76	33	3	1.90
Kuwait	460	334	126	27	4	3.15
Libya	829	657	172	21	6	4.30
Iraq	509	79	430	85	15	10.75
Total	6,091	3,216	2,875	47	100	71.90[d]

a. Derived from Ohnada (1981).
b. Includes mainly associated gas.
c. Assuming that 40×10^3 ft^3 natural gas is needed as feedstock and fuel to produce 1 mt of ammonia.
d. This amounts to 8.2% of estimated actual ammonia capacity in the whole world during 1979. In other words, it is equivalent to approximately 59 million mt of nitrogen. During 1979/80, world consumption of fertilizer nitrogen was 57 million mt.

produced in OAPEC countries was flared. This was approximately 2.9 trillion ft^3. Assuming that all the flared gas is used to produce ammonia, it will result in 71.9 million mt of ammonia, 47% of that in Saudi Arabia alone. The ammonia that could have been produced from flared gas amounts to about 82% of the estimated actual ammonia capacity in the whole world during 1979. In other words, the nitrogen equivalent from the ammonia that was not produced would have been slightly more than the actual nitrogen consumption of 57 million mt during 1979/80. Clearly, there is no apparent justification for wastage of such a scarce energy resource. Consequently, there is a need for worldwide effort to capture gas which is being flared and convert that into nitrogen fertilizer and food to feed the hungry.

Unlike oil, gas is difficult to ship across continents from countries that have a surplus to countries that have a deficit. However, it is possible to liquefy it before shipping. The process is highly capital intensive, and as much as 25% of the gas is consumed in supplying energy for liquefaction, refrigeration, storage, and transportation. Even though several projects are being constructed to produce and ship LNG, the technological and market problems at this stage are too serious to draw any definite conclusions about the feasibility of the process.[19] The existing LNG world trade is reported in Table 17. The major exporters of LNG include Algeria, Indonesia, and Malaysia. On the other hand, the major importers of LNG are the United States, Japan and

Table 17. Liquefied Natural Gas World Trade[a]

	LNG Exports			LNG Imports	
Countries	10^9 ft^3/day	% of Total	Countries	10^9 ft^3/day	% of Total
Algeria	4.50	50	United States	2.6	29
Indonesia	1.70	19			
Brunei	0.75	8	Japan	3.1	34
Malaysia	0.85	9			
Other[b]	1.20	13	Western Europe	3.3	37
TOTAL	9.0	100	TOTAL	9.0	100

a. Derived from Laoussine (1980).
b. Approximately 25% and 30% of this comes from Libya and Abu Dhabi, respectively.

19. According to Anderson (1981), international trade in LNG had grown from 1.472 billion m^3 in 1964 to 43.977 billion m^3 in 1979, representing a thirtyfold increase in the past 15 years. Furthermore, international trade in natural gas during 1977 was 10% of its marketed production, and LNG's share in international gas trade was 13.5%.

Western Europe. Technically it is possible to create ammonia capacity on the basis of using imported LNG. However, the LNG price may be too high to make it economically feasible to produce ammonia based on imported LNG.

The cost of transporting natural gas long distances is very high, whether by pipeline or by liquefaction and ocean shipment, and this means that the value of gas located in remote areas is low.[20] Therefore, it has been widely assumed that in the future, ammonia plants will be located in those areas of low-cost gas. However, the cost of building and operating plants in remote areas is high, and the cost of transporting ammonia or urea to consuming areas is also high. These costs tend to offset the advantage of a lower cost feedstock.

Government policies will not only influence the price of gas but also its use in the fertilizer sector. During the past few years, for example, approximately 3%-4% of total natural gas demand in the United States has been used to produce ammonia. The dual pricing mechanism (interstate versus intrastate) for natural gas resulted in higher gas prices for ammonia plants within the state and in gas scarcities for plants based on interstate gas. The impact of deregulation of natural gas prices on nitrogen fertilizer supply and prices is still unknown. However, according to The Fertilizer Institute (1980), gas curtailments in the United States resulted in substantial losses in ammonia production. In the last 10 years (1970-79), the total ammonia loss due to gas curtailments is estimated to be about 3 million short tons. This may be small in proportion to total ammonia production, but if such curtailments are true in other countries as well, the total ammonia loss could be substantial.

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20. According to Anderson (1981), pipeline transport of gas costs about two times that for crude oil, and the cost for sea transport for LNG is four to five times that for crude oil.

CHAPTER 7

IMPACT OF ENERGY PRICES ON FERTILIZER PRICES

The impact of an increase in energy prices is reflected on higher cost of fertilizer production, higher cost of fertilizer distribution, higher fertilizer prices, and eventually higher food prices. The purpose of this section is to analyze these linkages.

Trend in Oil, Urea, and Wheat Prices

The historical pattern of prices for crude oil, urea, and wheat is reported in Figure 13. A quick glance at the diagram indicates a direct relationship among these three prices. Up to 1970 there had been a decline in prices of urea and wheat. However, the crude oil price was stable at $1.80/bbl up to 1970. The oil price increased in 1971 while the wheat and urea prices were still declining. A major increase in oil price came in 1974 as a result of the OPEC decision to raise oil prices and the oil embargo.

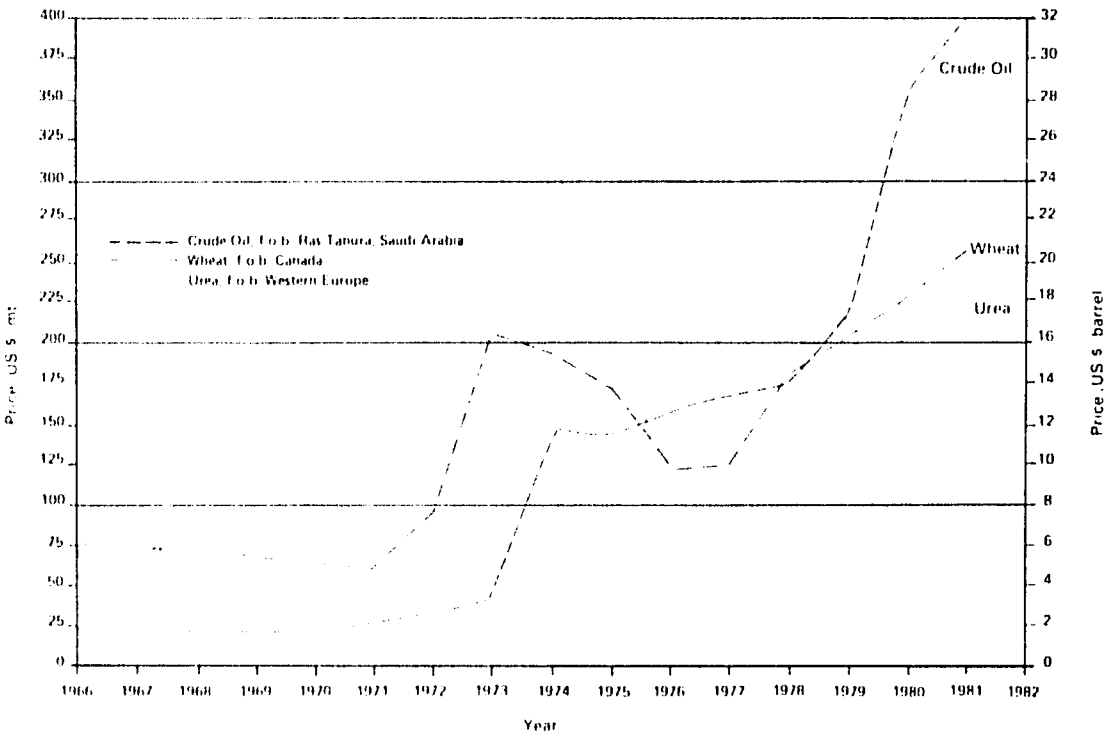

Figure 13. Historical Trends in International Annual Average Prices for Crude Oil, Urea Fertilizer, and Wheat.

An increase in oil prices set into motion economic forces that resulted in worldwide inflation, uncertainty, and disequilibrium in the international markets for commodities and fertilizer. The price of wheat and fertilizer increased due to both direct and indirect effects of oil price increases. Since energy is an input into fertilizer production and fertilizer is an input into crop production, an increase in energy prices resulted in higher fertilizer and crop prices. The energy price increases also had an indirect effect as these prices got reflected in the price structure of other goods and services in the economy.

However, the independent market forces in each of these commodity markets play their own roles. For example, the severe drought of 1972 led to a steep increase in wheat prices in the international market even before the major oil price increase. The prices of urea and wheat fell dramatically during 1975, despite the fact that oil prices stayed at the higher levels. From 1977 onward there has been slight upward pressure on prices, with substantial increases coming in 1979 and thereafter.

Clearly, energy is only one factor, albeit an important one, that influences fertilizer and food prices. Nevertheless, it is difficult to quantify the proportional increase in fertilizer and/or food prices, except in partial analysis. This is mainly because the costs of fertilizer production and crop cultivation are specific for each fertilizer, commodity, location, and technology used. For example, the production cost for urea will vary depending upon the plant size, capital costs, utilization rate, location, feedstock, and other input prices.

Historical Fertilizer Price Behavior

The development of centrifugal compressors (as opposed to the reciprocating type) and steam reforming of natural gas (and naphtha) as feedstocks made it feasible to build large ammonia plants. The resulting economies of scale coupled with the fall in energy requirements and stable energy prices were mainly instrumental in lowering per-unit cost of ammonia production. Since ammonia is a basis for all nitrogen fertilizers, these developments led to a historical declining trend (up to 1971) in prices of major nitrogen fertilizers.[21]

21. For further empirical evidence and the implications of the decline in real price of fertilizer on the fertilizer industry and economic development, see Sahota (1968); for the role of fertilizer prices in agricultural development and the evolution of fertilizer price policy, see Mudahar (1979b).

This decline in price of nitrogen fertilizers resulted in (1) a major push by various countries to expand fertilizer use especially for food crops, (2) expansion in fertilizer use by farmers either as a supplement to or substitute for organic manures, (3) agricultural strategies based on "package of practices" and "package of inputs" with fertilizer constituting an important factor of production, and (4) agricultural research strategies emphasizing the development of crop varieties which will absorb high levels of fertilizer use. However, this decline in fertilizer prices was reversed in 1971, followed by a dramatic increase during 1974. One of the major factors responsible for this dramatic increase was the shortage of energy supply and sudden increase in energy prices, resulting in direct and indirect upward pressure on fertilizer prices.

Fertilizer price is one of the major determinants of fertilizer use. Since most developing countries are net importers of fertilizer, export prices of fertilizer exert a major influence on domestic fertilizer prices and, hence, fertilizer use in importing countries. The historical trend in f.o.b. fertilizer prices from 1966 to 1981 is shown in Figure 11[22]. In addition to regular market forces, the behavior of fertilizer prices can be described by two other factors. These are technological developments in the fertilizer sector and energy prices. As discussed earlier, the fall in prices of energy and improvements in fertilizer production technology led to a declining trend in price of fertilizer up to 1971.

However, the declining trend in fertilizer prices reversed in 1971 and the prices continued to skyrocket during 1972-74, reaching peak levels during the first or second quarter of 1974/75. Peak level prices were over five times the price levels for 1971. The prices dropped during 1975 but stayed above the pre-1972 prices.

Clearly, energy price increases, although important, constituted only one factor responsible for the skyrocketing of fertilizer prices. This observation is based on two facts. First, fertilizer prices dropped after mid-1974 despite the fact that energy prices remained at the record high levels. Second, phosphate and potash fertilizer prices also experienced substantial increases even though these fertilizers are not so energy intensive as nitrogen fertilizers. For example, the increase in f.o.b. prices during 1974 over 1971 was about sevenfold for both urea and TSP. These price increases were not the result of energy price increases alone. Limited world fertilizer supply and a sudden increase in fertilizer demand due to "panic" buying played an important role.

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22. More recent f.o.b. price data for different fertilizers reported in the figure were obtained from Higgins (1980).

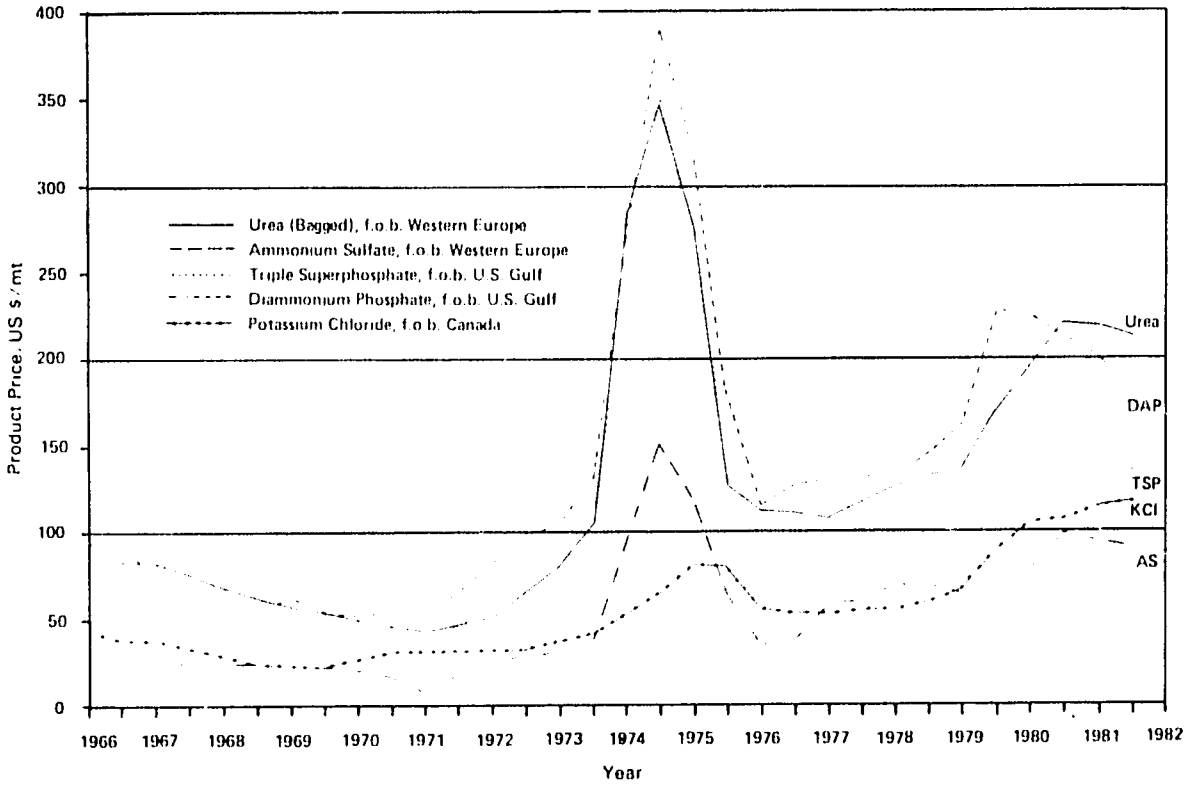

Figure 14. Historical Trend in International Semiannual Average Fertilizer Prices.

The fertilizer prices remained stable until the beginning of 1979, partly because the oil prices also remained stable during this period. During early 1979, the oil prices started increasing (due to OPEC price hike decisions). An increase in oil prices led to an increase in fertilizer production costs, fertilizer export prices, and fertilizer freight rates. The absolute increase in c.i.f. fertilizer prices was even higher than in f.o.b. prices. During the last 15 years, which witnessed a major growth in fertilizer industry, the fertilizer prices have generally been following the oil price movements. The energy prices will continue to increase, resulting in even higher prices for fertilizer and food. The developing food-, fertilizer-, and energy-deficit countries, already facing a serious balance of payment problem, may find it extremely difficult to recover economically.

Natural Gas Prices and Ammonia Production Costs

Since natural gas is a dominant feedstock for ammonia, analyzing the impact of an increase in natural gas prices on ammonia

production costs would be appropriate. As reported in Table 18, the share of natural gas costs (feedstock and fuel) in the ammonia production costs has increased from 38% in 1974 to 40% in 1980, and is expected to be 46% in 1983. The natural gas cost per unit of ammonia is the direct result of gas prices and the amount of gas used in ammonia production. The actual impact of gas prices is not fully reflected in ammonia costs since the gas requirements per unit of ammonia are declining and are expected to go down even further in response to various technological improvements.

Table 18. Impact of Natural Gas Prices on Ammonia Production Costs in the United States[a]

Cost Component	1980 US $/mt of Ammonia[b] Average in 1974[c]	New Plants in 1980[d]	New Plants in 1983[e]
Natural gas cost	34.00	78.75	128.00
Other variable costs	21.75	18.55	18.00
Fixed costs	18.40	46.95	66.05
Return on investment	14.70	52.90	64.70
TOTAL[f]	88.85	197.25	276.75
Share of natural gas in the total cost (%)	38.00	40.00	46.00
Natural gas price ($/Mcf)	0.85	2.25	4.00
Natural gas use (million Btu/mt of NH_3)[g]	40.00	35.00	32.00
Natural gas cost ($/mt of NH_3)[g]	34.00	78.75	128.00

a. Derived from Prentice (1980).
b. Assumes 1,035 mtpd centrifugal compressor ammonia unit employing the catalytic steam reforming process.
c. Plants in operation during 1974.
d. Plants commissioned in 1975-77.
e. Plants projected for 1983-85 commissioning.
f. Required f.o.b. price per metric ton of ammonia.
g. Assuming 1 million Btu = 1 thousand ft^3.

The energy conservation efforts and improvements in ammonia production technology are mainly responsible for lowering gas requirements and hence the potentially large impact of gas prices. If the gas requirements per unit of ammonia do not change (i.e., stay at 40 Mcf/mt of NH_3), the share of natural gas cost in total ammonia cost during 1983 will be 52%, rather than 46%. Furthermore, according to TFI (1980) production cost survey of plants in operation in the United States, the share of natural gas costs

increased from \$11/mt of NH_3 in 1970 to \$23/mt of NH_3 in 1975, and to \$59/mt of NH_3 in 1979. An increase in nonenergy variable and fixed costs also had a heavy impact on ammonia production costs, as indicated by the cost increases reported in Table 18.

Natural Gas Prices and Urea Production Costs

The economic impact of an increase in natural gas price on urea production costs is illustrated in Table 19. The urea production costs are influenced not only by natural gas prices but also by (1) capital costs, and (2) utilization rate of the fertilizer plant. Past experience indicates that the developed countries are able to build plants at lower capital investment and run them much more efficiently (above 90% of capacity) than the developing countries. On the other hand, the capital investment costs in developing countries, especially the remote locations, are very high (at least one and a half to two times those of developed countries). Furthermore, with few exceptions, the utilization rate in developing countries averages around 60% of designed capacity. As has been pointed out earlier, a major share of gas and oil reserves is located in developing countries and a large part of gas is flared. The fertilizer producers in developed countries have to pay generally higher prices for gas than those in developing gas-rich countries.

At a given price of natural gas and utilization rate, the share of energy costs in total urea production costs would be higher in developed than in developing countries. For example, at \$3/Mcf of gas, the share of energy cost would be 42%, 36%, and 30%, respectively, in developed, developing, and remote site plants. Since there are large differences in capital costs and gas prices prevailing in different locations, the impact of energy prices on urea production costs would be quite different. The share of natural gas in urea production costs, let us say in remote locations of Algeria with prevailing gas price of \$0.50/Mcf, will be only 7%. On the other hand, in the United States with gas price at \$3.50/Mcf, the share of natural gas in urea production costs would be 46%.

The economic impact of natural gas prices, capital costs, and capacity utilization rates on urea production is reported in Table 20. In addition to the impact of gas prices and capital costs on urea production costs discussed above, plant utilization rate exerts an important influence on urea production costs and energy needs. With few exceptions, the ammonia-urea plants in developing countries generally operate at about 60% of the designed capacity. Furthermore, the empirical evidence also indicates that the energy consumption per unit of ammonia is at least 25% higher when plants operate at 60% instead of 90% of capacity. For given capital costs, lower plant utilization rate results in higher urea production costs and a decline in the share of energy costs despite the fact that

Table 19. Economic Impact of an Increase in Natural Gas Prices on Urea Production Costs[a]

Natural Gas Price[b] ($/Mcf)	Energy Cost[c]	Scenario I[d] Total Urea Production Costs[g] ($/mt)	Scenario I[d] Energy as a % of Total	Scenario II[e] Total Urea Production Costs[g] ($/mt)	Scenario II[e] Energy as a % of Total	Scenario III[f] Total Urea Production Costs[g] ($/mt)	Scenario III[f] Energy as a % of Total
0.00	0	147	0	190	0	244	0
0.25	9	156	6	199	5	253	4
0.50	18	165	11	208	9	262	7
1.00	35	182	19	225	16	279	13
1.50	53	200	26	243	22	297	18
2.00	70	217	32	260	27	314	22
2.50	88	235	37	278	32	332	27
3.00	105	252	42	295	36	349	30
3.50	123	270	46	313	39	367	34
4.00	140	287	49	330	42	384	36
4.50	158	305	52	348	45	402	39
5.00	175	322	54	365	48	419	42
5.50	193	340	57	383	50	437	44
6.00	210	357	59	400	52	454	46
6.50	228	375	61	418	55	472	48

a. Derived from estimates made by Sheldrick (1980). The common basis for these estimates is: design capacity--1,650 mtpd bagged product, capacity utilization rate--90% for 330 days/year, and urea production--490,050 mtpy. P = plant investment costs, W = working capital, and T = total costs.

b. An increase in gas price of $0.1 Mcf will increase urea production costs by $3.5/mt.

c. Natural gas including fuel and gas for steam and power generation @ 35 Mcf/mt of urea. Energy costs are the same for all three scenarios.

d. Scenario I--developed site; P = $205 million, W = $15 million, and T = $220 million.

e. Scenario II--developing site with some infrastructure; P = $280 million, W = $20 million, and T = $300 million.

f. Scenario III--developing site remote location; P = $375 million, W = $25 million, and T = $400 million.

g. Urea production costs are divided into energy and nonenergy costs. Nonenergy cost includes other variable costs, fixed costs, and capital charges at 15%. These capital charges alone are $67, $92, and $122 for scenario I, II, and III, respectively. Nonenergy costs for scenario I = $147, scenario II = $190, and scenario III = $244.

Table 20. Economic Impact of Natural Gas Prices, Capital Costs, and Capacity Utilization Rate on Urea Production Costs[a]

Natural Gas Price ($/Mcf)	Scenario I, CUR 90%[b] Total Urea Production Cost ($/mt)	Scenario I, CUR 90%[b] Energy as a % of Total[c]	Scenario II CUR 90% Total Urea Production Cost ($/mt)	Scenario II CUR 90% Energy as a % of Total[c]	Scenario II CUR 60% Total Urea Production Cost ($/mt)	Scenario II CUR 60% Energy as a % of Total[d]	% Incremental Urea Cost Due to Capital Costs	% Incremental Urea Cost Due to Energy Costs
0.00	147	0	190	0	277	0	100	0
0.25	156	6	199	5	288	4	98	2
0.50	165	11	208	9	299	7	96	4
1.00	182	19	225	16	321	14	91	9
1.50	200	26	243	22	343	19	87	13
2.00	217	32	260	27	365	24	83	17
2.50	235	37	278	32	386	28	81	19
3.00	252	42	295	36	408	32	77	23
3.50	270	46	313	39	430	36	74	26
4.00	287	49	330	42	452	39	71	29
4.50	305	52	348	45	474	42	69	31
5.00	322	54	365	48	496	44	66	34
5.50	340	57	383	50	518	47	64	36
6.00	357	59	400	52	540	49	62	38
6.50	375	61	418	55	561	51	61	39

a. See Table 19 for the underlying assumptions.
b. CUR refers to capacity utilization rate.
c. Energy consumption @ 35 Mcf/mt of urea.
d. Energy consumption @ 43.75 Mcf/mt of urea or 25% higher over base of 35 Mcf.

energy consumption increases. For example, in Scenario II at a gas price of $3.00/Mcf, reduction in plant utilization rate from 90% to 60% increases urea production costs from $295/mt to $408/mt (38% increase) and decreases the share of energy in total cost from 36% to 32%.

Outlook for Fertilizer Prices

Fertilizer prices in the international market are influenced by expected fertilizer demand and supply, market imperfections resulting from price-fixing arrangements, and fertilizer production costs. The fertilizer production costs in turn depend upon (1) capital costs, (2) interest rates, (3) labor costs, and (4) energy costs. Barring any unforeseen technological breakthrough in fertilizer manufacturing, the fertilizer production costs will continue to increase, certainly not less than the general inflation rate. It is doubtful that the world fertilizer industry will experience the declining price trend of the 1960s again.

As reported in Table 21, the capital requirements of a 1,000-mtpd ammonia plant coupled with a 1,700-mtpd urea plant built in the United States to use natural gas increased from $47.0 million in

Table 21. Capital Requirements for 1,000-mtpd Ammonia and 1,700-mtpd Urea Facilities Using Natural Gas in the United States

Plant Unit	Cost Concept	Capital Requirements During[a] 1973[b]	1978[b]	1982[c]	1990[c]
		(US $ million)			
Ammonia	Battery limit	19.0	56.0	98.0	210.0
Ammonia	Total	28.5	84.0	147.0	315.0
Urea	Battery limit	10.5	27.8	48.6	104.0
Urea	Total	15.7	41.8	72.0	156.0
Storage and bagging	Total	2.8	7.8	13.4	29.0
TOTAL COST		47.0	133.6	232.4	500.0
Index (1973 = 100)		100	284	494	1,064

a. Assuming 3-year construction time. Estimates for 1973 and 1978 are for 1,000-mtpd ammonia plants, whereas, estimates for 1982 and 1990 are for 1,000-short-ton-per-day ammonia plants. The effect of this difference on investment costs is within the limits of accuracy of the estimates.
b. Shields et al. (1975).
c. Data for battery limit ammonia cost was obtained from James (1981). Other costs are assumed to be proportional.

1973 to $133.6 million in 1978 (a 184% increase), and are expected to increase to $500.0 million during 1990 (a 274% increase over 1978). Given the international monetary problems and financial uncertainties, the interest rates may remain high. The needed rate of return on investment may not be less than 20% on pretax basis. The labor costs will continue to increase by at least the same rate as the general cost of living. Finally, according to James (1981), the natural gas prices (the main feedstock for ammonia production) are expected to reach $6/Mcf by the mid-1980s in the United States after decontrol. Furthermore, since many gas contracts are up for renegotiation, the new gas prices are expected to be much higher than the existing contract prices. The new gas price contracts may also include an escalation clause in order to keep up with the general inflation. Given past experience, the prices of nitrogen fertilizers are expected to increase faster than the prices of phosphate and potash fertilizers.

Fertilizer Prices and Food Production Costs

The direct impact of an increase in energy and fertilizer prices on food production costs depends on the techniques used to produce food. The traditional agriculture that uses no modern inputs will be the least affected by energy and fertilizer price increases. On the other hand, modern agriculture based on energy-intensive production techniques (fuel, fertilizer, irrigation, and pesticides) will be seriously affected and will have to make major adjustments in response to changes in energy prices and energy supply.

In order to feed the ever-expanding world population and reduce the incidence of malnutrition, there is a need to expand food production through intensive cultivation. This would involve not only shifting practices in favor of modern production techniques but also increasing the intensity of their use. This would mean that agricultural production techniques in the future would be more energy intensive. The level of energy-derived input use, however, would depend on their economics and price relationships.[23]

The average share of energy in the form of fertilizer in total commercial energy used in agricultural production is approximately 45% in the world, 40% in developed countries, and 68% in developing

23. According to Warnken (1976), in Nicaragua the comparative advantage shifted from energy-intensive agriculture to traditional agriculture after the energy crisis because the input price increases based on fossil fuels were much more than the output price increases. Farmers in many other developing countries were also faced with similar situations.

countries. The impact of an increase in fertilizer prices on food prices depends on many factors. Among others, this includes level of fertilizer use, fertilizer response, crop prices received, and the total cost of cultivation. Since all these factors vary with the country, region, crop, and even location for the same crop, it is very difficult to realistically estimate the impact of fertilizer prices on food prices.[24]

The cost of fertilizer use is a major component in the total cost of crop cultivation in modern agriculture. Consequently, the impact of an increase in fertilizer prices (in absence of subsidies) will be substantial on the total cash costs for food production. This would be especially true on those farms in developing countries where labor is generally provided by the farm family. Under these circumstances if crop prices are deliberately held down (as is the case in many developing countries), the process of modernization would slow down as a result of lack of appropriate incentives to the farmer.[25]

The price relatives for nutrient and crop prices at the international level are reported in Table 22. These price ratios are calculated for a period of 10 years, starting with 1971, the year when the declining trend for fertilizer prices reversed itself. These international nutrient/grain price ratios are based on prices which do not include freight costs and domestic marketing costs. The results indicate that even after the energy-fertilizer-food crisis of 1973-75, there have been large fluctuations in the nutrient/grain price ratios, adding some uncertainty to the trade decisions of those involved in fertilizer and grain trade.

The results and international price data also provide further insights. First, based on the crop price structure during 1980, 1 mt of milled rice was equivalent to about 2.2 mt of wheat and 4.0 mt of corn. Second, based on the nutrient price structure during 1980, nitrogen from urea was 2.5 times more expensive, and

24. For example, according to Adams, King, and Johnston (1977), typical 1972 energy costs as a percentage of the total variable costs for different crops in California was as follows: beans, 16%; cotton, 22%; rice, 21%; sorghum, 30%; sugar beets, 21%; broccoli, 24%; cauliflower, 21%; onions, 9%; and potatoes, 16%.

25. Timmer (1975) has analyzed the interaction of energy (mainly fertilizer and fuel for irrigation) and food grain prices in the context of developing countries by using a simple macro model. The impact of a given change in energy price on food grain price depends on the elasticity of energy demand by farmers and associated food grain supply response. Furthermore, the short-run impact of a given change in energy price is quite different from the long-run impact. Also see comment by Konandreas and Green (1976).

Table 22. Price Relatives for International (f.o.b.) Nutrient and Crop Prices[a]

Year	N From Urea[b]			P_2O_5 From TSP[b]			K_2O From KCl[b]		
	Wheat	Rice[c]	Corn	Wheat	Rice[c]	Corn	Wheat	Rice[c]	Corn
1971	1.6	0.5	2.2	1.5	0.5	2.0	0.9	0.3	1.2
1972	1.3	0.7	2.8	1.5	0.8	3.2	0.6	0.3	1.2
1973	1.0	0.4	1.8	1.1	0.4	1.9	0.3	0.1	0.6
1974	3.6	1.6	5.4	3.4	1.5	5.1	0.5	0.2	0.8
1975	2.5	1.2	4.1	2.6	1.3	4.2	0.8	0.4	1.3
1976	2.0	0.8	2.7	1.7	0.7	2.2	0.8	0.3	1.0
1977	2.0	0.5	2.5	1.7	0.4	2.1	0.7	0.2	0.9
1978	1.6	0.6	2.6	1.2	0.5	1.9	0.5	0.2	0.9
1979	1.7	0.7	2.9	1.6	0.7	2.8	0.7	0.3	1.1
1980	2.0	0.9	3.6	1.7	0.8	3.1	0.8	0.4	1.4

a. Price relatives refer to kilograms of crop output needed to purchase 1 kg of nutrients. Both nutrient and crop prices are annual averages. Crop prices are from Canada for wheat and from the United States for rice and corn. Crop prices are obtained from FAO (1981c). The numbers are rounded to the nearest decimal.
b. Urea from Western Europe, TSP from U.S. Gulf, and KCl from Canada.
c. Milled, Texas, long-grain rice. The conversion ratio is 1 kg rough rice = 0.66 kg milled.

P_2O_5 from TSP was 2.2 times more expensive than that of K_2O from KCl.[26] Third, nutrient prices increased faster than grain prices, as indicated by the percentage increase in nutrient/grain price ratios at the international level from 1978 to 1980. The respective percentage increases for different price ratios are as follows:

Crop	N From Urea	P_2O_5 From TSP	K_2O From KCl
Wheat	23	43	44
Corn	38	62	63
Rice (milled)	41	64	71

Fourth, the percentage increase in the individual nutrient prices from 1978 to 1980 was 57% for N from urea (most energy intensive), 84% for P_2O_5 from TSP, and 85% for K_2O from KCl (least energy intensive). Fifth, the percentage increase in crop prices for the same period was 28% for wheat, 14% for corn, and 11% for milled rice.

The nutrient/grain prices faced by the farmers are generally quite different from those prevailing in the international market. These differences are generally due to (1) freight costs, since freight costs for 1 mt of N from urea would be about two times that for wheat; (2) marketing costs, since marketing costs for

26. Similar relationships based on nutrient prices paid by farmers in the United States during 1980 indicate that N from anhydrous ammonia was 1.2 times, N from urea was 2.1 times, and P_2O_5 from TSP was 2.3 times more expensive than that of K_2O from KCl.

nutrients are already included in the price paid by the farmers, unlike grain prices received by the farmers; (3) variable prices for a given nutrient depending upon the source of that nutrient; and (4) government policies affecting crop prices received by the farmers and fertilizer prices paid by farmers.

Most developed and developing countries have some set of government policies which influence directly or indirectly the nutrient/grain prices faced by the farmers. The farmers in the United States generally experience relatively less government interference than farmers in most developing countries, and the price relationships are determined by the market forces. Consequently, the nutrient/grain price ratios faced by U.S. farmers, as opposed to export prices, are reported in Table 23.

First, the percentage increase in individual nutrient prices paid by farmers from 1978 to 1980 was 35% for N from anhydrous ammonia, 32% for N from urea, 61% for P_2O_5 from TSP, and 41% for K_2O from KCl. Second, the percentage increase in crop prices received by the farmers for the same period was 33% for wheat, 45% for corn, and 14% for soybeans. Finally, the percentage change in the nutrient/grain price ratios faced by U.S. farmers from 1978 to 1980 is reported below:

Crop	N From Anhydrous Ammonia	N From Urea	P_2O_5 From TSP	K_2O From KCl
Wheat	1	-1	21	6
Corn	-7	-9	11	-3
Soybeans	18	16	41	23

However, on the basis of prices for just a few crops and fertilizers, one must not hasten to conclude that farmers in the United States during 1980 were better off than during 1978. The annual average indexes of prices received for all crops and prices paid for all fertilizers, fuel, credit (interest rate), and labor (wage rate) are reported in Figure 15. These indexes clearly indicate that fertilizer prices, fuel prices, and interest rates have been increasing faster than crop prices, especially from 1978 onward, resulting in a profit squeeze for the farmers. The economic situation for farmers in most developing countries is even less satisfactory mainly because (1) crop prices received are generally lower than what the market forces would dictate and (2) input prices are generally very high; in addition, there are growing pressures on national governments to reduce or even eliminate input subsidies if there are any.

Table 23. Price Relatives for Nutrient and Crop Prices in the United States[a]

	N From Anhydrous Ammonia			N From Urea			P_2O_5 From TSP			K_2O From KCl		
Year	All Wheat	Corn	Soybeans	All Wheat	Corn	Soybeans	All Wheat	Corn	Soybeans	All Wheat	Corn	Soybeans
1971	2.2	2.5	1.0	3.9	4.6	1.7	3.7	4.3	1.6	2.2	2.5	1.0
1972	1.7	1.7	0.7	3.0	3.2	1.2	2.9	3.0	1.2	1.7	1.7	0.7
1973	0.8	1.2	0.6	1.5	2.2	1.1	1.5	2.2	1.0	0.8	1.1	0.6
1974	1.8	2.3	1.1	3.3	4.2	2.0	2.7	3.4	1.7	1.1	1.3	0.6
1975	2.5	3.3	1.8	4.1	5.4	3.0	3.6	4.7	2.6	1.4	1.8	1.0
1976	2.5	3.0	1.0	4.0	4.7	1.6	3.6	4.3	1.5	1.7	2.1	0.7
1977	2.8	3.1	1.1	4.7	5.1	1.9	4.1	4.5	1.6	2.0	2.2	0.8
1978	2.1	2.5	0.9	3.7	4.6	1.7	3.3	4.1	1.5	1.7	2.0	0.7
1979	1.8	2.5	1.1	3.2	4.5	1.9	3.3	4.6	2.0	1.5	2.2	0.9
1980	2.1	2.4	1.1	3.7	4.2	1.9	4.0	4.6	2.1	1.7	2.0	0.9

a. Price relative refers to kilograms of crop output needed to purchase 1 kg of nutrients. The fertilizer and crop prices are obtained from different issues of USDA (1980a) and USDA (1981). The numbers are rounded to the nearest decimal.

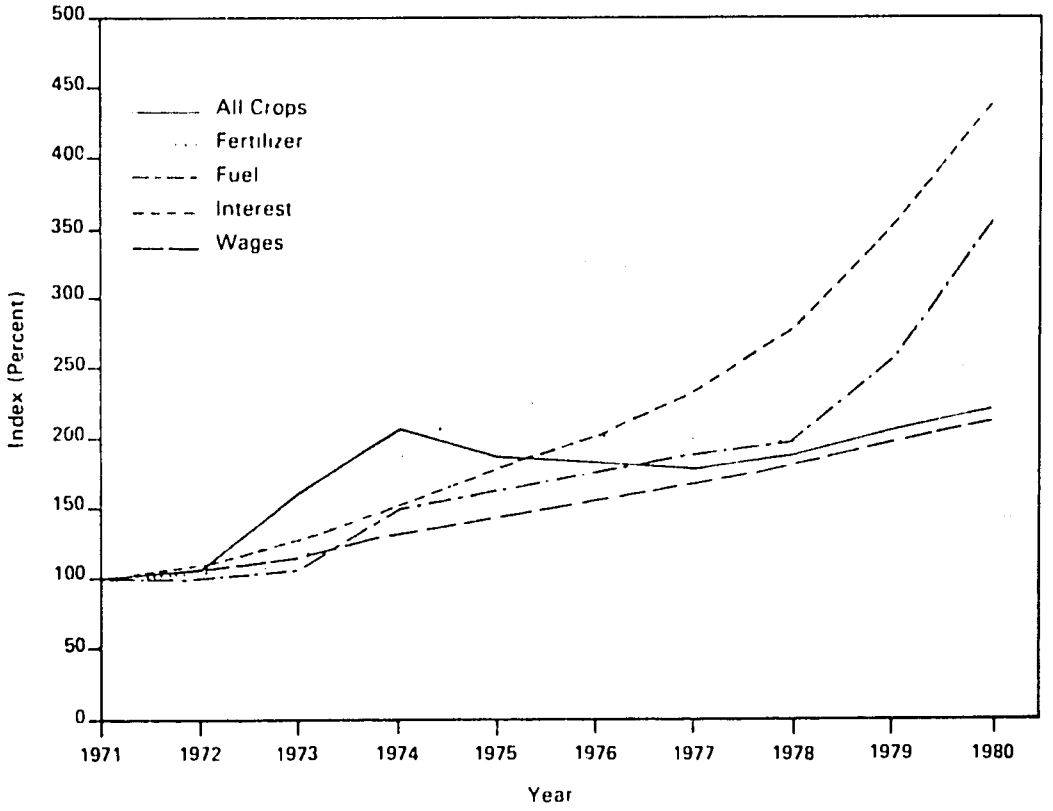

Figure 15. Annual Average Index of Prices Received and Paid by Farmers in the United States (1971=100).

Alternatives to Reduce Energy Costs

As has been discussed above, the energy prices and fertilizer and food production costs will continue to increase. There are several policy alternatives which will either reduce the impact of high energy prices per unit of fertilizer or food output, or shift the burden from one sector to another. In some cases, the country may not really have a choice. In such a case, it must use all available means to reduce the impact of high energy prices on the farming community. Some of these alternative means include:

1. Energy savings in fertilizer manufacturing through improved efficiency,
2. Supplementing plant nutrients from nonchemical supply sources,
3. Energy savings in fertilizer marketing through improved marketing efficiency,
4. Energy savings in fertilizer use through improvements in use efficiency,

5. Fertilizer subsidies, especially when government is deliberately following cheap food pricing policy,

6. Crop price supports or consumer subsidies when justified,

7. Development of irrigation infrastructure which would increase fertilizer productivity, and

8. Agricultural research and extension which would result in higher fertilizer response and improved efficiency.

The development and implementation of these programs would reduce fertilizer cost, increase fertilizer productivity, and improve the economics of fertilizer use. However, the cost effectiveness and implications with respect to other economic sectors would vary from one policy to another. The ultimate choice of a particular policy program for a particular country would depend on national goals and policy constraints faced by those countries. However, improvements in fertilizer production, distribution, and use efficiency are badly needed, and there is substantial scope for improvements. This would result in substantial gains in terms of energy savings and/or expanded food output.

CHAPTER 8

ENERGY REQUIREMENTS FOR FERTILIZER MANUFACTURING

The purpose of this chapter is twofold: (1) to estimate the energy requirements for manufacturing different types of nitrogen, phosphate, and potash fertilizers; and (2) to compare the energy requirement estimates for the various types of fertilizers, and alternative fertilizer manufacturing processes.

Assumptions Regarding Energy Use Estimates

Energy consumption of manufacturing plants may be reported on a battery-limits or on a total basis. Values reported by engineering and construction firms usually refer to battery-limits consumption when the plant is operating under near-optimum conditions at the production rate for which it was designed. Such battery-limits consumption values are significantly lower than typical total values.

Some energy consumption items that are included in total consumption but usually not in battery-limits consumption are:

1. Startups, shutdowns, and delays.
2. Operation at rates above or below design rate.
3. Pumping cooling water and recirculating it through cooling towers.
4. Preparation of boiler feedwater.
5. Lighting of buildings and plant area and heating, cooling, and ventilation of working areas.
6. Operation of mobile equipment such as power shovels, trucks, and locomotives.
7. Conveying products to storage, reclaiming from storage, bagging, and loading for shipment.
8. Unloading raw materials to storage, reclaiming from storage, and conveying to battery limits.
9. Losses of raw materials and products in handling and leakage of water, steam, and other fluids.
10. Reprocessing offgrade materials.
11. Disposal of liquid effluents and solid wastes.
12. Pollution control not included in original design.
13. Maintenance operations including lubrication.

Most of the total energy consumption values used in this study are taken from TFI's 1979 Energy Use Survey.[27] They refer to average energy use in the 1979 calendar year. The TFI Energy Use Survey is included as Appendix B. Most of the battery-limits values are taken from IFDC (1979), and when appropriate they are adjusted to total consumption by a factor. The TFI survey is based on information reported by 37 fertilizer manufacturing firms in the United States and Canada.

The energy unit equivalents used in TFI Energy Use Survey are reported in Table B-6. The heat equivalent of electricity is the amount of thermal energy required to generate 1 kWh and implies an efficiency of about 34% in conversion of thermal to electrical energy, including losses in transmission of electrical energy to the point of use. The assumed energy equivalent of steam is less than the actual energy content of even low-pressure steam and possibly refers to the amount of usable energy that can be extracted. When steam is generated onsite, a requirement of about 1,500 Btu/lb would be more appropriate depending on efficiency and on steam temperature and pressure.

In the case of ammonia production, the TFI total energy use per ton of NH_3 is about 11% higher than the battery-limits estimates from IFDC (1979) when the latter is converted from net to gross heating value of the natural gas used. A part of this difference can be attributed to the fact that the energy use reported in IFDC (1979) was based on a 1978 ammonia plant design whereas the TFI survey included many older, less energy-efficient plants. On the other hand, in the case of phosphoric acid manufacture, which is a much less energy intensive process with large offsite requirements (gypsum disposal), the total energy use may be nearly twice the battery-limits use.

The manufacturing process diagrams for commonly used finished fertilizers and fertilizer intermediates are developed in Appendix C.

Ammonia and Nitrogen Fertilizers

Ammonia

Ammonia is unique among fertilizers in that it uses as a chemical raw material a substance such as natural gas which can also be used as a fuel. This has led to the belief that manufacture of ammonia is energy intensive which is true in the sense that it consumes by chemical reactions materials that otherwise could be used to generate energy. In a modern ammonia plant only about

27. The TFI Energy Use Survey is in short tons. However, appropriate conversions into metric tons have been made unless otherwise specified.

one-third of the natural gas is used to generate energy and two-thirds is used as a raw material (feedstock). Much of the energy remains in the product as can be demonstrated by burning ammonia or exploding ammonium nitrate.

The amount of various feedstocks required per ton of ammonia in large, modern plants and their battery-limits energy equivalents are tabulated below (also see Table 14):

Fuel and Feedstock	Requirement Per mt of Ammonia	Energy Equivalent, GJ[a] Per mt of NH_3	Per mt of N
Natural gas	37,920 ft^3	36.0	43.9
Naphtha	0.89 mt	39.4	48.0
Fuel oil	1.00 mt	40.7	49.6
Coal	1.97 mt	52.3	63.8
Electrolytic hydrogen	10,200 kWh	107.6[b]	131.2[b]

a. Net heating value (LHV).
b. Fuel for generating electricity in a fuel-fired plant.

Source: IFDC (1979), Chapter XXV.

The energy requirement is lowest for plants using natural gas fuel and feedstock and increases as the C:H ratio in the feedstock increases (except for electrolytic hydrogen). No attempt has been made to estimate the energy required for producing the steel, alloys, and other materials required for plant construction but the energy component must be substantial and roughly proportional to the cost. Leach (1975) suggests that total plant construction energy use may be 3%-4% of operating energy use.[28]

The average energy use in ammonia plants as reported in the TFI survey for centrifugal plants is about 46.9 GJ/mt (HHV) or about 42.2 GJ/mt (LHV). Energy use is decreasing and will decrease further as energy-saving equipment and practices are adopted and new, energy-efficient plants are built. It is unlikely that the energy requirement can be decreased below about 32 GJ/mt for natural gas-based plants. A plant based on production of hydrogen by reforming ethanol could have a lower energy requirement because the reformer operates at a much lower temperature (300°C versus 900°C). On the other hand, some requirements of the U.S. Environmental Protection Agency may increase energy use in the United States.

Energy consumption can be held to a minimum by good maintenance such as repairing of steam leaks, replacing defective steam traps, and keeping heat exchange surfaces clean.

28. In other words, the energy needed in ammonia plant construction is 3%-4% of the energy needed to operate the plant for its entire useful life.

Depending on the efficiency of design and operation, 30%-50% of the energy used in a plant based on natural gas or naphtha feedstock is used as fuel for firing the reformer and generating steam and electricity. This fuel need not necessarily be the same as the feedstock. For example, when natural gas is scarce or expensive, fuel oil has been used to fire the reformer. Use of coal is possible but would require some changes in design or perhaps pregasification of the coal as opposed to direct firing.

For the purposes of this study, the present average energy requirement for ammonia production will be considered equal to the average reported for centrifugal plants by the TFI survey, 46.9 GJ/mt of ammonia = 57.2 GJ/mt of N.

Urea

Conversion of ammonia to urea solution requires an average of 5.53 GJ/mt of urea, and converting the urea solution to prilled or granulated product requires a further 4.07 or 2.53 GJ, respectively. Thus, the total energy input including that used for ammonia production is:

	Energy Use, GJ/mt of Urea (46% N)	
	Prilled	Granular
Ammonia manufacture	26.97	26.97
Urea synthesis	5.53	5.53
Prilling	4.07	-
Granulation	-	2.53
TOTAL	36.57	35.03
	GJ/mt of N	
TOTAL	79.50	76.15

The average energy use for conversion of ammonia to prilled urea is about 2.5 times the battery-limits value of 3.9 GJ/mt (IFDC, 1979). This difference can be accounted for in part by inclusion of older, less energy-efficient plants in the average. There is a wide range in reported energy use; the lowest value of the interquartile range is only 58% of the average. However, it is likely that the main reason for higher energy use is compliance with stringent pollution control regulations.

Control of dust and fume from the prilling operation requires high-energy scrubbing of a large volume of air followed by evaporation of the scrubber solution. Liquid effluents from the urea synthesis and evaporation units may require hydrolysis followed by steam stripping or ammonia distillation before discharge. These measures are energy intensive. As discussed in

Farris (1980), an alternate disposal of ammonia plant condensate (effluents) on agricultural land has been used and may be applicable for urea plants that are favorably located. Granular urea requires less energy than prilled urea partially because the pollution control problems are less difficult with the granular product.

The main forms of energy used in urea manufacture are steam and electricity, which can be generated by any fuel. Thus, an ammonia-urea complex that uses scarce or expensive natural gas or naphtha feedstock for ammonia production might well use coal or lignite to generate steam and electricity when the latter fuels are economically available.

Ammonium Nitrate

Production of ammonium nitrate involves three steps: production of nitric acid, neutralization of the acid with ammonia, and prilling or granulating the resulting product. The first two steps are exothermic and can produce steam for export. However, the average energy use reported is 1.71 GJ/mt for the two-step conversion of ammonia to ammonium nitrate solution. The interquartile range of 0.28-2.77 GJ/mt reflects the wide differences in the extent to which various plant operators utilize the heat of reaction to minimize net energy use. Here again, inclusion of older, less energy efficient plants raises the average. The means used to comply with pollution control regulations (NO_x from nitric acid units and fume from neutralizer) can be energy-intensive but low-energy methods are available.

Prilling or granulating the product including evaporating the solution and controlling air and water pollution consumes a further 2.92 or 2.39 GJ/mt, respectively. The total energy input is tabulated below.

	Energy Use, GJ/mt of Ammonium Nitrate (34% N)	
	Prilled	Granulated
Ammonia manufacture	20.29	20.29
Ammonium nitrate solution	1.74	1.74
Prilling	2.92	-
Granulation	-	2.39
TOTAL	24.95	24.42
	GJ/mt of N	
TOTAL	73.38	71.82

As in the case of urea, the difference in energy use between granulation and prilling probably is related to the more difficult pollution control problems.

Urea-Ammonium Nitrate Solution

Urea-ammonium nitrate (UAN) solution is a popular nitrogen fertilizer in the United States and several other countries. It is produced by mixing urea and ammonium nitrate solutions and adding water to adjust to the desired grade, which ranges from 26% to 32% N. The energy input is calculated as follows:

	GJ/mt of UAN (30% N)
Ammonia manufacture	17.38
Urea, 0.327 mt (solution)	1.81
Ammonium nitrate, 0.422 mt (solution)	0.73
Mixing, cooling, storage, etc.	0.25
TOTAL	20.17
Total per mt of N	67.20

Ammonium Sulfate

Ammonium sulfate is produced directly from ammonia and sulfuric acid, or from a solution which is obtained as a byproduct from manufacture of caprolactam, from scrubbing coke oven gas, or from various other processes.

The direct process is exothermic, and little energy is required. Production from byproduct solution requires a substantial amount of energy for evaporation of water from the solution which usually contains about 40% ammonium sulfate. Estimated energy requirements are taken from IFDC (1979). They do not include the energy involved in producing sulfuric acid, which may be positive or negative (see discussion under Sulfur and Sulfuric Acid). Also, energy for granulation is not included; some direct processes make a crystalline product of suitable size without granulation.

No allowance for energy for treating effluents is included; in most countries no treatment is necessary. In the case of by-product material, energy for the manufacture of ammonia is not included. If synthetic ammonia is used, its energy component is

charged to the process that produces the byproduct. Estimated energy use values follow:

	Energy Use, GJ/mt of Ammonium Sulfate (21% N)	
	Synthetic	Byproduct
Process energy	0.59	4.70
Ammonia manufacture	12.01	-
TOTAL	12.60	4.70
	GJ/mt of N	
TOTAL	60.00	22.40

Ammonium Phosphates

Although ammonium phosphates usually are considered as phosphate fertilizers, the most popular grade (diammonium phosphate [DAP]) contains 18% N (18-46-0). For present purposes, the energy component of nitrogen in ammonium phosphates is taken to be equivalent to the ammonia used in its manufacture--57.2 GJ/mt of N. The logic of this assumption will be discussed under Ammonium Phosphates.

Comparison of Energy Use for Nitrogen Fertilizer

For comparative purposes, the energy inputs for manufacture of various nitrogen fertilizers are tabulated below:[29]

Product	% N	Energy Input, GJ/mt of N
Ammonia	82	57.2
Urea		
Prilled	46	79.5
Granular	46	76.1
Ammonium nitrate		
Prilled	34	73.4
Granular	34	71.8
UAN solution	30	67.2
Ammonium sulfate		
Synthetic	21	60.0
Byproduct	21	22.4
Ammonium phosphates	10-21	57.2

29. The corresponding energy use estimates reported by Leach (1975), originally from Imperial Chemical Industries (ICI), are 61.3 GJ/mt of N from ammonia, 73.6 GJ/mt of N from prilled ammonium nitrate, and 79.0 GJ/mt of N from prilled urea.

Phosphate Rock

Phosphate rock is prepared for processing by mining, beneficiation, drying, calcining, and grinding or some combination of these steps. Not all of these steps are required in all cases. For example, several plants use processes that accept rock with only mining and beneficiation; the wet concentrate is fed directly to phosphoric acid production. Several other plants accept wet rock for wet grinding. Calcining is not necessary for the majority of rocks; when it is necessary it usually replaces drying. In some cases, however, calcining is followed by wet beneficiation, then by drying of the concentrate.

The energy use for the rock preparation steps that are reported in the TFI survey pertain to the United States, mainly Florida, and are not necessarily typical of world averages. The average grade of the ore mined in Florida is about 10%-12% P_2O_5, the concentrate is about 30% P_2O_5, and the P_2O_5 recovery is about 60%. This means 5 mt of ore must be mined and beneficiated to get 1 mt of commercial phosphate rock. In addition various amounts of overburden are removed and eventually replaced to reclaim the mined-out area.

In contrast, in most of the west and north African and the Middle East phosphate mines, the grades of the ore as mined are in the range of 25%-30% P_2O_5, and simple size separation (screening and/or washing) is used to beneficiate the ore. In a few cases beneficiation is not necessary.

For the purpose of this study, the lower value of the interquartile range of energy use from the TFI survey will be assumed to apply to the world average for mining and beneficiation, while average survey values will be accepted for the other steps. The accepted values are:

Energy Use in Phosphate Rock Preparation

Step	Thousands of Btu/Short Ton	MJ/mt
Mining and reclamation	188	219
Beneficiation	210	244
Drying	402	467
Calcining	902	1,049
Grinding	270	314

According to Sheldrick and Stier (1979), about 8% of the world's phosphate fertilizer is supplied by direct application of

ground phosphate rock to the soil. Rock sold for this purpose on the world market is mined, beneficiated, dried, and ground. The total energy use is 1.21 GJ/mt or 4.05 GJ/mt of P_2O_5 assuming an average grade of 30% P_2O_5. A larger amount of domestic rock is used for direct application, particularly in the U.S.S.R. and China, but also in some other countries. Most of this rock is used with only mining and grinding, and hence is usually lower in grade; the total energy use is only 0.53 GJ/mt or 2.12 GJ/mt of P_2O_5 assuming an average grade of 25% P_2O_5.

Phosphate rock sold on the world market for further processing is mainly dried but not ground before shipment. It is usually considered uneconomical to ship wet rock (about 15% moisture) farther than about 500 miles (800 km). Also some processes require dry rock even for plants adjacent to the mine. So for the purpose of this study, rock sold in world trade will be assumed to be mined, beneficiated, and dried, with an energy input of 0.93 GJ/mt or 2.91 GJ/mt of P_2O_5 (the average grade is about 32% P_2O_5). Grinding, when required, will be considered as part of further processing.

Sulfur and Sulfuric Acid

Sulfuric acid is required for producing about 80% of the world's phosphate fertilizer. As reported in Bixby (1980), the world production of sulfurous materials by type is estimated as follows:

Type	1980 Estimated Production of Sulfur: Millions of mt of S	1980 Estimated Production of Sulfur: % of Total S
Frasch-mined elemental sulfur	13.6	24.4
Recovered elemental sulfur	22.6	40.6
Pyrite	9.5	17.1
Other, mainly byproduct smelter acid	10.0	17.9
TOTAL	57.7	100.0

Of these forms of sulfur only Frasch-mined sulfur is energy intensive; it requires large quantities of fuel to superheat water under pressure which is pumped into the sulfur-bearing formation to melt the sulfur which is then pumped to the surface. The energy use is likely to vary from one mine to another; Huffman (1980) gives a range of 6.33-8.44 GJ/mt, with an average of 7.38 GJ/mt. Frasch-mined sulfur is expected to decrease as a percentage of the total in the future while recovered sulfur is expected to increase. Recovered sulfur at present is mainly that removed from natural gas and fuel oil; in the future more sulfur will be recovered from coal gasification and liquefaction and from processing tar sands. The energy component for recovered

sulfur is assumed to be zero, since any energy involved is charged to the main product, i.e., gaseous or liquid fuels.

Pyrite ore is mined, usually by open-pit mining; little or no beneficiation is needed. In some cases, pyrite is a byproduct of mining and beneficiation of nonferrous sulfide ore. For the purpose of this study the energy requirement is assumed to be the same per metric ton as for mining phosphate rock, 219 MJ/mt of pyrites or 438 MJ/mt of S. Most of the category "other forms" is byproduct sulfuric acid from smelting nonferrous sulfide ores (e.g., copper, zinc, and nickel). Recovery of the sulfur dioxide released in smelting operations is now mandatory in most countries to prevent atmospheric pollution. The resulting byproduct sulfuric acid must be disposed of to prevent water pollution. Whatever energy is used or released in the recovery process is charged or credited to the smelting process, so the energy component of acid used for fertilizer is taken as zero.

The net energy released and utilized in producing sulfuric acid from elemental sulfur is given in the TFI Energy Use Survey as 1.131 million Btu/short ton of 100% H_2SO_4 (1.315 GJ/mt). The wide range (+1.883 to -0.270 million Btu/short ton) presumably reflects differences in efficiency of energy recovery. Some other factors affecting energy use are whether sulfur is received in solid or liquid form and what measures are taken to prevent atmospheric pollution. In any case the average will be accepted as typical of current practice. The energy is released in the form of steam and is often used to concentrate phosphoric acid; in some plants the steam is used to generate electric power for in-plant use.

Production of sulfuric acid from pyrite generates somewhat less usable energy than production from sulfur; for the purposes of this study, it will be assumed that the net energy balance is zero. About 0.33 mt of elemental sulfur is required per metric ton of sulfuric acid. When using Frasch-mined sulfur the net energy use is:

Sulfur mining 7.38 x 0.33	=	2.44 GJ/mt
Sulfuric acid production		-1.32 GJ/mt
Net energy use		1.12 GJ/mt

Similar calculations have been made for the net energy use or recovery for other sources of sulfuric acid and used to calculate a weighted average as follows:

Net Energy Use (+) or Recovery (-) for Sulfuric Acid Production

Source	Net Energy Use, GJ/mt	% of Total H_2SO_4	Contribution to Total GJ/mt
Frasch sulfur	1.12	24.4	+0.27
Recovered sulfur	-1.32	40.6	-0.54
Pyrites	0.15	17.1	+0.03
Smelter acid	0.00	17.9	0.00
Weighted average		100.0	-0.24

Thus the net energy use per metric ton of sulfuric acid in the world as a whole is slightly negative; more energy is recovered than is used. However, countries that import elemental sulfur are not concerned with the energy required to mine it. Therefore in further calculations involving production and use of sulfuric acid, the manufacture of sulfuric acid will be considered a source of 1.32 GJ/mt of usable energy with average recovery.

Phosphoric Acid

About 60% of the world's phosphate fertilizer is made from phosphoric acid. The TFI survey data show four steps in production of phosphoric acid: preparation of phosphate rock, production of sulfuric acid, production of filter acid, and production of merchant or superphosphoric acid. Filter acid has a usual concentration of 28% P_2O_5; merchant acid, 54% P_2O_5; and superphosphoric acid, 70% P_2O_5. Another concentration, 42% P_2O_5, should be considered since this concentration is sufficient to produce granular TSP, DAP, and MAP by slurry processes. Plants that make these products often concentrate part of the acid to about 54% P_2O_5 and use a mixture of the concentrated and dilute acid equivalent to an average concentration of about 40% P_2O_5. Fertilizer companies participating in the TFI Energy Use Survey reported production of about 8 million short tons of P_2O_5 as filter acid of which 46% was concentrated to merchant-grade acid and 12% was further concentrated to superphosphoric acid.

One company in the United States uses a hemihydrate process which produces filter acid at a concentration of 42% P_2O_5. Since this process has an energy saving potential, it will be considered separately. Several plants using hemihydrate processes have been built recently in European countries and in Japan; they produce filter acid ranging from 40% to 52% P_2O_5. Phosphoric acid is usually shipped as merchant-grade acid (about 54% P_2O_5) both in domestic or export trade; this grade is also

suitable for making run-of-pile (nongranular) TSP. Superphosphoric acid (69%-72% P_2O_5) is also shipped and often converted to liquid fertilizer (ammonium polyphosphate solution) by the user. The estimated energy use for the various grades of phosphoric acid and for various processes is shown in Table 24.

Table 24. Energy Use for Phosphoric Acid Production[a]

Process	Dihydrate, Dry Rock Feed	Dihydrate, Wet Rock Feed	Dihydrate, Wet, Unground Rock Feed	Hemihydrate, Wet, Unground Rock Feed
	(GJ/mt of P_2O_5)			
Rock preparation[b]	3.09	1.49	1.49	1.49
Sulfuric acid[c]	-3.67	-3.67	-3.67	-3.67
Filter acid[d]	4.18	3.65	2.61	2.61
Concentrated to 42% P_2O_5[e]	2.86	2.86	2.86	-
Total for 42% P_2O_5	6.46	4.33	3.29	0.43
Concentrated to 54% P_2O_5	3.34	3.34	3.34	3.34
Total for 54% P_2O_5	9.80	7.67	6.63	3.77
Concentrated to 70% P_2O_5	3.13	3.13	3.13	3.13
Total for 70% P_2O_5	12.93	10.80	9.76	6.90

a. Assumptions: 94% P_2O_5 recovery; 3.32 mt of phosphate rock and 2.78 mt of H_2SO_4/mt of P_2O_5 recovered.
b. Mining, beneficiation, and (when required) drying.
c. Based on use of elemental sulfur with zero energy charge.
d. Including grinding when required.
e. Based on TFI average of 6.2 GJ/mt P_2O_5 for production of merchant grade from filter grade. Filter grade assumed to be 28% P_2O_5 and merchant grade 54% P_2O_5. Energy use assumed to be proportional to water evaporation. For hemihydrate process 42% P_2O_5 acid is obtained directly from the filter.

It will be noted that the energy use reported in the TFI Survey for the phosphoric acid production step (dry grinding) shows more than a twofold difference between the upper and lower values of the interquartile range. This wide range probably reflects, among other factors, differences in measures taken to control pollution such as scrubbing the fluorine-laden fumes generated during acid production, control of dust during dry grinding, and disposal of gypsum. The number of plants using wet rock feed is insufficient to show an interquartile range. In view of the small number using wet rock and the large variation in energy use for plants using dry rock, it is doubtful that there is a significant energy difference in the acid preparation step; the main saving for wet grinding is in the omission of drying in the rock preparation step. The TFI Survey shows that 31% of the phosphoric acid was produced from wet rock feed.

The OXY hemihydrate process is the only hemihydrate process known to be in use in the United States; it has been described by Mercando (1980) and Ceasar et al. (1980). However, several other hemihydrate processes are in use elsewhere. Hemihydrate processes in general have the advantage of producing a more concentrated filter acid, thereby saving the energy required to concentrate the acid to the required level. The steam saving in the OXY process is equivalent to 1.64 GJ/mt of P_2O_5, based on electricity generated from the steam (Caesar et al., 1980). Some hemihydrate processes produce acid as concentrated as 52% P_2O_5 (using high-grade rock). This would result in further savings when acid of this concentration is required. Because steam usually is available from an adjacent sulfuric acid plant any steam saved must be utilized to recover energy. In case of the OXY plant the steam is used to generate electricity.

A second energy-saving feature of the hemihydrate process is the use of wet, unground rock. This saves about 2.60 GJ/mt of P_2O_5 as compared with using dried, ground rock. At least two dihydrate processes as well as most hemihydrate processes are adaptable to using wet, unground rock provided the maximum particle size is less than about 1 mm. Most commercial rock meets this criterion. Using wet rock is economical when the plant is near the mine but not when the rock must be shipped long distances. The energy-saving features of the hemihydrate processes should encourage their rapid adoption, especially in energy-deficient countries. With good management a hemihydrate phosphoric acid plant operating in conjunction with a sulfuric acid plant should produce an excess of energy which could be used in other units of the complex. Other attractive features of hemihydrate processes are that the capital cost is somewhat lower than for dihydrate processes and the product acid is relatively free from sludge-forming impurities.

Another source of energy in phosphoric acid production is through recovery of uranium. All sedimentary phosphate rocks contain uranium in concentrations that usually are in the range of 50-200 ppm. Several plants in Africa, Europe, and the United States recover uranium from phosphoric acid. For those plants that use Florida phosphate rock, recovery of 1 lb of uranium oxide (U_3O_8) per short ton of P_2O_5 in phosphoric acid may be typical. This is equivalent to 0.5 kg of U_3O_8/mt of P_2O_5. This amount of uranium is capable of generating roughly 200 GJ of energy in nuclear reactors with current technology; this is 20 times the average energy use of manufacturing merchant-grade phosphoric acid. Uranium also can be recovered in nitrophosphate processes from solutions of phosphate rock in nitric acid.

Triple Superphosphate (TSP)

Granular TSP is made by one of two processes. In the two-step process, nongranular TSP is produced in the first, and

granulated in a second step. The nongranular TSP, also called run-of-pile TSP, also is used to make granular mixed fertilizers. In the slurry process, ground phosphate rock reacts with phosphoric acid of about 40% concentration, and the resulting slurry is granulated and dried. In both processes, the rock must be dried and finely ground. The usual grade of the product is 46% P_2O_5. Typical proportions of ground rock and phosphoric acid are:

mt of rock (33% P_2O_5)/mt of TSP	0.388
mt of acid P_2O_5/mt of TSP	0.346

Energy requirements for the two processes, based on average process energy from the TFI survey and phosphoric acid energy requirements from Table 24, are shown in Table 25.

Table 25. Energy Use in Production of Granular TSP

Process	GJ/mt of TSP[a] Dihydrate, Dry Rock Feed	Hemihydrate, Wet Rock Feed
A. Two-Step Process		
Rock for TSP	0.36	0.36
Acid P_2O_5 (as 54%)	3.39	1.30
Nongranular TSP[b]	0.41	0.41
Granulation	1.01	1.01
TOTAL	5.17	3.08
B. Slurry Process		
Rock for TSP	0.36	0.36
Acid P_2O_5 (as 42% P_2O_5)	2.24	0.15
Process energy[b]	1.74	1.74
TOTAL	4.34	2.25

a. 46% P_2O_5.
b. Process energy including rock grinding.

The data in Table 25 show that the two-step process is more energy intensive than the slurry process, mainly because it requires more concentrated phosphoric acid. However the slurry process is not entirely satisfactory for use with some unreactive rocks. The data also show that the total energy use for TSP is strongly influenced by the type of process used for preparation of phosphoric acid.

Ammonium Phosphates

The TFI survey shows process energy use equivalent to 0.942 GJ/mt for DAP and 1.175 GJ/mt for MAP (both assumed to be granular). There is no reason why MAP should be more energy intensive than DAP; the difference is assumed to be adventitious and related to the small number of responses for MAP shown in the energy survey. Therefore, the average energy use for DAP will be assumed to apply to MAP also. Nearly all of the DAP is produced as a standard grade (18-46-0), whereas numerous grades of MAP are marketed--11-48-0, 13-39-0, 11-55-0, 13-54-0, etc. Some of the grades contain ammonium sulfate. For the purpose of this study a grade of 11-54-0 will be assumed. The great majority of ammonium phosphate plants use a slurry process in which the phosphoric acid is used at an average concentration of about 40% P_2O_5. In this study an average concentration of 42% is assumed. Total energy use including that for phosphoric acid preparation by dihydrate and hemihydrate processes is shown in Table 26.

Table 26. Energy Use in Production of Granular DAP and MAP

Product	Phosphoric Acid Process: Dihydrate Process, Dry Rock Feed	Phosphoric Acid Process: Hemihydrate Process, Wet Rock Feed
	(GJ/mt)	
DAP (18-46-0)		
Acid P_2O_5 (as 42% P_2O_5)[a]	3.00	0.20
Process energy	0.94	0.94
Total, not including ammonia	3.94	1.14
Energy for ammonia[a]	10.40	10.40
Total, including ammonia	14.34	11.54
MAP (11-54-0)		
Acid P_2O_5[a]	3.52	0.23
Process energy	0.94	0.94
Total, not including ammonia	4.46	1.17
Energy for ammonia	6.36	6.36
Total, including ammonia	10.82	7.53

a. Assuming 99% recovery.

Monoammonium phosphate may also be made in nongranular form for use in granulation of mixed fertilizers. In this case it is usual to use acid containing 50%-54% P_2O_5, and the resulting product is not dried. In this case process energy may be only

about 0.38 GJ/mt, however, the energy input for concentrating the acid from 42% to 54% P_2O_5 will add about 1.8 GJ/mt of MAP, so the total energy input will be higher.

Some plants produce granular MAP or DAP from merchant-grade acid (54%), particularly when the acid is shipped from a distant source. As discussed by Achorn et al. (1980), processes are available for producing MAP or DAP from merchant-grade acid without drying. Thus, the process energy is decreased by eliminating the need for fuel for drying (about 0.34 GJ/mt) but this saving is not sufficient to offset the energy for concentrating the acid. However, when the energy required for transporting the acid is considered the total energy use may be less, depending on the shipping distance.

In comparing the three most popular phosphate fertilizers--TSP, DAP, and MAP--it seems logical to compare them on a P_2O_5 basis, omitting the energy input for ammonia. The comparison follows:

	GJ/mt of P_2O_5	
Product	Dihydrate	Hemihydrate
TSP	9.43	4.89
DAP	8.57	2.48
MAP	8.26	2.17

The comparison indicates that TSP is somewhat more energy intensive than DAP or MAP probably because the heat of reaction of ammonia with phosphoric acid is utilized to decrease energy use. However, the choice of the method used for preparing the phosphoric acid, dihydrate versus hemihydrate, gives the greatest opportunity for energy saving. Alternative ways of providing equal amounts of solid nitrogen and phosphate fertilizers may be compared as follows:

	Energy Use for Manufacture 0.18 mt of N and 0.46 mt of P_2O_5
1 mt of DAP	11.54 GJ
1 mt of TSP plus 0.39 mt of urea	2.25 GJ + 14.26 GJ = 16.51 GJ
0.85 mt of MAP plus 0.20 mt of urea	6.40 GJ + 7.31 GJ = 13.71 GJ

This comparison, assuming hemihydrate process, shows that a combination of TSP and urea requires 43% more energy than DAP for the same amounts of N and P_2O_5. A combination of MAP plus urea would require 20% more energy than DAP. Similar

calculations, assuming that the dihydrate process is used for all phosphate products, show energy advantages of 30% and 15% for DAP over TSP-urea and MAP-urea combinations, respectively. If energy for bagging and transport were added the difference would be even greater. This comparison does not imply that TSP and urea could be sold as a mixture; they are not compatible.

Single Superphosphate

Production of single superphosphate (SSP) is carried out in equipment similar to, and sometimes identical with, that used for nongranular TSP. Therefore the process energy, including rock grinding, is assumed to be the same per metric ton of product (0.41 GJ/mt). Most of the SSP is produced in nongranular form and used as such as an ingredient of granular mixed fertilizer. Some plants produce granular SSP by granulating the product as it comes from the den. This is a common practice in Australia and New Zealand. According to Sinte Maartensdijk (1976), battery-limits energy use for granular SSP made by ex-den granulation is 0.71 GJ/mt; adding 50% for offsite energy gives 1.11 GJ/mt. Granular SSP made by granulating nongranular SSP reclaimed from storage would require more energy; the energy use figure for granular TSP by the two-step process (1.42 GJ/mt) seems reasonable.

Production of 1 mt of SSP typically requires 0.626 mt of phosphate rock (33% P_2O_5) and 0.363 mt of sulfuric acid (100% basis); with this grade of rock a product containing 18%-20% available P_2O_5 is produced, depending on rock quality and product moisture content.

The sulfuric acid for making SSP may be supplied by an onsite sulfur-burning plant, but perhaps more often shipped-in acid is used, often smelter acid or "spent" acid from other industries. Sometimes SSP plants are located at smelter sites, but more often they are located in areas where the product (SSP or mixed fertilizer) is marketed. In the case of onsite sulfuric acid production from sulfur, there might be some difficulty in utilizing the surplus energy from sulfuric acid production unless there are other related operations (such as mixed fertilizer production) that can utilize it. For the purpose of this study, it will be assumed that SSP production uses shipped-in acid. Energy use is estimated to be:

	GJ/mt of SSP
0.626 mt phosphate rock (dry) x 0.93 GJ/mt	0.58
Process energy for nongranular SSP	0.41
Total for nongranular SSP (0.58 + 0.41)	0.99
Process energy for granular SSP	1.11
Total for granular SSP (0.58 + 1.11)	1.69

Comparisons of Energy Use for Phosphate Products

It is evident that energy use for phosphate fertilizers can vary widely depending on the phosphate rock preparation steps and on the phosphoric acid manufacturing process. However, the average energy use for phosphates is much lower than for nitrogen fertilizers. Triple superphosphate, the most popular straight phosphate fertilizer, requires less than 10 GJ/mt of P_2O_5 when made by the most popular combination of process steps, whereas urea, the most popular straight nitrogen fertilizer, requires about 80 GJ/mt of N. Also it is evident that recently developed technology is capable of reducing the energy use for phosphate fertilizers nearly to zero in some cases. On the other hand energy use for manufacture of synthetic nitrogen fertilizers will remain high although there are opportunities for significant savings. Average values for the use of energy for the more popular phosphate fertilizer intermediates and products are summarized in Table 27.

Table 27. Comparison of Energy Use for Phosphate Products[a]

Product	GJ/mt of Product	GJ/mt of P_2O_5
Phosphate rock for direct application		
Mined, beneficiated, dried, and ground, 30% P_2O_5	1.21	4.03
Same as above but granulated	2.06	6.87
Mined and ground only, 25% P_2O_5	0.53	2.12
Phosphoric acid, merchant-grade, 54% P_2O_5		
Hemihydrate process	2.04	3.77
Dihydrate process	5.29	9.80
TSP, nongranular, 46% P_2O_5		
Hemihydrate process	2.07	4.50
Dihydrate process	4.16	9.02
TSP, granular, slurry process, 46% P_2O_5		
Hemihydrate process	2.25	4.89
Dihydrate process	4.34	9.43
DAP granular, 18-46-0		
Hemihydrate process	1.14	2.48
Dihydrate process	3.94	8.57
MAP granular, 11-54-0		
Hemihydrate process	1.17	2.17
Dihydrate process	4.46	8.26
SSP, 20% P_2O_5[b]		
Nongranular	0.99	4.95
Granular	1.69	8.45

a. Does not include energy for transportation of raw materials or products. Use of recovered sulfur assumed; no energy charge.
b. No credit for energy from sulfuric acid production.

Potash Fertilizers

The TFI survey gives an average energy use of 2.55 GJ/mt of product for production of muriate of potash by shaft mining and beneficiation. Since this applies to an average of 8.2 million mt of product, it is presumably typical of energy use by the North American potash industry, but not necessarily applicable to other areas. Muriate of potash (fertilizer-grade potassium chloride) typically contains 60%-62% K_2O. Over 95% of the fertilizer potassium enters commercial channels in this form although much of it reaches the farmers in compound (mixed) fertilizers. The average includes all size grades; standard, coarse, and granular. Much of the coarse and granular potash is formed by roll compaction, a step that requires a slight amount of extra energy. In 1977, about 79% of the potash sold in North America was coarse or granular, but most of that exported was the standard (nongranular) grade. The roll compaction granulation process does not require that the product be dried, but it does use more mechanical energy than most granulation processes.

According to data reported in IFDC (1979), compaction machines used for granulating potash use 10-15 kWh/short ton of product. Total mechanical power is likely to be double this amount. The process also uses some energy as steam for preheating the charge. Assuming 15 kWh/short ton for compaction and 30 kWh/short ton total would give 349 MJ/mt electrical energy. Adding 100 MJ for preheating gives 449 MJ/mt versus 1,048 MJ/mt for granulation of compound fertilizers. These values are not necessarily comparable. Since granular mixed fertilizer is an end product, energy requirement values may include storage, bagging, and loading for shipment plus receipt of raw materials, storage, and reclaiming from storage.

Energy use for granulation is assumed to be equal to the lower value of the interquartile range for mixed fertilizer granulation, i.e., 0.66 GJ/mt. However, some unknown percentage of the beneficiated product is already in the coarse or granular size range and is recovered by merely screening, so it is not possible to calculate with the data at hand what the energy use for standard potash might be. Granular and coarse potash grades are used for bulk blending or direct application, while the standard grade is used mainly for formulating mixed, granular fertilizers.

Shaft mining is by far the most common method of mining potash ore; however, significant quantities are recovered by other methods which include (1) recovery from salt lakes by use of solar evaporation (e.g., Dead Sea and Great Salt Lake) and (2) solution mining. Solution mining is said to be energy intensive, but no reliable estimates of energy use are available. Solution mining is the only feasible method for extracting potash from some deposits deeper than about 1,500 m, because at greater depths the salt deposits are subject to plastic deformation, which

makes shaft mining impractical. One of the two solution mines in North America uses a unique energy-saving method; the solution at about 32°C is pumped to surface lagoons for concentration by solar evaporation. Crystals of sodium and potassium chloride are formed and are separated by flotation. This method is feasible only in arid regions, of course.

Energy use in mining per ton of product increases as the depth of the mine increases and as the grade of the ore decreases. The grade of the ore determines the number of metric tons of ore that must be mined per metric ton of product. The ore:product ratio is typically 2.3 in Canada, but in New Mexico and in some European mines the ratio may be 4, 5, or even 6.

In beneficiating the ore, a physical separation such as crushing followed by flotation is the least energy-intensive and is widely used. However, not all ores are suitable for this process. The main alternative is dissolution and selective crystallization for separation of soluble impurities; insoluble impurities are separated by sedimentation and washing. This method requires a substantial amount of energy (as steam) for evaporation and thermal cycling of solutions. Many producers use a combination of methods, recovering as much as possible of the potash by physical separation and an additional amount by evaporation and crystallization. Here again, solar evaporation can help save energy in arid climates. In either case the final product must be dried, and this accounts for a considerable portion of the energy use.

The main forms of energy that are required for mining and beneficiation are steam and electricity, which can be generated by any convenient fuel. Blouin (1974) gives energy use data for the flotation and crystallization methods, from which an energy use of 1.63 GJ/mt for flotation beneficiation and 6.6 GJ/mt for crystallization beneficiation have been calculated. These values do not include mining which is estimated at about 0.32 GJ/mt of ore, or 0.74 GJ/mt of product for an ore:product ratio of 2.3 which is typical for Canada. For the Carlsbad area, where the ore:product ratio is about 4, the energy use for mining would be 1.28 GJ/mt of product assuming the same mine depth. These estimates presumably do not include granulation.

UNIDO (1967) gives the energy use for beneficiation by flotation in the Carlsbad (New Mexico) area (ore:product ratio = 3.81) as 2.0 GJ/mt of product. So the total estimated energy use for mining and beneficiation would be 3.38 GJ/mt for the Carlsbad area.

Energy use in much of the European potash production is higher than in North America production because the ore is low grade, more complex, and finer grained. As a result, less of the potash can be recovered by flotation and more must be recovered by dissolution and recrystallization. Leach (1975) gives an energy use estimate of 3.9 GJ/mt of product for the one producer

in England and 4.6 GJ/mt for other European mines. These estimates include energy for mining. Of the 4.6 GJ/mt, 82% was supplied as steam indicating extensive use of the dissolution-crystallization method for beneficiation.

Information in UNIDO (1967) indicates that potash recovered from the Dead Sea in 1965 required about 5.8 GJ/mt for processing. Probably there have been energy-saving improvements since 1965. The potash is deposited in the solar evaporation lagoons in the form of carnallite, a hydrated potassium-magnesium chloride mixed with common salt. This material must then be processed by dissolution and recrystallization to recover a high-grade potash product.

Energy use for potash products other then the muriate of potash are not available. It is likely that products such as sulfate of potash and double sulfates of potash and magnesium, which can be recovered by mining and beneficiating deposits containing sulfate, will have energy uses per ton of product within the range of muriate of potash. Since they are less concentrated than the muriate, the energy use per metric ton of K_2O may be higher. However, they contain sulfur and magnesium which are secondary elements, so the concentration of nutrient elements may be higher. Typical compositions of these potash materials are:

Potash Product	Composition, %			
	K_2O	MgO	S	Total
Muriate	60-62	-	-	60-62
Sulfate	50	-	17	67
Langbeinite	21	[illegible]	22	62
Kalimagnesia	30	10	20	60

There is some local use of unrefined ores or partially refined ores especially when the impurities may contain useful nutrient elements. In addition to magnesium and sulfur, most partially refined ores contain sodium. Although sodium is not an essential plant nutrient, some crops such as sugar beets respond to it, and sodium can replace potassium to some extent in crop production.

Nitrophosphates and Mixed Fertilizers

Nitrophosphates

Nitrophosphates are fertilizers that contain both nitrogen and phosphorus and that are made by processes involving at one step

the dissolution of phosphate rock in nitric acid. There are several such processes which are described in Chapter XV of IFDC (1979). The products contain ammonium phosphate, dicalcium phosphate, and ammonium nitrate. A typical product grade is 20-20-0 or 15-15-15, if potash is added. The water solubility of the phosphorus in nitrophosphates depends on the relative amounts of dicalcium phosphate and ammonium phosphate and ranges from about 30% to 80% of the total phosphorus depending on selection of the process. Since dicalcium phosphate is soluble in ammonium citrate solution, nearly all of the phosphorus in nitrophosphates is "available" by the analytical methods used in most countries (water-soluble plus ammonium citrate-soluble).

The most popular nitrophosphate processes also produce a straight nitrogen coproduct which may be calcium nitrate, calcium ammonium nitrate (CAN, a mixture of calcium carbonate and ammonium nitrate), or straight ammonium nitrate, at the option of the producer. Because the process produces two products, energy comparisons are complex. However, a comparison of energy use for two options of nitrophosphate processes with the energy use for the same amounts of nitrogen and phosphorus in the form of diammonium phosphate (18-46-0) and ammonium nitrate is reported in Table 28. The energy for nitrophosphate

Table 28. Energy Use for Nitrophosphate Processes and Comparison With DAP and AN

Item	1 mt of 23-23-0 (80% Water Soluble) +0.95 mt of CAN (26% N) Requirement	Energy, GJ	1 mt of 20-20-0 (30% Water Soluble) +0.715 mt of CAN (26% N) Requirement	Energy, GJ
Phosphate rock, dried	0.719 mt	0.67	0.624 mt	0.58
Ammonia	0.333 mt	15.62	0.235 mt	11.02
Nitric acid (100% basis)[a]	1.069 mt	14.24	0.838 mt	11.16
Electricity	210 kWh	2.22	80 kWh	0.84
Steam	1.66 mt	3.86	1.22 mt	2.83
Fuel oil	7.30 kg	0.30	7.30 kg	0.30
Subtotal		36.91		26.73
Allowance for offsites[b]		4.74		3.35
TOTAL		41.65		30.08
Energy Use for Equivalent Amounts of DAP and Ammonium Nitrate				
DAP (18-46-0)[c]	0.500 mt	7.18	0.435 mt	6.24
AN (34% N) granular[d]	1.138 mt	27.79	0.906 mt	22.12
TOTAL		34.97		28.36

a. Energy for ammonia to nitric acid plant assuming 95% recovery. The nitric acid process is assumed to have a net energy balance of zero.
b. Allowance is 10% of energy for ammonia plus 25% of other energy.
c. 14.34 GJ/mt of 18-46-0 (see Table 25).
d. 24.42 GJ/mt of ammonium nitrate (see section titled "ammonium nitrate").

processes was taken from IFDC (1979) and is battery-limits energy use. Therefore, an allowance was made for offsite energy use as noted in Table 28 to the estimates comparable with the DAP and ammonium nitrate figures from the TFI survey.

The comparison shows that the nitrophosphate processes, especially the 80% water-soluble option, are somewhat more energy intensive than the DAP-ammonium nitrate alternative. There are several reasons for this difference. To obtain a nitrophosphate product with high P_2O_5 water solubility, it is necessary to cool the solution by mechanical refrigeration for removal of a high percentage of calcium nitrate; hence, the electrical energy requirement is high. Also, a large amount of water is added in the nitrophosphate processes in the nitric acid, and in the filtration and washing steps. This water must be evaporated and this necessitates high steam consumption.

The main advantage of the nitrophosphate processes is that sulfur is not required; thus, there is a saving in cost but not necessarily a saving in energy unless the sulfur is assumed to be mined by the Frasch process. As noted in a previous section only about 24% of the world sulfur consumption in all forms is Frasch-mined sulfur, and this percentage is decreasing. Nevertheless, a nitrophosphate process can be a good choice from the viewpoint of economics and foreign exchange for countries that lack an indigenous supply of sulfur or sulfuric acid. The difference in energy use is small, however, especially for the low water-soluble option.

Mixed Fertilizers

The TFI Survey gives the average energy use for granular mixed fertilizers as 1.048 GJ/mt; for bulk blends as 0.179 GJ/mt; and for fluid mixtures as 0.629 GJ/mt. These data include energy for unloading raw materials and conveying them to storage, reclaiming raw materials from storage, conveying the product to storage, and reclaiming it and loading for shipment.

Although the process of granulation in itself is more energy intensive than bulk blending, the raw materials are likely to require less energy. All materials for bulk blending must be granular when received, and extra energy is required for that purpose. In other words, it is not necessarily cheaper or less energy intensive to granulate two, three, or more materials separately than to granulate them together.

The main opportunity for decreasing energy use in granulation of mixed fertilizer lies in utilizing chemical heat for drying. The Tennessee Valley Authority (TVA), according to Achorn et al. (1980), has promoted a pipe reactor or pipe-cross reactor for that purpose and numerous plants both in the United States and elsewhere have adopted this process. They report that no fuel is required for drying most (sometimes all) of the grades

that they make. It is likely that producers who report an energy use of 660 MJ/mt (lower value of the interquartile range) use little or no fuel.

Energy use for bulk blending is small and probably not much more than that required for a regional storage and distribution facility. Fluid mixed fertilizer facilities vary widely in type. The principal types of fluid fertilizers are clear liquids and suspensions. Suspensions require more energy than liquids because they are viscous and must be agitated in storage to keep them mixed. Also many producers use granular materials and must use an intensive mixer to break up the larger particles when making suspensions. Data for separate estimates for clear liquids and suspensions are not available.

Secondary Elements and Micronutrients

Secondary Elements

The secondary elements, calcium, magnesium, and sulfur are just as essential as the primary nutrient elements, and very often are lacking, particularly in developing countries. The term "secondary elements" is unfortunate because it has led fertilizer industry planners to ignore them or to expect them to be furnished incidentally without charge. In the past, adequate amounts of the secondary elements have been supplied by SSP, ammonium sulfate, unrefined potassium ores, and fillers such as dolomite. The modern fertilizer industry has been led or permitted to manufacture the "highest analysis" fertilizers meaning those containing a maximum percentage of $N + P_2O_5 + K_2O$. As a result, the secondary elements have been "squeezed out."

In developed countries, alert agricultural research organizations have detected secondary element deficiencies, and economical means have been developed for preventing them. For example, in Norway all compound fertilizers for domestic use contain 7% kieserite (a magnesium sulfate mineral) which supplies magnesium and sulfur. In developing countries deficiencies are less likely to be detected and corrected promptly.

The most energy-efficient method for supplying needed amounts of secondary elements, assuming that needs can be accurately assessed, may be to include them in mixed fertilizers in the amounts required, using whatever materials are available. For example, SSP and ammonium sulfate when used at common application rates would supply more sulfur than is usually needed, but these materials can be included in mixtures in amounts locally required. Likewise, calcium sulfate (gypsum) is a waste product from phosphoric acid manufacture, and can be utilized to supply calcium and sulfur in mixed fertilizers. The effect on process energy would be minor, but the effect of the additional weight on transportation costs would be appreciable.

An alternative means for supplying secondary elements is by direct application of locally available minerals such as limestone, marl, chalk, dolomite, serpentine or olivine, or byproduct slags (blast furnace or basic slag). These materials often are used in large amounts to improve the soil by correcting acidity or salinity or by improving soil structure. When used for this purpose the materials are called "soil amendments." However, it is difficult to distinguish between nutritional effects and soil improvement effects in some cases. Mining and fine grinding of a local mineral for direct application would require roughly 0.5 GJ/mt.

Micronutrients

Although micronutrients are very important they are used in such small quantities that they do not contribute appreciably to energy use. However, they are often expensive, especially when imported. There is a need for identifying local micronutrient minerals that can be used in mixed fertilizers or for direct application. Failure to correct micronutrient deficiencies will lead to inefficient use of primary nutrients and thus waste the energy involved in manufacturing them.

CHAPTER 9

ENERGY REQUIREMENTS FOR FERTILIZER DISTRIBUTION AND APPLICATION

The purpose of this chapter is to estimate energy requirements for transportation (both raw material and final products), packaging, and application of nitrogen, phosphate, and potash fertilizers.

Energy for Transportation of Nitrogen

In this study no attempt will be made to estimate an average energy requirement for mining or extracting ammonia feedstocks and transporting them to the plant site. For natural gas plants located in or near the gas fields, this energy would be small. Transportation of natural gas by pipeline up to 3,000 km probably would consume less than 1 GJ/mt of ammonia. However, liquefaction of natural gas and ocean shipment is energy intensive and may consume as much as 10 GJ/mt of ammonia. Transportation of crude oil by ocean shipment over a distance of 10,000 km might consume about 2 GJ/mt.

Many developing countries import fertilizer by ocean shipment from sources 3,000-8,000 miles (4,839-12,904 km) distant. On arrival the products may be transported several hundred miles inland by rail, truck, barge, or river boat, or some combination of these methods. Typical energy requirements for transportation by various means are reported in Table 29. Assume, as an example, that fertilizer is shipped 8,000 km by ocean vessel, 800 km by rail, and 160 km by truck. The total energy use per metric ton is:

Distance/Mode	GJ/mt
8,000 km by ocean vessel	1.44
800 km by rail	0.40
160 km by truck	0.32
TOTAL	2.16

The total energy use per metric ton of N is:

Product	% N	Energy, GJ/mt of N
Ammonia	82	2.63
Urea	46	4.70
Ammonium nitrate	34	6.35
Ammonium sulfate	21	10.29

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Table 29. Typical Energy Requirements for Fertilizer Transportation

Transportation Mode	Energy Requirement Btu/Short Ton-Mile	kJ/mt-km
Ocean vessel[a]	250	180
River barge[b]	270	195
Pipeline[c]	410	296
Rail[c]	700	505
Truck[d]	2,800	2,019

a. Calculated from data in Shields et al. (1975).
b. Calculated using data from several sources. See text for assumptions.
c. Lee (1974).
d. Byrne and Huffman (1980).

Obviously shipment of anhydrous ammonia is the least energy-intensive means for shipping fertilizer nitrogen and is in fact widely used for overseas shipment and for inland shipment in some countries. However, special ships, barges, railcars, or trucks are required. An adequate supply of suitable oceangoing ships is available, but in many countries suitable conveyances for inland shipment are not. Therefore, imported ammonia often is converted to solid nitrogen fertilizers at the port. Unfortunately, urea cannot be produced economically from imported ammonia because pure carbon dioxide (CO_2) is required for its manufacture. A supply of CO_2 is available as a byproduct at no cost at ammonia plants, but it is seldom available elsewhere at a reasonable cost. So use of imported ammonia is limited to direct application or the manufacture of ammonium nitrate, phosphate, or sulfate or some combination of these compounds.

Energy for Transportation of Phosphates

Few countries have both phosphate rock and sulfur (or sulfuric acid), so they must choose whether to import finished phosphates, intermediates such as phosphoric acid or nongranular MAP, or the necessary raw materials. The choice of what to import and transport may vary from country to country; however, some general observations may be in order.

The manufacture of 1 mt of P_2O_5 in the form of phosphoric acid requires about 3.32 mt of phosphate rock (32% P_2O_5) and 0.95 mt of elemental sulfur or 2.78 mt sulfuric acid. Therefore, if a country has phosphate rock that can be mined and beneficiated at reasonable cost, or if it has a low-cost source of sulfuric acid, it should consider using these resources. For countries that have none of these raw materials, the energy required to import them may be considerable.

For example, Indonesia has the problem of importing raw materials, intermediates, or finished phosphates. The nearest sources of sulfur are in the Persian Gulf area, and the nearest phosphate rock available for export is in Jordan. Energy for ocean shipment of these materials to Surabaya is calculated below, assuming an energy use of 180 kJ/mt-km:

Phosphate rock, 3.32 mt x 9,600 km x 180 kJ =	5.74 GJ
Sulfur, 0.95 mt x 8,500 km x 180 kJ =	1.45 GJ
Total per metric ton of P_2O_5	7.19 GJ

The alternatives of importing merchant-grade phosphoric acid or TSP from Tunisia require less energy even though the distance is longer:

TSP, 2.17 mt x 12,640 km x 180 = 4.94 GJ/mt of P_2O_5
Phosphoric acid, 1.85 mt x 12,640 km x 180 - 4.21 GJ/mt of P_2O_5

If phosphoric acid becomes available for export from Jordan to Indonesia, the energy use for transport will be about 3.2 GJ/mt of P_2O_5, less than half the requirement for transporting the raw materials.

When a country needs to import both nitrogen and phosphate, importation of DAP rather than TSP and urea will save transport energy and cost. For example, 1 mt of P_2O_5 can be supplied by 2.17 mt of either TSP or DAP but the latter also supplies 0.39 mt of N which is equivalent to 0.85 mt of urea. Transport of 2.17 mt of DAP from Tampa, Florida, to Santos, Brazil (9,322 km), requires 3.64 GJ, whereas to transport the same amount of N and P_2O_5 as TSP and urea would require 5.07 GJ. Further transport inland would increase the saving; for example inland transport from Santos to Uberaba by truck (600 km) would require 2.63 GJ for DAP and 3.66 GJ for TSP plus urea. Thus, shipment of DAP from Tampa to Uberaba would save about 2.5 GJ for 1.0 mt of P_2O_5 and 0.39 mt of N as compared with shipment of an equivalent nutrient amount in the form of TSP and urea.

There has been a growing trend to produce high-analysis phosphates at or near the mine in order to take advantage of energy and cost savings. This trend has been accelerated by the lower grade of phosphate rock at many mines. Also there has been a growing effort in developing countries to identify and utilize indigenous phosphate deposits. Despite these trends the amount of phosphate rock moving in overseas trade has increased in recent years in actual tonnage if not in percentage of total production. According to the British Sulphur Corporation (1980a), 52 million mt of rock moved in seaborne trade, about 41%

of total production during 1979. Exports and imports by regions as percent of total trade were:

Seaborne Trade in Phosphate Rock[a]

Region	Exports	Imports
	- - - - - -(%) - - - - -	
Africa	49	-
North America	26	6
Eastern Europe	13	22
Asia[b]	9	16
Oceania	3	7
Western Europe	-	45
Latin America	-	4
TOTAL	100	100

a. Includes trade within regions.
b. Includes Christmas Island.

In comparison, world phosphate trade in finished fertilizers and intermediates amounted to 5.8 million mt of P_2O_5 which is roughly equivalent to 20 million mt of phosphate rock or nearly 16% of total rock production. Thus trade in phosphate rock plus fertilizer accounted for 57% of phosphate rock production. The remaining 43% presumably was consumed mainly within the countries of origin although small percentages were exported by land or as nonfertilizer phosphorus compounds.

The total amount of sulfur that moves in international trade is not precisely known. However, in 1979, the five major exporting countries--Canada, France, Mexico, Poland, and the United States--exported about 13.7 million mt, about 39% of world production of elemental sulfur. Some of these exports involved extensive use of energy for transportation. For example, Canada is the leading sulfur exporter, and most of her exports are recovered sulfur from the province of Alberta. Recently when a large phosphate plant started operation in Uberaba, Brazil, a large percentage of the sulfur requirement, as reported by the British Sulphur Corporation (1980b), came from Canada. The estimated energy use for transportation of 1 mt of sulfur is:

Alberta to Vancouver by rail 1,350 km	0.68 GJ
Vancouver to Santos by ship 16,026 km	2.34
Santos to Uberaba by truck 600 km	1.21
TOTAL	4.23 GJ

In this instance there is only a small energy saving due to utilization of indigenous phosphate rock as compared with importation of phosphoric acid from Morocco to Santos, manufacture of finished phosphate fertilizer at Santos, and inland transport of

the products. The main advantage of utilization of indigenous rock is the saving in foreign exchange.

Sulfur is an essential nutrient which is often deficient in developing countries, including most of Brazil. So the cost and energy use for importation of sulfur should not be charged entirely to the manufacture of phosphate fertilizers. The sulfur in the form of calcium sulfate, a byproduct of phosphoric acid production, may be distributed to the farmers as such, or incorporated in mixed fertilizers. Alternatively, SSP is a good source of both phosphate and sulfur and may be distributed as such or incorporated in mixed fertilizers.

Energy for Transportation of Potash

Most of the potash is mined in the developed countries of Eastern Europe, Western Europe, and North America, so most of the potash used in the developing countries of Asia, Africa, and Latin America must be imported. Canada supplies about half of these imports. Most of Canada's overseas exports go through the port of Vancouver. An example of the estimated energy use in the transportation of potash from the potash-producing province of Saskatchewan to a developing country is given below:

	GJ/mt
Saskatchewan to Vancouver by rail, 1,800 km	0.91
Vancouver to Bombay by ship, 17,625 km	3.18
Inland transport, 800 km by rail	0.40
Inland distribution by truck, 160 km	0.32
TOTAL	4.81

Thus, the energy for transport in this illustration exceeds the energy for production, which probably is about 2.4 GJ/mt for most Saskatchewan producers. Likewise, transport cost to market areas in developing countries often exceeds the product cost f.o.b. at the mines.

Considerations on Energy Use for Transportation

Energy use for transportation of products and raw materials was discussed to some extent in previous sections of this study. In this section we will discuss the source and variability of the energy use data and the types of energy required.

Energy use data, as reported earlier in Table 29, for ship and barge transport are for one-way trips; if the vessels must return empty the energy use will be much higher. So arranging

for a backhaul is important in saving both energy and cost. The data for rail and truck transport are from literature references that do not specify whether a load factor is involved in energy use calculations.

Energy for ocean transport depends on the speed, size, and condition of the vessels. In two illustrations given in Shields et al. (1975), the energy use for vessels equipped for ammonia transportation was 130 kJ/mt-km for a 15,000-mt vessel with a speed of 13.5 knots (25 km/hour) and 208 kJ/mt-km for a 13,191-mt vessel with a speed of 16.25 knots (30 km/hour). Another source gives an energy use of 103 kJ/mt-km for a 15-knot bulk carrier of 20,700-mt capacity. Leach (1975) gives estimated energy consumptions for bulk carriers that range from 50 kJ/mt-km for a vessel of 153,000-mt capacity to 200 kJ/mt-km for 7,000-mt vessel; the speed is not stated. The data are for fully loaded vessels and include all energy inputs.

Energy for construction of ships was estimated to add only about 2% to these figures.[30] Probably a typical ship size for ocean transport of fertilizers or raw materials would be about 15,000 mt; Leach (1975) reports 186 kJ/mt-km for a 14,000-mt vessel. Vessels for coastal shipping usually are small (1,000-5,000 mt) and slower than oceangoing vessels. Because of their slow speed they may be as energy efficient as the larger ocean vessels. The fuel commonly used is heavy fuel oil. Freight vessels also use a relatively small amount of diesel fuel to operate electric generators to supply power for the ship's mechanical devices including gear for loading and unloading cargo. The amount of diesel fuel is relatively small--less than 10% of the total energy.

The energy use for river barges shown in Table 29 is calculated for barges of the type used in the United States on the Mississippi River System and other inland waterways. It applies specifically to a tow of eight barges, each of 2,500-short-ton capacity, propelled by a 6,500-hp tugboat at an average speed of about 250 km/day (average of upstream and downstream including delays for passing through locks). Breach (1973) gives a figure of 400 Btu/mt-mile (about 260 kJ/mt-km) for barge transport which may apply to smaller barges that are used in European canals.

Pipeline transportation of fertilizers is used mainly for anhydrous ammonia and for fertilizer solutions. However, phosphate rock has been transported as a slurry in water. For instance, a phosphate rock concentrate is currently being transported from the mine to the factory in Brazil (Tapira to Uberaba) a distance of 120 km at a rate of 900,000 mtpy.

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30. In other words, energy needed in ship construction may be only 2% of the energy needed to operate the ship for its useful life.

Energy use for pipeline transport can vary widely, depending on pipe size and flow rate. The usual problem is to achieve an economic balance between capital investment, which increases with pipe size, and operating expense (mainly energy) which decreases with increase of pipe size, for a given flow rate. The energy use values in Table 29 are approximately those for a commercial ammonia pipeline.

Energy use for pipelines is mainly for pumps which may be driven by electric motors or by diesel engines. One advantage of pipeline transportation is that there is no backhaul problem. For this reason pipeline transport is probably relatively more efficient than would be inferred by comparing the values in Table 29.

Energy for rail transportation can vary depending on size of the train and the type of locomotive. The figures in Table 29 presumably are typical of the United States where diesel-engine locomotives are widely used although some lines are electrified. Coal-fired steam locomotives are much less efficient.

Leach (1975) quotes data from British Rail that suggests that the energy input for a fully loaded freight train is 360 kJ/mt-km for fuel only. If this figure is comparable with that given in Table 29 (505 kJ/mt-km) it would indicate that a load factor has been applied to the latter.

Truck transport is the least energy-efficient method of those given in Table 29. The data presumably apply to conditions in the United States where most trucks are powered by diesel engines and move on paved highways with gentle grades. Leach (1975) quotes data on fuel energy use for various truck sizes on rural roads as follows:

	Truck Size		
Nominal capacity, mt	7.00	12.00	20.00
Actual load, mt	5.46	13.03	20.64
Energy kJ/mt-km			
One way	1,800	913	741
Round trip, return empty	3,322	1,578	1,328

Fertilizer distribution requires trucks of all sizes, but the longer hauls usually are in larger size trucks. In developing countries truck size is likely to be limited by the load-bearing capacity of the roads, and energy use may be increased by rough or muddy road surfaces and steep grades. Leach (1975) suggests that energy for manufacturing trucks and maintaining them may amount to as much as 25% of the fuel energy. Maintenance includes lubricant, tire replacement, antifreeze, and repair parts.

Most fertilizer must be transported by truck for some part of its journey to farms. In many developing countries other forms of transportation are lacking or inadequate. Obviously energy

use for transportation is an important part of the total energy picture, and careful planning is needed to minimize it.

Energy for Packaging of Fertilizers

Nearly all fertilizers used in developing countries reach the farmers in bags. Leach (1975) reports that Imperial Chemical Industries (ICI) has estimated that the energy use for manufacturing a polyethylene fertilizer bag of about 50 kg capacity is 21 MJ. Because 20 such bags are required per metric ton of fertilizer, the energy use would be 420 MJ/mt. Leach (1975) indicates 620 MJ/mt is consumed in the bagging operation giving a total of 1,040 MJ/mt for bags and bagging. However, much of this mechanical energy is used in conveying and loading for shipment and presumably is included in the TFI figures for finished products. Most of the fertilizers produced in North America are distributed in bulk.

Energy for Application of Fertilizers

Achorn et al. (1980) give the energy use for application of fertilizer for U.S. conditions as:

Material	Energy Use	
	Thousand Btu/Short Ton	MJ/mt
Anhydrous ammonia	1,520	1,767
Granular solids	506	588
Fluids	354	412

The application methods are subsurface injection for anhydrous ammonia and surface application for solids and fluids. A common practice is to follow surface application of fertilizers with incorporation in the soil by tilling operations. These energy use figures are for highly mechanized farming and have little relevance for most developing countries where application often is done by human labor and animal power. However, urea should be either deep-placed or incorporated soon after application. Failure to do so can result in losses of up to 50% of the applied nitrogen in upland farming; the results are even more serious for flooded rice culture, according to Craswell and Vlek (1979), Engelstad (1979), and Hignett (1980a). Urea is the most energy intensive of all nitrogen fertilizers and the most frequently used. Application methods that lead to loss of two-thirds of the nitrogen constitute an enormous wastage of energy. Clearly proper placement can provide great energy savings. Even though more energy may be required for subsurface placement, the energy savings through prevention of losses will far outweigh increased use of energy.

CHAPTER 10

ENERGY SAVINGS IN FERTILIZER MANUFACTURING

The preceding analysis documents the fact that fertilizer manufacturing, especially nitrogen, is not only energy intensive but heavily dependent on nonrenewable energy resources. Fertilizer manufacturing innovations that will reduce energy requirements and/or replace scarce energy with relatively abundant energy resources can go a long way toward expanding fertilizer supply and reducing fertilizer prices. The purpose of this chapter is twofold: to describe technological innovations for saving or replacing scarce energy, and to discuss their economic implications. The energy requirements for the fertilizer sector discussed earlier are based primarily on U.S. technology, processes, management, and efficiency. As a result, the energy requirements in developing countries may be underestimated. Conversely, there may be even greater possibilities for energy saving in developing countries through improvements in fertilizer technology and management.

Energy Savings Through Improvements in Technology

Since rather limited processing, and hence energy, is required for potash fertilizers, the energy saving innovations will be discussed only in the context of nitrogen, phosphate, and granular fertilizers.

Nitrogen Fertilizers

As has been pointed out earlier, ammonia forms the basis of nitrogen fertilizers. The historical developments in energy requirements for ammonia production are reported in Table 30. Over time, the average energy requirements have been reduced from 190 GJ to 47 GJ/mt of ammonia. As reported in Appl (1976), the energy requirement of ammonia manufacture has decreased from 88 GJ/mt for coke-based plants (1920-40) to about 42 GJ/mt in 1965 and 36 GJ/mt in 1976 for natural gas-based plants. Further improvements are possible, but at the expense of increased investment cost and complexity. Some of the energy-saving improvements may be uneconomical, especially in countries where natural gas is cheap and plentiful.

Reductions in energy requirements have been made possible through (1) improvements in ammonia synthesis process, (2) switching to more efficient feedstock and fuel, (3) use of modern large plants with resulting economies of scale, (4) peripheral technological developments, and (5) reduction in energy wastage. It may not be practical to reduce energy needs to the theoretical minimum (23 GJ/mt) in commercial ammonia plants.

Table 30. Reduction in Energy Use in Ammonia Synthesis Over Time

Time Period	Synthesis Process	Average Energy Use, GJ/mt NH_3	Source
Early 20th century (1910)	Electric arc process	574[a]	Appl (1976)
Early 20th century (1910)	Cyanamide process	190	Appl (1976)
Early 20th century (1915)	Water electrolysis	117	Appl (1976)
Mid 20th century (1940)	Classical H-B process:coke	88	Appl (1976)
Mid 20th century (1960)	Modern H-B process:naphtha	55	Tatchell and Lewis (1977)
1970s	Modern H-B process:natural gas	47[b]	TFI (1980)
Practical minimum	Modern ammonia plants	32	Tatchell and Lewis (1977)
Theoretical minimum	Modern ammonia plants	23[c]	Tatchell and Lewis (1977)

a. The electric arc process produced nitric acid, not ammonia. The energy use is about 700 GJ/mt of N, equivalent to 574 GJ/mt of ammonia.
b. Average of energy use for ammonia plants (both reciprocating and centrifugal) in operation in the United States and is based on TFI energy use survey in latter part of the 1970s.
c. Some other calculations of the theoretical minimum energy requirement range from 19.2 to 21.2 GJ/mt of NH_3, depending on the assumptions made as to state (gas or liquid) of reactants and reaction product, amount of oxygen introduced as air in secondary reforming, reference temperature, and natural gas composition.

However, there exists a large potential for reducing the energy needs from 47 GJ/mt to the practical minimum of 32 GJ/mt in the commercial production of ammonia.

The fertilizer industry and research institutions seem rather active in finding ways to reduce these energy requirements. This effort began mainly after the energy-fertilizer crisis of 1973/74 when energy prices almost quadrupled. Prior to that time the main emphasis of research and development in the nitrogen fertilizer industry had been on finding ways to reduce capital investment. As a result, the older ammonia plants are relatively less energy efficient in ammonia production than the modern plants.

The major technological developments which led to energy efficiency in ammonia synthesis are chronicled by Quartulli and Buividas (1976) and summarized in Table 31. The technological advances in ammonia production in the last 30 years have been phenomenal, especially with respect to plant size and energy use. First, before 1952 the typical size of a single-train ammonia plant was 136 mtpd. Now it is possible to build a "jumbo" size commercial ammonia plant with a single-train capacity of up to 1,534 mtpd or even larger. Second, the total energy requirements for ammonia production declined from 55.8 GJ/mt in 1952 to 36.2 GJ/mt in the 1970s, implying a reduction of 19.6 GJ/mt or a 35% reduction in energy use. This was mainly due to reduction in power requirements from 13.4 GJ/mt to a negligible amount. The energy for ammonia production in the form of feedstock and fuel first increased from 34.9 GJ/mt in 1963 to 43.0 GJ/mt in 1964, then suddenly declined by 6-7 GJ/mt. This decline in energy use may be explained by changes in the design features of the newer plants, including use of high-pressure steam, a more energy-efficient CO_2 removal system, and preheat of the combustion air.

Table 31. Technological Developments and Energy Use for Ammonia Synthesis Based on Natural Gas[a]

Development Phase, Year	Plant Size[b] (mtpd)	Reformer Pressure (psig)	Synthesis Pressure (atm)	Feedstock and Fuel (GJ/mt NH_3)	Power (GJ/mt NH_3)	Total Energy Use (GJ/mt NH_3)	Major Process Improvement
Up to 1952	136[c]	5	320	42.4	13.4	55.8	Haber-Bosch process was developed in early 20th century
1953	147[d]	60	320	41.8	11.4	53.2	First increase in reformer pressure to 60 psig
1955	91-272	125	320	37.2	9.8	47.0	a. First use of centrifugal compressor for synthesis gas compression to 400 psig b. First single train 272-mtpd unit
1960-62	91-327	275	320	35.5	7.9	43.4	a. Use of low-utility carbon dioxide removal processes and further increases in reformer pressure b. Improved reformed tube materials
1963	290	400	320	34.9	7.3	42.2	a. Further increases in reformer pressure b. Greater recovery of heat of reaction c. Introduction of low temperature shift catalyst
1964	545	275	320	43.0	2.2	45.2	a. First use of centrifugal compressor for compression of synthesis gas to 2,000 psig b. First 545-mtpd single-train unit
1965-75	545-1,543	450-480	150-230[e]	36.0-37.2	0.2	36.2-37.4	a. First use of all-centrifugal compressor design with high-efficiency energy cycle b. Single-train design to 1,543-mtpd unit

a. Energy estimates refer to LHV.
b. Single train units.
c. With three parallel synthesis loops.
d. With two synthesis loops.
e. Synthesis pressure varies with plant capacity.

In order to understand and develop energy-saving principles, it may be useful to summarize the basic steps involved in ammonia production from natural gas by the standard steam reforming method. These basic steps are:

(a)	Primary Steam Reforming	$CH_4 + H_2O \rightarrow CO + 3H_2$
(b)	Secondary Reforming	$CH_4 + \frac{1}{2}O_2 + (2N_2) \rightarrow CO + 2H_2 + (2N_2)$
(c)	Shift Reaction	$CO + H_2O \rightarrow CO_2 + H_2$
(d)	Carbon Dioxide Removal	Physical separation
(e)	Methanation	$CO + 3H_2 \rightarrow CH_4 + H_2O$ $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$
(f)	Ammonia Synthesis	$3H_2 + N_2 \rightarrow 2NH_3$

These chemical reactions take place in several steps. The temperature ranges from 1200°C to -33°C and the pressure from about 40 to 200 atm. Except for steam reforming of methane, all the reactions are exothermic; i.e., heat is released in the process. The primary energy-saving efforts in ammonia production need to be directed at but not limited to (1) recovering heat in the reforming process, (2) improving efficiency of energy use in CO_2 recovery and removal, (3) recovering and recycling H_2 from the purge stream, and (4) further improvements in the synthesis process.

The basic steam-reforming process which is in use in the great majority of plants is represented by the much-simplified diagram in Figure C-1. The overall net chemical reaction which takes place in several steps is approximately:

$$\underset{\text{Methane}}{7CH_4} + \underset{\text{Water}}{10H_2O} + \underbrace{8N_2 + 2O_2}_{\text{Air}} \rightarrow \underset{\text{Ammonia (liquid)}}{16NH_3} + \underset{\text{Carbon Dioxide}}{7CO_2}$$

The weight of the reactants per metric ton of ammonia is:

Reactant	Weight, kg/mt of NH_3
Methane	412
Water	662
Nitrogen	823
Oxygen	235
TOTAL	2,132
Products	
Ammonia	1,000
Carbon dioxide	1,132
TOTAL	2,132

The 412 kg of methane is the approximate minimum amount that must be used as feedstock in the steam-reforming process. It is equivalent to about 20,300 ft^3 (574.4 m^3) of methane at 0°C and 1 atm pressure. Its net heating value is about 4,925 million kcal, 19.5 million Btu, or 20.6 GJ (natural gas typically contains 93%-95% methane, 3%-4% ethane and higher hydrocarbons, and small percentages of nitrogen). This energy input in feedstock, 20.6 GJ, is approximately the theoretical minimum energy requirement for producing 1 mt of ammonia by the steam-reforming process. The overall chemical reaction shown above is the sum of several chemical reactions, some of which are endothermic (absorb heat) and some exothermic (release heat). The reaction as a whole is very slightly exothermic. If all of the heat and energy applied or released could be recovered, there would be no need for external energy.

The complexity of the ammonia production process precludes a close approach to the theoretical minumum energy requirement. The several steps of the process take place at different temperature levels ranging from -33°C to 1200°C, and at pressures from atmospheric to 200 atm. So external energy as fuel and mechanical power must be applied to meet these requirements. In fact, much of the cost of a modern ammonia plant is in energy recovery devices--heat exchangers, boilers, condensers, and power recovery equipment. It is likely that further efforts to conserve energy beyond the use of the latest proven design will result in only marginal gains. However, much energy usually can be saved by applying proven technology.

The average energy use reported in U.S. plants in 1979 was about 40.0 million Btu (42.2 GJ)/mt of ammonia (LHV). Many of these plants were built or designed between 1963 and 1973 when about 40 million Btu/mt was a common guaranteed battery-limits consumption. Between 1973 and 1978 improvements were introduced which lowered the total gas consumption from about 40 to 34 million Btu by lowering the fuel consumption. The two most important improvements were (1) preheating the combustion air for the primary reformer furnace and (2) generating steam from waste heat at a pressure sufficiently high to drive the turbines for the compressors and still have the exhaust steam at a pressure high enough to supply process steam for the reformer. Most plants built or designed after 1973 incorporated these features except in countries where natural gas cost was too low to justify the additional investment.

Also, since 1973 numerous other energy-saving changes have become available. Many are highly technical, and no attempt will be made to describe them in detail. These are some of the more important energy-saving improvements:

1. Several methods for utilizing purge gas have been developed and utilized. Purge gas is the gas purged from the synthesis loop (see Figure C-1). It contains nitrogen, hydrogen, argon, and methane. By utilizing the purge gas to make more ammonia, the feedstock requirements can be reduced by 5%-8%. In some methods the argon can be recovered for sale. An alternative is to remove argon and methane before the synthesis loop and thereby eliminate the need for purging;

2. The synthesis reactor (converter) has been redesigned to lower the pressure drop or increase the conversion per pass or both;

3. More energy-efficient systems have been developed for removing and recovering carbon dioxide;

4. Continual improvements of catalysts used in several steps of the process have increased their effectiveness, lowered the pressure drop, and extended their life;

5. More thorough cleaning or purification of the natural gas, steam, and air entering the process has increased the life of catalysts and lengthens the time between shutdowns. A recent news article reports that an ammonia plant has operated continuously for 633 days at well above design capacity; and

6. Ammonia can be recovered from the synthesis loop by absorption in water under pressure and later released as a gas by lowering the pressure. This would save much of the energy now used for liquefaction of ammonia and later vaporization for use in urea or ammonium nitrate production.

Several more drastic revisions of the basic flowsheet have been proposed, but it is unlikely that a decrease of more than 10% in energy consumption below that of the latest proven design will be practical. For the near future the greatest energy savings will come from application of proven technology and more careful maintenance and operation of present plants.

According to Chemical Economy Research Institute (CERI) (1979), the energy entering the ammonia plant (35.60 GJ/mt of NH_3) consists of natural gas for the process, natural gas for fuel, and electric power. On the other hand, energy leaving the ammonia plant consists of ammonia (17.60 GJ), energy absorbed in cooling water (12.60 GJ), heat losses, and heat absorbed in cooling air (5.40 GJ). Assuming no import or export of steam, the implied energy efficiency in ammonia production is about 50%. Any effort to reduce energy consumption must make full use of steam, reduce heat transferred to the cooling water, and reduce heat losses to the surroundings. One way to reduce energy consumption is to use the S-200 Radial Flow Converter (developed

by Haldor Topsoe A/S in 1976) which reduces gas circulation and refrigeration requirements. According to CERI (1979), "it is quite realistic to state that in the 1980s new plants with consumption figures around 6.3 to 6.5 Gcal/mt (i.e., 26.4 GJ to 27.2 GJ/mt of ammonia) will be in operation."

Many other energy-saving innovations involving changes in design and processes are discussed by Agarwal (1981); Buividas (1979); Buividas, Czuppon, and LeBlanc (1978); Chari (1979); Spear (1979); and Van Weenen and Tielrooy (1980). Chari (1979) has discussed an approach developed by C-E Lummus which has the potential of reducing energy requirements between 26 and 28 million Btu/short ton of ammonia (i.e., 30.2 GJ to 32.5 GJ/mt of ammonia). The required modifications and improvements include reformer combustion air preheat, improved CO_2 removal system, pressure optimization in synthesis, cryogenic recovery of hydrogen from purge gas, and improvements in ammonia reactor design.

Pullman Kellogg (now M.W. Kellogg) announced in a press release in August 1980 that a new 1,100-short-ton-per-day ammonia plant would be built in Canada designed for an energy consumption of less than 27 million Btu/short ton (31.4 GJ/mt LHV). The announcement noted that further reductions in energy consumption were possible but were not considered economical at present.

Kellogg's design includes a horizontal ammonia converter in which a catalyst with smaller-than-normal size particles is used. This change reduces power for recycling synthesis gas by increasing conversion per pass and lowering the pressure drop. The design also includes recovery of hydrogen from purge gas by selective permeation through membranes (developed by Monsanto) and a low energy CO_2 separation process (Selexol process, developed by Allied Corporation). More efficient heat recovery from reformer flue gas decreased the gas temperature to 250°F (120°C). The heat recovered was used to preheat combustion air and feedstock. Numerous other energy-saving features were included, some of which were not disclosed.

It should be noted that energy efficiency in all manufacturing processes depends not only on the process and equipment design, but also on how efficiently it is operated. Buividas (1979) gives a checklist of 27 housekeeping items that will help keep ammonia plants operating at high efficiency.

As has been pointed out earlier, the major emphasis on research dealing with improvements in energy efficiency began about the time that large-scale ammonia plants (with a capacity more than 600-short-tons-per-day) became popular. Consequently, small-scale ammonia plants, which may be the only feasible alternative for certain countries, did not undergo the same degree of technological improvements as have the large plants. A process

(developed by KTI Corporation) which is considered energy efficient and is especially suited for small (less than 600-short-tons-per-day) ammonia plants is described by Van Weenen and Tielrooy (1980). This process is known as PARC process--for Pressure swing adsorption purification, Ammonia synthesis, and Rankine Cycle power recovery.

As described by Van Weenen and Tielrooy, these are the major energy-saving features of the PARC process:

1. Combustion air is enriched with oxygen from 21% to 26%, and preheated to 600°F;

2. The reformer flue gas is cooled to 300°F;

3. Gas from the high-temperature shift converter is cooled from 750°F to 150°F in a two-stage Rankine Cycle process, which is used to generate electricity;

4. Any excess steam is also used to provide heat to the Rankine Cycle, generating additional electric power;

5. Refrigeration in the ammonia synthesis loop is unnecessary;

6. There is no purge gas in the ammonia synthesis loop; and

7. The high energy-consuming carbon-dioxide removal system used in conventional processes is replaced with an energy efficient Pressure Swing Adsorption (PSA) purification system.

The energy calculations made by Van Weenen and Tielrooy indicate that the energy requirements are slightly lower for small ammonia plants using PARC process than for large ammonia plants using conventional process.

The manufacture of bulk, prilled urea in the United States requires an average of 79.5 GJ/mt of N, of which about 74% is the ammonia energy input and 26% is accounted for by conversion of ammonia to prilled urea. Thus the energy requirement for conversion of ammonia to urea is substantial and the means for reducing it warrant attention. In fact, much attention has been given to energy-saving improvements in the urea manufacturing process. The lower value of the interquartile range in the energy use survey was about 12 GJ/mt of N which is probably typical of the more modern plants and is about half of the average value of 21 GJ/mt of N. A contractor's estimate for battery-limits energy requirements may be as low as 3.07 GJ/mt of urea (6.67 GJ/mt of N). However, this estimate does not include some offsite requirements or disposal of liquid effluents.

The main liquid effluents are water condensed from the evaporator vapor, which contains fractional percentages of

ammonia, and liquor scrubbed from the prilling tower exhaust gases which contains fractional percentages of urea. In some cases these effluents require energy-intensive methods for disposal or recycling. The lower energy requirement for granulation as compared with prilling appears to be connected with the stringent requirements in the United States for prevention of atmospheric pollution and disposal of liquid effluents. In countries where regulations are more flexible, the energy requirements of the two methods may be about the same.

It may be concluded that the energy requirement for conversion of ammonia to urea in modern, new, efficiently operated plants can be reduced to about half of the present U.S. average. In conjunction with application of more energy-efficient ammonia technology, the total energy use can be reduced from 79.5 to about 52.0 GJ/mt of N (HHV) for bulk prilled or granular urea f.o.b. factory. Any energy saving beyond this point is likely to be small and perhaps economically marginal, barring unforeseen breakthroughs.

Since ammonia is the major energy-intensive intermediate input in urea production, any energy savings in ammonia production would also be reflected in urea production. However, technological improvements in urea technology can result in further reductions in energy use. Some of these energy-saving innovations are discussed by Pagani and Granelli (1979), and by Pagani, Mariani, and Meijerink (1980). The production of urea can be described as

$$CO_2 + 2\ NH_3 \rightarrow NH_2COONH_4$$

$$NH_2COONH_4 \rightarrow CO(NH_2)_2 + H_2O$$

In other words, carbon dioxide is reacted with ammonia at a high temperature (about 180°C) and pressure (140-200 atm) to form ammonium carbamate. This is followed by elimination of water from ammonium carbamate to form urea. In a conventional urea reactor an excess of ammonia is used and the conversion efficiency for carbon dioxide is 65%-70%; for ammonia it is 32%-35%. The energy efficiency of urea production can be improved through high conversion efficiency in the urea reactor and efficient recycling of unreacted ammonia and ammonium carbamate. Pagani and Granelli (1979) claim that Montedison (from Italy) has developed a urea process known as IDR (isobaric double recycle) process which reduces energy requirements through high conversion efficiency and easy recycling.

One of the most energy-efficient urea processes in common use is the Stamicarbon stripping process which has been described by Kaasenbrood and Chermin (1977). In this process most of the unconverted reactants are stripped from the urea solution by the incoming carbon dioxide stream at synthesis pressure and elevated temperature, thereby saving much of the

energy for recycling the unconverted ammonia and ammonium carbamate.

As noted previously, the average energy use for producing urea from ammonia in the United States is 2.5 times greater than the value given in IFDC (1979), and this value was selected as an average of utility requirements of several processes. This large difference is attributed mainly to stringent EPA air and water pollution control regulations and to energy-intensive means that are used to meet them. Therefore it may be concluded that the most fertile field for energy reduction in urea manufacture will be in finding more energy efficient means for conforming to regulations or perhaps in setting more cost-effective pollution control goals. It should be noted that the average energy use in converting ammonia to prilled urea is about 21 GJ/mt of N, so potential savings in this process are comparable to those that may be made in the ammonia process.

The ammonium nitrate process generates a substantial amount of heat in the chemical reactions involved, particularly in the nitric acid production and neutralization steps. Modern facilities convert this heat into steam and mechanical energy for use in the process and often show a positive energy balance in the form of steam for export. This is particularly true of European plants. European manufacturers have long been more concerned with energy conservation than American manufacturers who until recently were more concerned with minimizing the initial investment. The difference in viewpoint is said to be related to differences in rate of depreciation allowances for tax purposes. The TFI survey shows an interquartile range of 0.28 to 2.77 GJ/mt of ammonium nitrate in solution form and 2.22 to 6.76 GJ/mt in prilled form. This wide range can be attributed to the survey's inclusion of many older plants which were built when energy was cheap. Some of these plants have been compelled to adopt energy-intensive pollution control measures to meet standards that have been established since the plants were built.

One important point in the ammonium nitrate process is the nitrogen recovery which is assumed to be 96% in this study. Most of the nitrogen losses are in the nitric acid plant. In the conversion of ammonia to nitric oxide (NO), side reactions occur which result in loss of fixed nitrogen as elemental nitrogen. Also, the tail gas contains oxides of nitrogen which must be recovered or destroyed to meet pollution requirements. Destruction methods involve a loss of fixed nitrogen and are often less expensive than recovery for some older plants. Most modern European plants and some new U.S. plants have a relatively high nitrogen recovery, perhaps as high as 98% for the ammonium nitrate process as a whole. Recovery of dust from the prilling tower to meet pollution regulations has contributed to high energy consumption in many plants. As in the case of urea, this problem is less for granulation.

Application of proven technology for new plants coupled with efficient operation should be capable of reducing energy consumption to about 2 GJ/mt of ammonium nitrate. In conjunction with energy savings in ammonia production and better nitrogen recovery, the total energy use for bulk prilled ammonium nitrate could be reduced from 24.95 GJ/mt to about 17.2 GJ/mt or 50.7 GJ/mt of nitrogen, as compared with the present U.S. average of about 73.4 GJ/mt of N. Some of this energy reduction may not necessarily be economical.

Many European countries do not permit production of straight ammonium nitrate because of potential fire and explosion hazards. In these countries, CAN is popular. This product is a mixture of ammonium nitrate granulated with chalk, limestone, or dolomite. The usual nitrogen content is 26% N, but products in the range of 21% to 28% are being or have been produced. The calcium and magnesium contents have some value in controlling soil acidity and in furnishing nutrient elements which may be deficient.

Production of ammonium sulfate from sulfuric acid and ammonia releases a large amount of chemical heat. The most common process, vacuum crystallization, disposes of this heat by evaporation of water that is added for that purpose. The water vapor is later condensed, and its heat is released at such a low temperature that little use can be made of it. However, the heat of reaction can be used when ammonium sulfate is produced as an ingredient of compound fertilizers by adding ammonia and sulfuric acid to other ingredients. The heat generated assists granulation and helps to dry the product.

The probable maximum savings in energy use for new plants using available technology for selected nitrogen fertilizers are summarized in Table 32.

Table 32. Probable Maximum Savings in Energy Use for Selected Nitrogen Fertilizers

Product/Process	Energy Use Present	Energy Use Future	Energy Savings
	- - -(GJ/mt of N)- - -		(%)
Ammonia	57.2	42.9	25
Urea (prilled)			
Ammonia input	58.7	44.0	25
Synthesis	12.0	6.7	44
Finishing	8.9	3.5	61
Urea total	79.6	54.2	32
Ammonium nitrate (prilled)			
Ammonia input	59.7	44.8	25
Conversion	13.7	5.9	57
AN total	73.4	50.7	31

Phosphate Fertilizers

As compared with nitrogen fertilizers, phosphate fertilizers require much less energy in their manufacture. However, despite low energy intensity, the possibilities for saving energy are there. Various energy reducing innovations for phosphate fertilizers (mainly for phosphoric acid) are discussed by Hignett (1980b); Hornbeck (1978); and Stevenson, Earl, and Gardner (1979). The potential for energy savings in phosphate rock mining may be rather limited. The energy consumption in phosphate fertilizer manufacturing, however, can be reduced through (1) wet grinding of rock, (2) use of the hemihydrate process in phosphoric acid manufacture as opposed to the dihydrate process, (3) generation of electric power from waste heat, and (4) other modifications in design and processes.

First, wet grinding of rock eliminates the need for drying and, hence, saves energy. According to Hignett (1980b), through wet grinding the power requirements can be reduced 30%-40%. Furthermore, wet grinding reduces dust losses and air pollution by dust. It seems that the process has already been accepted by industry, especially for the newer plants. Still more energy can be saved by eliminating grinding entirely which is possible in several processes when the rock is of such fineness as that commonly found in world trade. Some Florida plants use unground, undried rock.

Second, energy requirements can be reduced by switching from the dihydrate to the hemihydrate process in phosphoric acid production. In the case of the hemihydrate process no heat energy is required to concentrate the phosphoric acid for most uses. In case of the dihydrate process, this energy is supplied as steam from the sulfuric acid plant. Since the sulfuric acid plant is a net energy exporter, use of the hemihydrate process will only increase the energy surplus, unless, of course, an alternate use is found for this surplus energy.

Third, the byproduct energy derived from the sulfuric acid plant in the form of high pressure steam can be used to generate electric power. According to Stevenson, Earl, and Gardner (1979), "it is practical to consider generating up to 85%-90% of the electric power requirements of the phosphate fertilizer complex internally."

Total possible savings for TSP, DAP, and MAP were calculated according to the following assumptions: (1) rock drying and grinding for phosphoric acid production will be eliminated, (2) concentration of phosphoric acid will be eliminated by using a hemihydrate process, (3) energy recovery from the sulfuric acid plant will be increased to that reported by the upper value of interquartile range in the TFI survey, and (4) process energy will be reduced to that reported by the lower value of the interquartile range. The resulting reductions in energy use are summarized in Table 33.

Table 33. Probable Maximum Savings in Energy Use for Selected Phosphate Fertilizers

Product	Energy Use, Present	Energy Use, Future	Energy Savings
	- - -(GJ/mt of P_2O_5)- - -		(%)
Phosphoric acid	6.5	-1.2	118
TSP	9.4	2.6	72
DAP[a]	8.6	0.5	94
MAP[a]	8.3	0.2	98

a. Not including energy for ammonia input.

Granular Fertilizers

TVA has developed processes to make granular fertilizers which promise substantial energy savings. These include (1) a "falling-curtain" granulation process, (2) a "melt-type" granulation process, and (3) the pipe-cross reactor process. With the exception of the latter, these processes are still at preliminary stages of testing and will take some time before they are adopted in commercial plants. As reported in Farm Chemicals (Nov. 1979), the falling-curtain process can reduce energy by 30% plant investment needs by 40% and dust generation by 90%, over conventional granulation process. Young and Lee (1975), on the basis of preliminary data, claim that a melt-type granulation process can also save energy. Finally, TVA (1978) has reported that the use of a pipe-cross reactor reduces or eliminates the need for fossil fuels for drying granular fertilizers. Instead, chemical heat produced in the process itself is used to dry the granular product during processing. In addition use of this reactor is claimed to improve product quality and reduce air pollution. In the case of DAP manufacture, the use of a pipe-cross reactor eliminates the need for the preneutralizer and the slurry pumps used in a conventional DAP plant.

Energy Savings Through Operational Efficiency

For a given technology, energy requirements for fertilizer manufacturing can also be lowered through improvements in operational efficiency, better management, and conservation. In the past when energy was cheap, energy conservation practices did not receive high priority. Events of the last few years have changed all this and heightened consciousness of the need to save and conserve as much energy as possible in operating fertilizer manufacturing complexes.

Perhaps the most urgent energy-saving step for developing countries is to increase the capacity utilization rate of their present plants, which is now often 60% or less. Operation of an

ammonia plant at such low capacity utilization can increase the energy consumption significantly. The main cause of poor capacity utilization in many cases is interruptions in electric power supply and voltage fluctuations which cause frequent shutdowns. In such cases, it would seem worthwhile to generate electricity onsite as recommended by the World Bank for new plants. In an ammonia-urea complex there is a need for both steam and electric power, and a steam-electric cogeneration plant would conserve energy.

As shown in Figure 16, it is generally assumed for the sake of simplicity that energy use on a per unit basis (GJ/mt of fertilizer) remains constant at different plant utilization rates. In other words, there is no correlation between energy use and operational efficiency. However, in actual practice this may not be true. Rather, there seems to exist an inverse relationship between energy use and plant utilization rate. This is mainly due to a fixed energy use component which does not change when the plant is shut down. Furthermore, the larger the number of interruptions to achieve a given utilization rate, the lower the energy efficiency. Improvements in plant utilization rate not only increase energy efficiency but also lower per unit production cost and increase fertilizer supply.

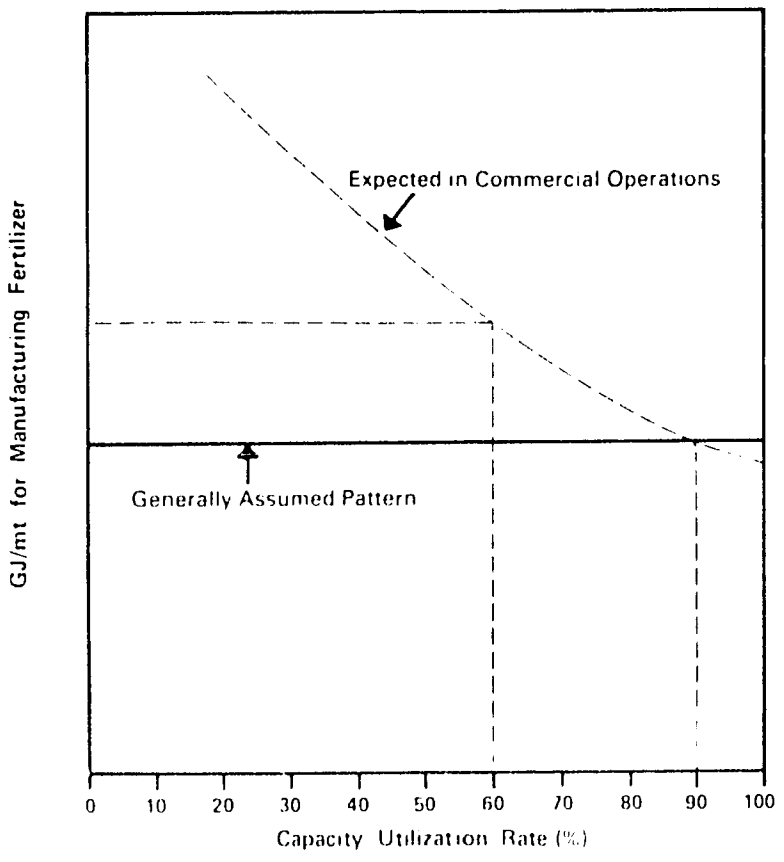

Figure 16. Energy Requirements for Manufacturing Fertilizers at Different Capacity Utilization Rates.

The energy use depends on the rate and continuity of operation. For instance, as reported in Gupta (1978), in a naphtha-based plant in India, the naphtha consumption was 1.26 mt/mt of ammonia when operating at 60% of capacity (reduced rates and shutdowns). However, the naphtha consumption dropped to 0.95 mt/mt of ammonia when the plant was operating at 96% of capacity (no shutdowns). Similar data are also reported by Mukherjee (1978) for a natural gas-based plant. According to Tangri (1978), operating modern ammonia plants at 60% and 40% of the rated capacity results in 14% and 15%, respectively, higher energy use.

In addition, energy use at a given level of utilization rate can also be reduced through common sense measures dealing with energy conservation. As reported by TFI (1980), the net goal to improve energy efficiency through conservation in the United States by 1980 (compared with 1972) is 15% for N production, 18% for P production, and 22% for fertilizer mixing. By the end of the period July-December 1978, the fertilizer industry (designated companies), on the average, had been able to improve energy efficiency by 13.5%. By the end of 1980, the average energy saving amounted to about 16%/mt of product.

According to the TFI Energy Use Survey, the practices which contributed to the energy efficiency improvement in the fertilizer sector, listed in descending order of frequency, are:

1. Heat recovery from more efficient heat exchangers;
2. Increased plant capacity utilization and improved operations;
3. Better controls of plant operations and energy use through use of improved technology and computers;
4. Plant modifications and changes in equipment design;
5. Insulation;
6. Use of new and improved catalysts;
7. Steam trap maintenance programs;
8. Hydrogen recovery at ammonia plants;
9. Improved general maintenance; and
10. Lighting improvements.

Energy Substitution Possibilities

Substitution of energy sources in fertilizer manufacturing involves (1) replacing scarce with abundant nonrenewable energy resources and (2) replacing nonrenewable with renewable energy resources. Energy substitution possibilities are limited but they do exist, mainly for nitrogen fertilizer manufacturing. However,

the situation may vary from one country to another, depending upon the economics, raw material reserves, level of industrialization, and size of the fertilizer market.

Ammonia From Nonrenewable Resources

It has been documented earlier that ammonia is the basis of nitrogen fertilizers and natural gas is the most preferred feedstock for ammonia production. On the basis of the known estimated reserves, one can conclude that there is plenty of natural gas to produce nitrogen fertilizers for the foreseeable future. However, the final use of natural gas in the fertilizer sector would depend on the comparative economics and the opportunity cost of gas. According to Exxon (1980), sufficient natural gas reserves are believed to be available. "However, most are in remote areas, and the facilities required to move the gas to market are expensive and entail considerable commercial risk. Nevertheless, between now and 1990, LNG imports into Europe and Japan are expected to increase fivefold. Lead times for projects to import LNG currently average 7-10 years. Problems related to gas delivery, rather than resource base, are likely to limit gas use over this period."

According to Spear (1979), "the general feeling in the ammonia industry seems to be that natural gas will continue to be the predominant feedstock for the foreseeable future, or at least while stocks last. Any radical departure from conventional technology with its dependence on hydrocarbon feedstocks, is unlikely, however, to have any immediate effect on today's ammonia producer whose main operating concern must remain energy saving." This may be true for world aggregate but the production and trade patterns of ammonia would shift in favor of countries with abundant natural gas reserves. Those countries currently with a large ammonia capacity based on natural gas but with limited natural gas reserves may (1) either scrap their capacity or (2) import feedstock or (3) use domestic alternative energy resources that are more abundant to replace natural gas. In addition to the availability of alternative energy sources, the substitution possibilities will also be influenced by technological, economic, and security considerations.

With the exception of Blouin (1974), very little systematic work has been done to evaluate energy (feedstock and fuel) substitution possibilities in the fertilizer sector. As discussed earlier, ammonia can be produced from natural gas, naphtha, fuel oil, coal, or hydrogen derived from the electrolysis of water. Electrolytic hydrogen is prohibitively expensive unless electricity is abundant and cheap. Ammonia is being produced commercially through partial oxidation of coal in India and South Africa. In the United States, ammonia from coal gasification is being produced on a pilot basis by TVA. At this stage, ammonia from coal is not yet economically feasible and many technological problems remain to be solved.

The ease or difficulty of substituting one feedstock for another is illustrated by the order developed in Table 34 in which plants designed to use any given feedstock can use, with relatively small modifications, any feedstock above it. For example, a plant designed to use coal can use light or heavy oil, naphtha, or natural gas although much of the equipment will be oversize or unnecessary. Conversely, a plant designed to use natural gas cannot use coal without changes so extensive as to exceed the cost of the original plant.

Table 34. Order of Substitutability of Ammonia Feedstocks

Order	Feedstock	Substitutability
1	Electrolytic hydrogen	↑
2	Natural gas	
3	LNG	Increasing
4	LPG	Difficulty
5	Refinery gas[a]	of
6	Coke-oven gas[a]	Feedstock
7	Naphtha	Substitution
8	Light oil	
9	Heavy oil	
10	Coal	↓

a. These feedstocks are variable in composition so their exact place may be in question.

Blouin (1974) identified several problems for producing ammonia from coal. These are (1) poor operating experience, (2) high original capital costs, (3) great variability in coal quality, (4) high fuel losses, (5) high labor costs, (6) high steam requirements, and (7) limited capacity of individual gasifiers. However, according to preliminary estimates made by Nichols, Williamson, and Waggoner (1978) and Waggoner, Lee, and Foster (1980), given current trends in energy prices, it appears that in the not too distant future ammonia from coal may become economically competitive with ammonia from natural gas. This position is further reinforced by Buividas (1980), who notes that "rising energy prices will make coal a competitive feedstock for ammonia production by the middle of this decade and coal based ammonia could predominate by the end of the century."

Ammonia From Renewable Resources

It is technically feasible to manufacture ammonia from "biogas." Biogas is gas generated by anaerobic fermentation of organic wastes or crop residues. It contains 50%-60% methane;

the remainder is mainly carbon dioxide. Purification procedures are the same as those used for natural gas. The residue after fermentation contains fertilizer nutrients in a relatively concentrated form so the biogas route recovers both energy and plant nutrients. Hundreds of thousands of small biogas units are in use in China and to a lesser extent in India and other countries.

The technical feasibility of generating biogas from urban waste (garbage and sewage sludge) has been demonstrated in the United States. The main difficulty is in separating the degradable from the nondegradable portion of the waste. Biogas is also recovered from sanitary landfills in the United States in amounts sufficient to supply a small ammonia plant (about 200 mtpd) although the gas has not been used directly for that purpose. Some of the biogas is purified and sold to natural gas pipelines, so it is possible that ammonia plants that draw their supply from general-use pipelines may be using a small percentage of methane derived from biogas.

Ammonia may also be made by steam reforming of ethanol, and ethanol may be produced by fermentation of grain or carbohydrates from other sources (sugarcane, potatoes, or cassava); with somewhat more difficulty, ethanol can be produced from cellulosic biomass--straw, cornstalks, and wood waste. Conceivably, an energy farm designed for that purpose could supply a full-scale ammonia plant. However, at present the main emphasis is on producing alcohol for motor fuel, either straight or in mixtures with gasoline.

Biomass can be used directly for ammonia feedstock by partial oxidation or pyrolysis methods. In fact, a small ammonia plant in India operated for several years with wood feedstock. One difficulty with most biomass is that its moisture content is so high that most of its energy is spent in evaporating its moisture content. Also, nitrogen fertilizer values in biomass are lost in high-temperature processes.

Electrical energy is renewable when generated from hydropower, tidal waves, wind, or solar energy. However, in most locations, electric power from these sources is far from adequate to supply the demand, and 90% or more of the electricity is generated by burning fossil (or nuclear) fuel. In such cases use of electrolytic hydrogen for ammonia production would result in a net increase in fossil fuel use. Only in locations where the amount of available or potential electrical energy greatly exceeds the demand can this source be considered.

In some locations where the hydroelectric potential exceeds the foreseeable demand for electricity, the use of this renewable energy source for nitrogen fertilizer production may be economically feasible, particularly in remote locations where the alternative of importing fertilizers is very expensive. In the past, many ammonia plants were based on electrolytic hydrogen. During the 1930s there were 21 such plants in developed countries. Most of

them were closed because of the growing demand for electric power for higher value uses.

The electrolytic ammonia process has relatively little economies of scale. For plants with a capacity of less than about 250 mtpd of ammonia, an electrolytic hydrogen-based ammonia plant is less expensive than a natural gas-based plant. For example, in 1978 a 100-mtpd electrolytic ammonia plant was estimated to cost about US $20.0 million, whereas a natural gas-based plant of the same size would cost US $25.0 million (IFDC, 1979).

The energy requirement for an electrolytic ammonia plant is about 10,000 kWh/mt of ammonia, including compression and air liquefaction to supply nitrogen. Thus, the energy cost is approximately $100/mt of ammonia when electricity costs $0.01/kWh. The main operating costs other than electricity are capital charges. As with all small plants, capital charges per unit of output are relatively high.

The electrolysis of water also produces oxygen which may be used in other industries such as steel. It is technically feasible to produce electrolytic hydrogen with offpeak electricity. The hydrogen can be stored as a metal hydride to permit continuous operation of the ammonia plant. Offpeak electric power often is quite inexpensive, but its use would involve higher capital costs because of low capacity utilization of electrolyzers.

Where low-cost electricity is available it can be used in a hydrocarbon steam-reforming plant to supply heat for the reforming process ("electroreforming"). For example, a plant that uses naphtha as feedstock would require only about 17.3 GJ/mt of ammonia in the form of naphtha, which is about half that required when naphtha is used for both fuel and feedstock (Silberring, 1981). Electrical heating of the reformer and electric-driven motors would supply the remainder of the energy. Since electrical energy can be used more efficiently than fuel energy, less total energy would be required.

Electricity can also be used to fix nitrogen by the arc process. However, with a given amount of electricity, four times as much nitrogen can be fixed by the electrolytic hydrogen process. Also, the arc process produces nitric acid, not ammonia, and hence only low-grade nitrogen fertilizers such as calcium or sodium nitrate (13%-16% N) can be made.

Ammonia produced from electrolytic hydrogen can be used to make ammonium sulfate, nitrate, or phosphate, but urea cannot be produced unless some external source of carbon dioxide is available. The ammonia can also be used to make nitrophosphate fertilizers by converting part of the ammonia to nitric acid for acidulation of phosphate rock.

At this stage, "nitrogen from sun" based on the electric arc process powered by solar energy does not seem a practical and

viable alternative to the conventional processes. Generation of electricity by utilizing temperature differential of ocean currents--Ocean Thermal Energy Conversion (OTEC)--is in an advanced state of development. The process must be carried out at a location in an ocean where there is a large temperature differential between the upper and lower ocean currents. Since it is infeasible to transmit the electricity ashore, it must be utilized where it is generated. Production of ammonia via electrolytic hydrogen is one of the most likely uses. The ammonia produced would be shipped ashore where it could be used to make any nitrogen fertilizer although production of urea would require an economical supply of carbon dioxide which would be difficult to obtain.

There has been much research aimed at developing a process that would fix nitrogen at normal temperatures and pressures. Two enzymes have been isolated which together fix nitrogen biologically. By using these enzymes molecular nitrogen has been converted to ammonia in vitro. This research has led attempts to simulate the natural process by entirely chemical means using organo-metal catalysts. Some ammonia was produced, but the catalyst was destroyed. Chatt (1976) has summarized this work and said, "It is unlikely that the Haber process can be beaten as a process for the production of nitrogen fertilizer in bulk." Rather, he hopes to find a catalyst that would fix nitrogen dissolved in irrigation water so that there would be a small but persistent application of ammonia during irrigation. He states that this goal is still far distant, but he can see it as a definite possibility. All of these methods for fixing nitrogen require a substantial energy input, but the energy can come directly or indirectly from solar radiation.

Downstream Energy Substitution

Energy substitution possibilities for downstream nitrogen facilities, and for phosphate and potash fertilizers, are more hopeful. The urea process, for example, uses energy in the form of steam and electricity which may be generated by any convenient fuel. The same is true of potash mining and refining, and to a large extent of phosphate processes. A relatively small amount of fuel is used for product drying. In direct-fired dryers a clean fuel is needed (oil or gas) to avoid contamination of the product. However, coal could be used indirectly by using steam generated by coal to heat air for drying.

Energy Use and Economies of Scale

With the development of the centrifugal compressor (as opposed to the reciprocating type) and other technological

improvements, it is possible to produce ammonia by building modern large-scale or even "jumbo" ammonia plants. These large-scale ammonia plants have been mainly responsible for lowering unit cost of production through improved energy efficiency and economies of scale. However, these large ammonia plants may not be suitable for all the countries and under all the prevailing conditions. The construction of large ammonia plants in the absence of appropriate economic justification can result not only in tremendous wastage of energy but also in very high cost of production. Clearly, bigger is not always better.

Many considerations dictate that countries invest in smaller rather than larger ammonia plants. These considerations include (1) smallness of domestic market for fertilizer, (2) limited export possibilities, (3) lack of financial resources, (4) limited supply of foreign exchange, (5) nature and availability of raw material, and (6) national goals and public policy. Ennis and Lesur (1977) have evaluated the relevance of small-scale ammonia plants as compared to large-scale ammonia plants for those developing countries which are characterized by uncertain fertilizer market and unfavorable construction conditions.

The preliminary results of Ennis and Lesur (1977) are reported in Table 35. First, the investment cost for the 300-short-ton-per-day ammonia plant is less than one-third that of the 1,000-short-ton-per-day plant. This is due to better control on construction, shorter construction time, reduced possibility for overruns, and amenability to prefabrication and skid mounting.

Table 35 Energy Use and Variation in Ammonia Production Costs by Plant Size[a]

Cost Components	Favorable Construction Conditions and Assured Market		Unfavorable Construction Conditions and Uncertain Markets		
	300 stpd[b] (Skid Mounted)	1,000 stpd (Conventional)	300 stpd (Skid Mounted)	1,000 stpd With Operating Rate 700 stpd	1,000 stpd With Operating Rate 1,000 stpd
Natural gas--feedstock ($/st)	48.2	48.2	48.2	48.2	48.2
Other variable cost ($/st)	34.3	28.0	34.3	28.0	28.0
Fixed cost ($/st)	45.4	39.6	45.6	66.0	46.3
Returns on investment ($/st)	58.1	56.8	63.5	97.8	68.5
Total production cost ($/st)	186.0	172.6	191.6	240.0	191.0
Energy use (Btu x 10^6)	32.3	30.9	32.3	30.9	30.9
Cost of energy ($/st)	80.8	74.1	80.8	74.1	74.1
Share of energy in total costs (%)	43.4	42.9	42.2	30.9	38.8
Plant investment (million $)[c]	23.0	75.0	25.4	90.4	90.4

a Derived from Ennis and Lesur (1977).
b stpd = short tons per day.
c January 1977 prices for U.S. Gulf location.

Second, the cost of producing ammonia would be $49.00/short ton higher for the 1,000-short-ton-per-day plant operating at 70% of capacity (due to small market) than for the same plant operating at full capacity or for the 300-short-ton-per-day plant operating at full capacity. Third, the large-scale plants are slightly more energy efficient, but the margin is rather small. Furthermore, as discussed earlier, with the use of more energy-efficient processes the small plants could be as energy efficient as the large plants.

If the conclusions drawn by Ennis and Lesur (1977) are valid, then for a large number of developing countries the small-scale ammonia plants may be better investments than the large-scale plants. However, we need to further verify these results under an alternative set of technological and economic scenarios. It is extremely difficult, time consuming, and expensive to build large-scale ammonia plants in countries with limited infrastructure and poorly trained manpower.

As reported in Table 36, even for countries like India (which is the fourth largest producer of nitrogen fertilizers in the world) the overruns with respect to both investment and time are extremely high. These overruns result in high production costs (much higher than those which were used to justify the establishment of the plant in the first place) which eventually get reflected in high market prices for fertilizer to the farmers. Unless certain preconditions are met, it may not be appropriate to build large plants for the sake of building them. Small-scale plants may be better and more beautiful.

Table 36. Estimated Cost Overruns for Building Fertilizer Plants in India[a]

Plant Location	Time Period, Date: Approved	Scheduled Completion	Completed[b]	Cost: Budgeted	Actual	Overrun, Actual/Budgeted
				- - (million Rs) - -		
Barauni	12/67	-	-	351	916	2.6
Bhatinda	8/74	1/78	1979	1,384	2,006	1.5
Durgapur	2/66	12/69	1977	381	1,022	2.7
Gorakhpur	1972	4/75	1976	118	184	1.6
Haldia	11/71	10/76	1980	880	2,434	2.8
Namrup Exp.	12/67	1/81	1976	295	749	2.5
Nangal Exp	10/72	3/76	1978	756	1,339	1.8
Panipat	2/75	5/78	1979	1,397	1,876	1.3
Ramagundam	10/69	7/75	1979	712	1,971	2.8
Sindri Modern	1/73	2/78	1979	889	1,672	1.9
Sindri Rationa.	12/67	10/71	1979	230	604	2.6
Talcher	10/69	7/75	1979	705	1,965	2.8
Trombay IV	9/74	4/77	1979	440	763	1.7
Trombay V	10/75	4/78	1981	1,114	1,798	1.6

a. Adapted from Kharbanda and Stallworthy (1980).
b. Completion dates 1979 and onwards are not established since plants were not completed at the time of this study

Economics of Energy Savings and Substitution

Before making any changes in existing or even in new fertilizer plants which are supposedly more energy efficient, it is extremely important to ask, "How much energy is being saved and at what cost?" Saving energy for the sake of saving it does not provide a very strong economic justification for large capital investments. For example, in a large fertilizer complex, the saved or surplus energy may be wasted if there is no alternative use for it in the complex, and especially if it is not feasible to export it. Furthermore, for countries which have large energy resources or which flare a large amount of gas, there may be very little incentive to save energy, especially if it is achieved at large capital investment. However, for those countries, especially developing countries, which depend on imports to meet all or part of their energy, fertilizer, and food requirements, it is extremely important to consider modifications which involve energy saving or substitutions as long as these changes assure expanded domestic fertilizer production and relatively stable fertilizer prices.

The potential economic implications of energy saving and energy substitution innovations in fertilizer manufacturing are developed in Table 37, under different scenarios. The final impact of these innovations on fertilizer production cost depends on the magnitude of energy saving and the capital expenditure incurred to achieve those savings under a certain set of circumstances. Even if energy prices remain constant, the production costs may still increase if the reduced energy costs are not large enough to compensate for increased capital expenditure. However, production costs would increase in response to an increase in energy prices even if energy savings compensate for an increase in capital costs. In the long run, up to certain limits, energy-saving innovations may involve substituting capital for energy, i.e., the use of more capital and less energy. For those countries which are in short supply of both energy and capital, such modifications may not provide significant fertilizer cost relief or security assurances.

The available evidence on the implications of energy-saving/substitution innovations on capital expenditure is rather mixed. However, most energy-saving innovations have been demonstrated in full-scale plants and have generally proven cost effective. Some innovations involve relatively small capital costs and some have been used in India. An innovation that results in savings of both energy and capital in North America or Western Europe may not always result in similar savings in developing countries. Most innovations which promise significant energy savings at the commercial level do involve additional capital investments. However, the magnitude of additional capital investment may vary with the type of innovation.

Table 37. Economic Implications of Energy Saving and Energy Substitution Innovations in Fertilizer Manufacturing: Alternative Scenarios[a]

Scenario	Energy Price	Energy Use	Capital Expenditure Related to Energy Use	Fertilizer Production Cost
A	→	↓	↓→	↓
B	→	↓	↑	↑→ ↓
C	→	↑	↑→	↑
D	↑	↓	↓→	↑→ ↓
E	↑	↑	↑→	↑
F	↑	↓	↑	↑

a. Arrows pointing to the right indicate that the value remains constant; arrows pointing down indicate that the value decreases; and arrows pointing up indicate an increase. Thus, under Scenario A, if the energy price remains constant, the energy use decreases and the capital expenditure remains constant or decreases, then the fertilizer production cost will decrease.

Technological modifications which involve energy substitution (for example, substituting coal for natural gas in ammonia production) generally involve higher capital investment whether they are accomplished through retrofitting or through establishing a new plant. Furthermore, there is also need to consider the implications of energy saving/substitution innovations on the demand for trained manpower, demand for foreign exchange, degree of complexity, and the degree of reliability. These are rather serious problems in most developing countries. For example, the enormous capital cost and very poor reliability in developing countries have made all ammonia-from-coal plants economically disastrous with the possible exception of those in South Africa. Even there the main justification is national security.

CHAPTER 11

ENERGY SAVINGS THROUGH SUPPLEMENTARY SOURCES OF NITROGEN

Several conclusions emerge from the analyses presented in the preceding chapters. First, the requirements for plant nutrients will continue to grow at a rapid rate in order to meet the growing demand for food, feed, and fiber. Second, the chemical sources of nutrient supply may become relatively more unstable, inadequate, and expensive over time, especially in response to increasing energy prices, capital costs, and imperfections in the international markets for energy, capital, and fertilizer. Third, there is a growing need to find technologically feasible and economically viable alternatives to supplement--not necessarily replace--chemical sources of plant nutrients. The purpose of this chapter is to evaluate these alternative sources of plant nutrients. Since energy supply and prices greatly influence the supply and price behavior of nitrogen fertilizers, the major focus of this chapter will be on nitrogen supply sources.

Alternative Sources of Nitrogen Supply

A systematic analysis of individual nitrogen supply sources is not possible without first determining the possible alternatives and their contributions to the overall nitrogen supply system. However, the amount of current and systematic information available on this subject is rather limited. That which does exist seems too speculative, fragmentary, and sometimes even inconsistent to draw any definite conclusions. Despite these shortcomings, the available information does point out that the nonchemical sources of nitrogen are too important to be ignored in fertilizer research and policy analysis.

Wittwer (1976) provided preliminary estimates of alternative sources of nitrogen for crop production for the world as a whole. These estimates are reported in Table 38. According to these estimates, the nitrogen fixed by legume crops alone was about the same as that supplied by chemical fertilizers during 1975. The total amount of nitrogen fixed biologically was approximately four times that supplied chemically. Other sources of nitrogen to soil include lightning, combustion, and ozonization. These estimates, however, do not include nitrogen supplied by organic fertilizers. Aldrich (1972), as reported in FAO (1975), has provided such estimates for major sources of nitrogen in the United States; these are reported in Table 39.

These estimates indicate that in the United States during 1970 nitrogen supplied by organic matter and organic fertilizers was

Table 38. Sources of Nitrogen for Crop Production in the World During 1975

Nitrogen Source	Million mt
Industrial fixation (chemical fertilizers)	42
Biological fixation: total	175
Agricultural soils	90
Crop legumes	40
Crop nonlegumes	9
Meadows and grasslands	45
Lightning	10
Combustion	20
Ozonization	15

Table 39. Sources of Nitrogen for Crop Production in the United States During 1970

Nitrogen Source	Million mt/Year	% of Total
Release from soil organic matter	20	37.0
Livestock manure	10	18.5
Human waste	2	4.0
Fixed by soil organisms[a]	10	18.5
Added in rainfall[b]	5	9.0
Chemical fertilizers	7	13.0
TOTAL	54	100.0

a. 22.5 kg/ha.
b. 5.6 kg/ha.

more than four times that provided by chemical fertilizers. The nitrogen fixed biologically was also more than the chemical sources of nitrogen. The nitrogen supplied by crop residues, though not specified separately, seems to be included in organic matter nitrogen estimates. According to the above estimates, 87% of the nitrogen for crop production in the United States during 1970 was supplied by nonchemical sources, almost 18% biologically and 60% by organic sources.

In addition to these aggregate estimates, rather rough estimates are also available for nitrogen supply, on a per hectare basis, for agriculture in the temperate zones. These estimates, as reported by Flaig, Nagar, Sochtig, and Tietjen (1978), are given in

Table 40. Alternative Natural Nitrogen Supply Sources in Temperate Zone

Nitrogen Source	Kilograms Per Hectare Per Year
Mineralization of soil organic matter[a]	30-270
Addition of organic manure	40
N fixation by free living bacteria	10
N fixation by legumes	100-200
N fixation by precipitation	10

a. From which one-third is used for plant nutrition.

Table 41. Sources of Nitrogen Supply in Mid-Europe Agriculture During Early 1970s

Nitrogen Source	Kilograms Per Hectare	% of Total
Mineral fertilizers	83.0	55.5
Organic manures	40.0	26.8
Seed content	1.5	1.0
N fixation by symbiosis	5.0	3.3
N fixation by asymbiosis	10.0	6.7
N fixation by precipitation	10.0	6.7
TOTAL	149.5	100.0

Table 40. These estimates also indicate that in temperate zones a large amount of nitrogen is fixed by nonchemical sources. The two major sources of this nitrogen supply are symbiotic biological nitrogen fixation and nitrogen supplied by organic fertilizer or the mineralization of organic matter. Similar estimates of nitrogen supply are also available for mid-Europe during the early 1970s. These estimates were originally made by Buchner and Sturm (1974) and are reported in Table 41, as documented in Flaig, Nagar, Sochtig, and Tietjen (1978).

The results reported in Table 41 indicate that about 55% of the total nitrogen supply was in the form of chemical fertilizers. The proportion of total nitrogen supplied by organic sources was

approximately 28% and by biological sources, about 10%. Even though the organic and biological sources of nitrogen supplied in mid-European agriculture are very important, the chemical fertilizers are the major sources of nitrogen. These results seem to contradict the results discussed earlier. However, one must keep in mind that these estimates deal with one of the most intensively farmed agricultural areas in the world where fertilizer use became popular very early and where the nutrients cannot be replenished as quickly as they are taken out without the intensive use of chemical fertilizers. These results also underlie the fact that as the agriculture sector modernizes and cultivation becomes more intensive, the dependence on chemical fertilizers, especially nitrogen, as fast-acting nutrient suppliers will also increase.

Such estimates, on the aggregate or on a per hectare basis, for tropical or subtropical agriculture are not available. However, because of (1) use of animals as major source of power, (2) large area under legume crops, (3) relatively low intensity of land use for agriculture, and (4) low level of use of chemical fertilizers, we can hypothesize that a significant percentage of the total nitrogen used in crop production is supplied by organic and biological sources.

Over time, at least two major structural changes taking place in developing countries will determine the relative importance of alternative sources of nitrogen supply. First, the adoption of modern agricultural technology and an increase in cropping intensity would increase the demand for nutrients supplied by chemical fertilizers. Second, an increase in energy and fertilizer prices, relatively uncertain or inadequate supply of chemical fertilizers at the farm level, and general lack of incentives would favor the use of organic and biological sources of nitrogen. These economic and technological forces would be acting simultaneously. The final response of a region or country with respect to the importance of chemical fertilizers in agricultural development would depend on a large number of factors. These factors are greatly influenced by the stated national goals and by government policy designed to achieve those goals.

Organic Sources of Energy and Nitrogen

Up to the middle of the 20th century, the organic or biofertilizers were the major sources for replenishing plant nutrients in the soil. For several reasons they were soon supplemented, or even in some cases replaced, by chemical fertilizers. First, the chemical fertilizers on nutrient basis were rather inexpensive, and the fertilizer price kept declining until the beginning of the 1970s. Second, in areas with a high population pressure or intensive agriculture, the quickest way to supply plant nutrient requirements was through the use of chemical fertilizers. Third, in some

countries government policy deliberately focused on providing incentives (subsidies) and facilities to expand the use of chemical fertilizers. However, the energy and fertilizer crisis of 1973-75 provided the needed stimulus to explore and develop alternative nutrient sources to either replace or supplement the nutrient supply from chemical fertilizers.

Crop residues, household wastes, and livestock wastes form the basis of organic fertilizers. The organic fertilizers can be classified by source:

1. Animal residue--dung and urine;
2. Crop residues, including green manure;
3. Rural compost;
4. Night soil--human feces and urine;
5. Urban sewage sludge;
6. Urban compost; and
7. Miscellaneous sources of plant and animal origin.

The biofertilizers are not only a rich source of organic matter but also a good source of nutrients. However, there may not be a consensus among scientists that organic matter in the soil is crucial for crop production.

The soils in tropical and subtropical regions generally have less humus content than the soils in temperate regions. This further enhances the value of bio-fertilizers as major sources of organic matter for tropical and subtropical soils. On the other hand, some scientists believe that organic matter is oxidized so rapidly in tropical soils that it has little value as a soil conditioner. The humus content or the organic matter is believed to (1) increase the water-retaining capacity of the soil, (2) reduce the soils' susceptibility to erosion, (3) increase airflow in the soil, (4) provide energy for micro-organisms, (5) provide nutrients through mineralization, and even (6) improve the efficiency of chemical fertilizers. Consequently, evaluating organic fertilizers purely on the basis of plant nutrient supply may underestimate their true value as fertilizers or soil amendments.

The economic and technological characteristics of chemical and organic fertilizers are compared in Table 42. As has been pointed out earlier, the raw materials for organic fertilizers are the byproducts of other biological and/or economic activities. The conversion of these raw materials into organic fertilizers not only increases their economic value but also solves the disposal problem which could otherwise be a health hazard. The economic advantages of organic sources as fertilizers are:

1. They are a good source of primary, secondary, and micro plant nutrients which are generally released slowly over time.

Table 42. Economic and Technological Characteristics for Chemical and Organic Fertilizers

Characteristics	Chemical Fertilizers	Organic Fertilizers
1. Primary nutrient content	Relatively high.	Relatively low.
2. Other nutrients	Only when prescribed in the grade, with some exceptions.[a]	Both secondary and micronutrients are normally present.
3. Nutrient composition	Predetermined.	Highly variable.
4. Nutrient availability	Immediately after application P and K get fixed in soil and become available over time.	Slowly released through mineralization over time.
5. Organic matter	Absent.	Normally high.
6. Direct manufacturing cost	Relatively high and increasing.	Relatively small and stable.
7. Transportation cost	Relatively small but transported over long distances.	Relatively high but transported only over short distances.
8. Ease in handling	Relatively easy to handle and clean.	Relatively bulky, messy, and difficult to handle.
9. Direct energy use--manufacturing	Highly energy intensive, especially nitrogen.	Almost negligible. Rather a good source of energy through bioconversion.
10. Direct energy use--distribution	Relatively low.	Relatively high.
11. Raw material exhaustability	Supply depends largely on nonrenewable finite raw materials.	Supply depends largely on renewable infinite resources.
12. Spatial availability	Highly localized.	Highly diffused and decentralized.
13. Fodder land requirement	None.	Large but needs to be accounted only when livestock is kept mainly for fertilizer production.
14. Environmental pollution	Known to create water and air pollution.	Solves the disposal problem. Pollution depends on the efficiency in collection, storage, distribution, and application.
15. International trade	Largely traded in the international market.	Does not enter the international market.
16. Amenability to economic analysis	Relatively easy and straightforward.	Relatively difficult to account for the costs and benefits.

a. Some chemical fertilizers contain S, Ca, or micronutrients derived from phosphate rock or basic slag that are not identified in the grade.

2. They are a good source of organic matter which has beneficial effects on soil texture and structure.

3. Their use solves the waste disposal problem and hence protects the environment from air and water pollution.

4. They are a good source of energy through bioconversion into biogas (methane).

5. They are a decentralized and timely source of plant nutrients and even energy.

The use of organic fertilizers is not free from some problems; however, these problems basically revolve around their safe and efficient collection, processing, storage, distribution, and application. The organic fertilizers are rather bulky and expensive to transport. If these fertilizers are not properly applied, they could also be a health hazard. In many Asian countries the use of cattle dung and crop residues as fertilizer also competes with their use as fuel for cooking. There may also be direct competition for certain oil cakes used as animal feed.

The nutrient content of different organic fertilizers varies depending upon the source, method of processing, and degree of nutrient loss in processing and storage. The average nutrient content in animal- and plant-based organic fertilizers is reported in Table 43. These organic fertilizers provide not only nitrogen but also other primary (P_2O_5, K_2O), secondary, and micronutrients.

Table 43. Average Nutrient Contents in Selected Organic Manures and Plant Residues in India[a]

Broad Category	Specific Manure	Average Contents, %			
		N	P_2O_5	K_2O	Total
Bulky organic manures	Farmyard manure	0.5-1.5	0.4-0.8	0.5-1.9	1.4-4.2
	Compost (urban)	1.0-2.0	1.0	1.5	3.5-4.5
	Compost (rural)	0.4-0.8	0.3-0.6	0.7-1.0	1.4-2.4
	Green manure	0.5-0.7	0.1-0.2	0.6-0.8	1.2-1.7
Oil cakes	Castor	5.5-5.8	1.8-1.9	1.0-1.1	8.3-8.8
	Neem	5.2-5.3	1.0-1.1	1.4-1.5	7.6-7.9
	Cottonseed (decort.)	6.4-6.5	2.8-2.9	2.1-2.2	11.3-11.6
	Groundnut	7.0-7.2	1.5-1.6	1.3-1.4	9.8-10.2
Manure of animal origin	Dried blood	10.0-12.0	1.0-1.5	0.6-0.8	11.6-14.3
	Fish manure	4.0-10.0	3.0-9.0	0.3-1.5	7.3-20.5
	Bird guano	7.0-8.0	11.0-14.0	2.0-3.0	20.0-25.0
	Bonemeal (raw)	3.0-4.0	20.0-25.0	-	23.0-29.0
	Sludge (activated, dry)	5.0-6.5	3.0-3.5	0.5-0.7	8.5-10.7
	Sludge (settled, dry)	2.0-2.5	1.0-1.2	0.4-0.5	3.4-4.2
	Night soil	1.2-1.3	0.8-1.0	0.4-0.5	2.4-2.8
	Human urine	1.0-1.2	0.1-0.2	0.2-0.3	1.3-1.7
	Cattle dung + urine	0.60	0.15	0.45	1.2
	Horse dung + urine	0.70	0.25	0.55	1.5
	Sheep dung + urine	0.95	0.35	1.00	2.3
	Poultry manure	1.0-1.8	1.4-1.8	0.8-0.9	3.2-4.5
Ashes	Coal	0.73	0.45	0.53	1.7
	Household	0.5-1.9	1.6-4.2	2.3-12.0	4.4-18.1
Plant residue	Rice hulls	0.3-0.5	0.2-0.3	0.3-0.5	0.8-1.3
	Groundnut husks	1.6-1.8	0.3-0.5	1.1-1.7	3.0-4.0

a. Derived from FAI (1980) and ICAR (1969).

In most developing countries, a major part of plant nutrients contained in many organic fertilizers is lost as a result of inappropriate collection, processing, storage, and application techniques. It appears that China not only converts most of the available organic wastes into organic fertilizers for crop production, but does this rather efficiently. However, other developing countries may be equally efficient in this respect.

According to the preliminary estimates made by FAO (1978a) which are reported in Table 44, in China during 1977 the estimated potential supply of plant nutrients from organic fertilizers was 8.3, 5.1, and 9.7 million mt of N, P_2O_5, and K_2O, respectively. In contrast, during the same year, the chemical fertilizers supplied 4.6, 1.4, and 0.3 million mt of N, P_2O_5, and K_2O, respectively. On the average, the nutrient supply for cropped land is estimated to be 177 kg/ha from organic fertilizers and 48 kg/ha from chemical fertilizers during 1976/77. Two other estimates are reported in Flaig, Nagar, Sochtig, and Tietjen (1978). First, as originally estimated by Van Voorhoeve (1974), the potential annual production of plant nutrients from organic wastes in the developing world during 1980 could be 60 million mt of N, 20 million mt of P_2O_5, and 49 million mt of K_2O. Second, as originally reported by Jaiswal (1971), the annual supply of nutrients from night soil alone in India could be 2.6, 0.3, and 0.5 million mt of N, P_2O_5, and K_2O, respectively.

Table 44. Estimated Annual Supply of Primary Plant Nutrients From Organic Fertilizers in China, 1977[a]

Source	Nutrients, '000 mt			
	N	P_2O_5	K_2O	Total
Night soil	762	254	381	1,397
Cattle manure	2,460	1,233	3,288	6,981
Pig manure	2,855	2,284	2,855	7,994
Goat and sheep manure	390	195	780	1,365
Poultry manure	336	269	143	748
Plant residues	819	546	1,638	3,003
Green manure	192	48	192	432
Mud and silt	360	187	216	763
City garbage	78	52	130	260
Oilseed cakes	28	4	8	40
Other	40	20	40	100
Total from organic fertilizers	8,320	5,092	9,671	23,083
Average from organic, kg/ha of cropped land[b]	64	39	74	177[c]
Total from chemical fertilizers (1976/77)	4,598	1,355	344	6,297
Average from chemical, kg/ha of cropped land[b]	35	10	3	48

a. Derived from FAO (1978a) and FAO (1981a).
b. Assuming that the cropped land is approximately 130 million ha.
c. Average quantity of organic material is approximately 13 mt/ha/year.

India is another developing country which makes heavy use of organic fertilizers. For comparative purposes, the estimated nutrient supply from compost (rural plus urban) and chemical fertilizers is reported in Table 45. The estimated nutrient supply from compost in India has increased from approximately 3.0 million mt in 1969/70 to 4.8 million mt in 1979/80, indicating a 60% increase. During 1969/70, the amount of nutrients supplied by compost alone was 1.5 times that of nutrients supplied by chemical fertilizers. Since the supply of chemical fertilizer is growing faster than compost, the nutrients from compost were 91% of that supplied by chemical fertilizers during 1979/80. However, the amount supplied by compost varies in nutrient content. During 1979/80, the shares of N, P_2O_5, and K_2O in nutrients supplied by compost were 30%, 25%, and 45%, respectively. Through proper composting and storing techniques the total supply of plant nutrients from compost may be enhanced still further.

Clearly, the organic fertilizers are a major source of plant nutrients in China, India, and other developing countries. However, the storage and transportation costs of plant nutrients in organic fertilizers are much more than those from the chemical fertilizers. Furthermore, even in China the organic fertilizers are not adequate to meet their nitrogen requirements; these are being supplemented through recent additions of several large ammonia/urea plants.

In addition to supplying plant nutrients and organic matter for crop production, the organic wastes and residues are also a good source of energy. Cattle dung, in particular, is a very good source of biogas (methane). The value of cow dung as a source of nitrogen and biogas is reported in Table 46. Through the traditional approach for processing dung, 1,000 kg of fresh dung produces approximately 1.25 kg of nitrogen and 500 kg of manure. However, when processed through a biogas plant, the same 1,000 kg of fresh dung can produce 2.50 kg of nitrogen (no loss), 730 kg of manure, and 2,000 ft^3 of biogas. The energy value of biogas is approximately 500-600 Btu/ft^3. Furthermore, the biogas plant approach is also more hygienic because it reduces the number of pathogens normally found in animal wastes. Biogas plants using mainly night soil, pig manure, and crop residues as feedstocks are fairly popular in China. The Government of India is giving a major push to install biogas plants (based on cattle dung) in villages in order to supply both plant nutrients and energy for household use.

The bullocks in India are not only a major source of draft power (for tillage, irrigation, and transportation), but also a source of energy (fuel or biogas) and fertilizer. According to Sanghi and Blase (1976), on an annual basis, one bullock can supply 35.7 kg of nutrients (including 19.4 kg N, 2.7 kg P_2O_5, and 13.6 kg K_2O); 0.294 x 10^6 kcal of useful heat as fuel, or 0.438 x 10^6 kcal of useful heat as biogas. However, according to them, the plant nutrients supplied by waste residues of six cattle (assumed number of cattle per farm household) may not be adequate

Table 45. Estimated Nutrient Supply From Compost and Chemical Fertilizers in India[a,b]

Year	Nutrients From Compost				Nutrients From Fertilizer				Nutrient From Compost as % of Nutrients From Fertilizers			
	N	P_2O_5	K_2O	Total	N	P_2O_5	K_2O	Total	N	P_2O_5	K_2O	Total
	(million mt)											
1969/70	0.92	0.75	1.35	3.02	1.36	0.42	0.21	1.99	68	179	643	152
1970/71	0.96	0.79	1.42	3.17	1.49	0.46	0.23	2.18	64	172	617	145
1971/72	0.99	0.82	1.46	3.27	1.76	0.56	0.30	2.62	56	146	487	125
1972/73	0.98	0.80	1.44	3.22	1.78	0.59	0.33	2.70	55	136	436	119
1973/74	0.91	0.75	1.33	2.99	1.83	0.65	0.36	2.84	50	115	369	105
1974/75	1.12	0.92	1.65	3.69	1.77	0.47	0.34	2.57	63	196	485	144
1975/76	1.20	0.99	1.76	3.95	2.15	0.47	0.28	2.89	56	211	629	137
1976/77	1.28	1.05	1.88	4.21	2.46	0.64	0.32	3.41	52	164	588	123
1977/78	1.38	1.14	2.03	4.55	2.91	0.87	0.51	4.29	47	131	398	106
1978/79	1.42	1.17	2.09	4.68	3.42	1.11	0.59	5.12	42	105	354	91
1979/80	1.46	1.19	2.14	4.79	3.50	1.15	0.61	5.26	42	103	351	91

a. Totals may not be exact because the numbers are rounded off.
b. Derived from data reported in FAI (1980) and various previous issues.

to supply all the plant nutrient requirements for a 2-ha farm with intensive agriculture.

The Council for Agricultural Science and Technology (1975) has estimated that the annual methane production from animal wastes, on per head basis, is approximately 9,855 ft^3 for beef cattle, 6,570 ft^3 for dairy cattle, 1,314 ft^3 for swine, and 73 ft^3 for poultry. Furthermore, Makhijani and Poole (1975) have made estimates for nitrogen and energy supply from agricultural and animal wastes in six selected villages in developing countries. According to their estimates, the annual per capita potential energy supply from these wastes ranges from 3.6×10^6 Btu to 31.0×10^6 Btu as biogas; potential nitrogen availability for cultivated land ranges from 20 kg/ha to 65 kg/ha. Because of organizational, technical, and financial problems faced by most villages in developing countries, it may not be possible to achieve these potential sources of energy and nitrogen. However, the potential advantages are large enough to make all efforts to achieve them worthwhile.

The yield response to applications of organic fertilizers is definitely positive, but for several reasons the magnitudes of such responses are not really known. First, with few exceptions, a rather limited amount of systematic research has been done on determining yield response, even under experimental conditions.[31]

Table 46. Economic Value of Cow Dung as a Source of Nitrogen and Biogas[a]

Item	Measuring Unit	Economic Value Through Traditional Approach	Economic Value Through Biogas Plant Approach
Fresh cow dung[b]	kg	1,000	1,000
Organic matter loss by decomposition	kg	500	270
Final cow dung manure	kg	500	730
Nitrogen in fresh dung	%	0.25	0.25
Nitrogen in fresh dung	kg	2.50	2.50
Nitrogen loss by decomposition	kg	1.25	None
Biogas production	ft^3	None	2,000

a. Derived from Singh (1975), originally from Garg et al. (1971).
b. Moisture content in dung is approximately 74%-82% (80% on average).

31. Different aspects of organic sources as fertilizers, their role in crop production and individual country case studies are discussed in several seminars, proceedings, and reports published by FAO. The FAO and other related publications include FAO (1975); FAO (1976); FAO (1978a, 1978b); Flaig, Nagar, Sochtig, and Tietjen (1978); and Jewell (1975).

Second, the interaction effect between nutrients supplied by organic fertilizers and those supplied by chemical fertilizers makes it difficult to isolate the yield effect which can be attributed to organic fertilizers. Third, the organic fertilizers are not really standardized; their composition varies a great deal, resulting in a variable yield response.

However, there are several effects which explain the increased crop yield due to the application of organic fertilizers:

1. The nutrient effect--organic fertilizers increase supply of primary nutrients.
2. The interaction effect--organic fertilizers supply micro, secondary, and/or primary nutrients which are not generally supplied by chemical fertilizers, and thus improve nutrient interaction and balance.
3. The water effect--organic fertilizers improve water-retaining capacity, especially important for rainfed agriculture.
4. The microorganism effect--organic fertilizers increase the activity of microorganisms in the soil and thus improve the availability of plant nutrients.
5. The structure effect--organic fertilizers improve the soil texture, structure, and airflow, with improved physical, chemical, and biological growth conditions as the result.

It is these multiple yield effects, however, that make it difficult to isolate and measure the contribution of individual effects. Because these effects of organic fertilizers vary from soil to soil, from farm to farm, and from crop to crop, it is difficult to measure and generalize the contribution of organic fertilizers. Based on the results reported in FAO (1978a); for example, the yield increase per ton of compost applied in China varies from 43 kg for maize to 24 kg for wheat, 29 kg for millet, 37 kg for sorghum, 181 kg for potatoes, 451 kg for sugar beets, and 14 kg for soybeans.

Biological Fixation of Nitrogen

Biological nitrogen fixation refers to fixation of atmospheric nitrogen, which is not directly utilized by the plants, into ammonia or other usable form of nitrogen. Approximately 79% of air is

nitrogen. The biological process of converting atmospheric nitrogen into usable form is rather complex and not yet very well understood. The fundamental and applied research in this area has been rather limited. This limitation may be partly attributed to relatively inexpensive nitrogen available from chemical fertilizers, a lack of research funds, limited immediate payoffs, and a lack of organizing interdisciplinary teamwork. The energy/nitrogen crisis of 1973-75 has given a needed boost at both national and international levels to research related to biological nitrogen fixation. However, it might take several years before a technology applicable under farmers' field conditions is developed, commercially available, and transferred to cereal crops.

Two biological processes are responsible for fixing atmospheric nitrogen. These are (1) symbiotic fixation of nitrogen and (2) asymbiotic fixation of nitrogen. Symbiotic fixation of nitrogen refers to fixing of nitrogen by bacteria, known as Rhizobium, in symbiotic relationship with the host plant, mainly legumes. Blue-green algae are known to fix nitrogen in symbiotic relationship with azolla. Asymbiotic fixation of nitrogen, on the other hand, refers to fixing of nitrogen by free-living bacteria as well as blue-green algae with no direct relationship with plants. A large number of factors, some of which are known and some of which are not, determine the amount of nitrogen fixed biologically. Both of these biological sources are extremely important from the economic point of view since they may furnish a cheaper source of nitrogen at the farm level than either organic or chemical fertilizers. The potential of biological fixation for expanding nitrogen supply for crop production is important enough to justify major public investments in research on this problem.

A good summary of the state of the art and ongoing research programs with respect to biological nitrogen fixation is available in Wittwer (1976) and Beringer and Day (1981). The available literature appears to agree on four empirical observations. First, the nitrogen fixation is influenced by the growth of bacteria and/or the host plants, including their nitrogen requirements. Second, the nitrogen fixation is determined to a great extent by the degree of photosynthetic activity in the host plant or the availability of carbon dioxide. Third, there seems to exist a negative correlation between the amount of nitrogen fixed biologically and the presence of nitrogen supplied by chemical fertilizers. Fourth, there are large numbers of bacteria known to fix nitrogen, but their fixing ability varies a great deal.

The Rhizobium species, which are known to be relatively important for crop production, are summarized by Wittwer (1976), and listed in Table 47. There may be other species of bacteria which are still unknown or known to fix nitrogen in plants of relatively low economic importance. The amount of nitrogen fixed by these bacteria varies a great deal depending upon the Rhizobium strain, crop, and other chemical, physical, and biological factors.

The range of nitrogen fixed by selected legume crops is reported in Table 48. These estimates are first-order approximations, and the amounts of nitrogen fixed biologically may vary widely under differing field conditions.

Table 47. Selected Nitrogen-Fixing Rhizobial Species of Significance in Food Production

Organism	Host Plant
Rhizobium japonicum	Soybeans
Rhizobium phaseoli	Kidney beans, navy beans
Cow pea Rhizobium	Cowpeas, mung beans, chick-peas, pigeon peas, winged beans, and peanuts
Rhizobium leguminosarum	Broad beans
Rhizobium meliloti	Alfalfa
Rhizobium trifolii	Clover

Source: Wittwer (1976).

Table 48. Nitrogen Fixed by Selected Legume Crops

Crop	Range of Nitrogen Fixed (kg/ha)
Chick-peas	103
Clover	45-673
Cowpeas	73-354
Groundnut	72-124
Guar	41-220
Lentil	88-114
Lucerne	56-463
Lysine	145-208
Pigeon peas	168-208
Soybeans	55-168

Source: Nutman (1976).

As reported in Stout (1979), the process of biological nitrogen fixation involves

$$N_2 + 160 \text{ kcal} \rightarrow 2N$$
$$2N + 3H_2 \rightarrow 2NH_3 + 13 \text{ kcal},$$

in which atmospheric nitrogen (N_2 or $N \equiv N$) and hydrogen are converted into ammonia (NH_3). A net input of 147 kcal is required to fix 1-g mole of nitrogen. This energy is normally provided by the host plant in the case of symbiotic fixation, and produced by the free-living bacteria in the case of asymbiotic fixation. In the case of blue-green algae, however, energy is either provided by azolla or produced independently.

In addition to continuing basic and applied research, the planners at the national and international levels need to focus their efforts on taking advantage of what is already known about biological nitrogen fixation. The major effort should be on expanding the area under legume crops and improving legume yields. This is important for several reasons. First, legumes are an important source of protein, especially in developing countries where animal protein is expensive and energy intensive. Second, legumes are more or less self-sufficient with respect to their nitrogen requirements. Third, legumes may also add nitrogen to the soil to be taken up by the following crop in the rotation or by other crops in a cropping system. According to Heichel (1978), for example, an alfalfa crop yielding 3,000 lb of protein per acre fixes 380 lb of nitrogen biologically.

As reported in Table 49, 148 million ha was under selected legume crops in the world during 1979. Most of these legume crops are known to fix large amounts of nitrogen biologically. It is also worthwhile to note that, with the exception of soybeans and dry peas, more than 90% of the world's area under other major legume crops (including dry beans, chickpeas, lentils, and groundnut) is in the developing countries. Any research aimed at either increasing legume yields or increasing their nitrogen fixing capacity will go a long way toward ameliorating the food problem in the developing countries of the world. However, such research has received neither major attention nor funding in the past. It is about time to give this research a high priority at national and international levels. There is no doubt that lack of research on legumes and major strides in the case of rice and wheat have led to a decline in the area under legume crops. As reported in Wittwer (1976); Whitney, Koch, and Waeck (1976); and Parker and Skinner (1980), major efforts are currently underway to expand the planting of legumes in the farming systems to provide a major source of protein and nitrogen.

Another major effort needs to focus on developing and applying rhizobia technology. This can be directed toward at least three program areas. First, improve the efficiency of known Rhizobium strains in known legume crops to fix more nitrogen. Second, develop Rhizobium inoculants and carriers for nonlegume food crops, especially cereals. Third, transfer the nitrogen-fixing genes to other bacteria or crop varieties. All these programs involve long-term research and their promise of significant results is rather uncertian at this stage. There are too

Table 49. Area Under Selected Legume Crops in Developing Countries During 1979[a,b]

Crop	Developing Market Economies					Asian CPE	Developing Countries	World	Developing Countries as a % of the World
	Africa	Latin America	Near East	Far East	Total				
	('000 ha)								
Dry beans	2,076	7,030	228	9,341	18,675	4,418	23,093	25,486	91
Dry broad beans	630	362	186	-	1,178	5,400	6,578	7,006	94
Dry peas	460	177	33	695	1,365	4,600	5,964	10,500	57
Chick-peas	329	191	292	9,380	10,192	-	10,193	10,364	98
Lentils	106	104	359	1,119	1,688	-	1,689	1,848	91
Other pulses[c]	7,847	145	476	10,146	15,351	358	15,850	17,320	92
Soybeans[d]	227	9,838	116	1,497	11,678	14,776	26,455	56,737	47
Groundnut	4,984	898	1,040	8,517	15,439	2,570	18,011	18,932	95
TOTAL	16,659	18,745	2,730	40,695	75,566	32,122	107,833	148,193	73

a. The data on area harvested under forage crops known to fix N are not readily available on a regional basis.
b. Derived from FAO (1980).
c. This includes area under other pulse crops such as cowpeas, pigeon peas, vetch, lupins, etc.
d. 50.3% or 28,542,000 ha of the harvested soybean area is in the United States.

many unknowns, even to speculate on the extent of potential payoffs. However, these programs seem to be worth trying.

The blue-green algae and azolla (through blue-green algae) are known to fix nitrogen. These were partly responsible for stable paddy yields in many Asian countries (especially China and Vietnam) before the use of chemical sources of nitrogen became popular. As reported in FAO (1978a), azolla can fix large amounts of green manure and nitrogen. The results reported in Table 50 clearly indicate that azolla could be a major source of nitrogen for paddy and other crops. Azolla is reported to produce even more than 500 kg/ha of nitrogen. However, its growth is believed to be improved with applications of phosphate fertilizers.

Table 50. Yields of Nitrogen From Various Methods of Application of Azolla Pinnata in China

Application Method	Green Material (mt/ha)	Nitrogen (kg/ha)
As a Green Manure Crop:		
Plowing under only	22.5	61.2
Plowing under and hand burying once	45.0	122.4
Plowing under and hand burying twice	67.5	183.6
Plowing under and hand burying three times	90.0	244.8
As a Nitrogen Fixer:		
10 harvests in 100 days	157.5	428.4

Blue-green algae are well known for fixing nitrogen, especially in paddy fields. However, the amount of nitrogen fixed by blue-green algae depends on the nitrogen available in the floodwater for paddy. As has been reported in Roger et al. (1980) and McCune and Stangel (1981), the presence of urea or ammonia in the floodwater following fertilization (especially by broadcasting) encourages the growth of green algae which compete with rice plants for the fertilizer nitrogen but discourages the growth of nitrogen-fixing blue-green algae. On the other hand, deep placement of urea supergranules or use of SCU not only reduces this direct competition for fertilizer nitrogen but also encourages the blue-green algae to fix atmospheric nitrogen by keeping the applied nitrogen out of the flooded water. Furthermore, there is also a need for other nutrients such as P and Ca for efficient biological fixation of nitrogen. But a lot more research needs to be done before either azolla or blue-green algae can be considered

the sole source of nitrogen for intensive rice cultivation, especially with high-yielding modern crop varieties.[32]

Large-scale programs for biological nitrogen fixation involve public funding for research and private expenditures by the users. Since the investment required for research is expected to be large and long term, and the potential benefits of these investments are expected to be large but somewhat uncertain, public investment seems to be the best alternative to finance research in biological nitrogen fixation. In the absence of public funding the research may not even get properly started. On the other hand, once the technology becomes available, the costs to farmers using it may not be very high. They would basically include the cost of Rhizobium inoculants, which is expected to be small, and the labor cost, which may not be a problem in most developing countries since labor is abundant and cheap. At this stage it is not yet known whether there will be a trade-off between crop yield and nitrogen fixation, and if so what its magnitude will be. However, the available empirical evidence indicates that once all the factors are taken into account the rhizobial technology can be a major and even cheaper source of nitrogen, which can go a long way to solve the world's food problem.

32. According to Venkataraman (1981), who heads All India Coordinated Project on Algae, the use of nitrogen-fixing, blue-green algae, in the absence of chemical nitrogen fertilizer, could produce 20-30 kg of biologically fixed nitrogen per hectare of rice crop per season, resulting in a 10%-15% increase in yield.

CHAPTER 12

ENERGY SAVINGS THROUGH EFFICIENT FERTILIZER MARKETING

One of the crucial constraints to expanded fertilizer use is its lack of availability at the farm level, even when there may be plenty of it at the national level. Sometimes fertilizer is available to the farmer but at the wrong time, or it may be too expensive to make its use profitable. The availability and price of energy play an important role not only in facilitating fertilizer distribution, especially through transportation, but also in determining the distribution costs and, hence, fertilizer prices at the retail level. The purpose of this chapter is to examine the prospects of reducing energy use and thereby distribution costs through efficient fertilizer marketing.

Magnitude and Components of Fertilizer Marketing Costs

The fertilizer price at the retail level is determined by its production and marketing costs. As has been reported in Mudahar (1978), the fertilizer marketing costs can sometimes be as high as 50% of its retail price. These marketing costs are generally the sum of several costs, including wholesalers' commission, retailers' commission, transportation costs, storage costs, handling costs, insurance, interest on stocks and facilities, and other overhead costs. Transportation costs, both international and domestic, appear to be the most important of the cost components. Transportation costs, in turn, are determined by transportation mode, energy use, and energy prices.

The average energy use for packaging, transportation, and application is 8.6 GJ/mt N, 9.8 GJ/mt P_2O_5, and 7.3 GJ/mt K_2O. Out of this, packaging accounts for 30%, 27%, and 24%, whereas transportation accounts for 52%, 58%, and 63% for N, P_2O_5, and K_2O, respectively. In the case of P_2O_5 and K_2O, since their manufacturing is relatively less energy intensive, packaging and transportation account for approximately 46% of the total energy needs on a nutrient basis. Increases in energy prices during 1972/74 and more recently have substantially increased the fertilizer distribution costs, and in particular transportation costs. According to Allen (1980), the energy component alone, in terms of fuel costs in importing and marketing imported fertilizers, has increased eightfold from $2.00/mt in 1972 to $16.00/mt in 1980.

Most of the developing countries depend on imports to meet all or part of their fertilizer and/or raw material requirements. The major difference between the c.i.f. and f.o.b. price is the freight cost for importing fertilizers. The freight rates for various ports (origin to destination ports) are not readily available. Since India

imports all kinds of fertilizers, the freight rates for fertilizer shipment from several ports may reflect a general trend and also the magnitude of an increase in freight rates in general.

The average freight rates for fertilizer shipments for major fertilizers are reported in Table 51. During 1980 the average freight costs from North America to India were approximately $60/mt. The share of freight costs in c.i.f. fertilizer prices in India during 1980 was approximately 19% for urea, 21% for DAP, and 36% for KCl. These freight costs not only are a large share of fertilizer prices, but the major increase in these rates took place during 1979/80, after remaining stable for several years. There may be other factors which might have led to this significant increase in freight rates, but an increase in energy prices during 1979/80 was certainly the leading determinant. The same is true for domestic transportation costs for fertilizer.

Table 51. Average Freight Rates for Fertilizer Shipments in the International Market

Fertilizer Product	Shipment Route From	Shipment Route To	Freight Rate, $/mt[a] 1976	1978	1980	% Increase 1976-78	1978-80
Urea	Netherlands	W.C. India	18.18	24.94	49.19	37	97
DAP	U.S. Gulf	W.C. India	27.75	30.00	60.50	8	102
Phosphate rock	Aqaba	W.C. India	8.75	8.81	20.43	1	132
KCl	Vancouver	W.C. India	23.63	21.25	59.80	-10	181
Sulfur	Vancouver	E.C. India	24.75	22.17	59.00	-10	166

a. Average for the data reported by British Sulphur Corporation (1980c).

Approaches to Reduction of Energy and Marketing Costs

The reduction of fertilizer marketing costs is essential to keeping retail fertilizer prices low, and the conditions in many areas offer a large potential for such reductions. The marketing costs can be reduced through (1) improvements in the operational efficiency of the fertilizer marketing system, (2) improvements in energy use efficiency in the fertilizer distribution system, and (3) improvements in fertilizer distribution technology or changes in patterns of distribution. Some of the selected areas which offer possibilities for significant reductions in energy use and marketing costs are discussed below.

One of the most important strategies for reducing marketing costs for a given amount of nutrient is to use fertilizers with high nutrient content. On a per unit plant nutrient basis, such an

approach will reduce the costs for packaging, handling, transportation, storage, and other related overhead items. For example, assuming a linear relationship, the distribution of 1.0 million mt of N in the form of ammonium sulfate may cost twice as much as that in the form of urea.[33] It is these significant cost economies in distribution which led the fertilizer industry and farmers in developed countries to prefer high analysis over low analysis fertilizers.

It is also for these reasons that the production, consumption, and trade of nutrients in the form of low analysis fertilizers has declined. Some developing countries, however, may be taking longer to switch away from the low analysis fertilizers partly because of previous grade preferences and high adjustment costs. Also, the attainment of "high analysis" usually involves leaving out secondary elements, which is not always in the best interest of the farmers.

The energy and marketing costs can also be reduced by importing and distributing part or all of the fertilizer in bulk rather than in bags. Such a strategy reduces handling costs, packaging costs, transportation costs, and other related costs. In many developed countries a large proportion of finished fertilizer is distributed in bulk. As reported in Sikder (1980), for example, the share of solid fertilizers distributed in bulk is approximately 50% in the United States, 50% in the Federal Republic of Germany, 45% in Denmark, 25% in Sweden, 25%-30% in France, and 30%-40% in the German Democratic Republic.[34]

On the other hand, in most developing countries a wholesale switch to bulk distribution is just not possible. For at least two reasons, most of the fertilizer at the retail level must be available in sealed small bags: (1) the amount purchased by an average farmer is small because the average farm is small and the average fertilizer use is low, and (2) the possibility of adulteration is higher in bulk fertilizer than in the fertilizer sold in sealed bags. This, of course, does not preclude importing fertilizer in bulk and distributing it in bulk up to at least the major transhipment points. However, this will require additional capital expenditures for specialized transportation equipment and bagging facilities. Furthermore, in many humid and semihumid tropical countries,

33. However, the manufacture of urea requires about 20 GJ/mt of N more energy than ammonium sulfate. So from an energy viewpoint alone urea is not the best choice.

34. According to the U.S. Department of Agriculture (USDA) (1980b), the share of total fertilizer distributed in the United States during 1979/80 was 51% as dry bulk, 13% as dry bagged, and 36% as fluid. This implies that approximately 87% of total and 80% of dry fertilizer was distributed as bulk.

there is a relatively high possibility of fertilizers, especially those which are hygroscopic, deteriorating through bulk distribution.

Regardless of the product grade, however, the marketing costs can also be reduced by limiting the number of times the fertilizer is handled, i.e., loaded and unloaded. This reduction can result in lower labor costs, less time in transit, and reduced fertilizer losses. As reported in Mudahar (1979b), various estimates of fertilizer loss in transit range from 5% to 30% in developing countries. Furthermore, through better scheduling of imports and inland distribution, the fertilizer storage costs can also be lowered. However, it is important to keep in mind that during the off-season the fertilizer needs to be stored near the consuming areas. Such a strategy could facilitate fast delivery and timely availability of fertilizer to farmers. Finally, the energy and marketing costs can be significantly reduced through efficient and appropriate fertilizer transportation systems.

Energy and Cost Implications of Fertilizer Transportation

Fertilizer transportation accounts for a major share of the costs and energy use in distribution. Since most developing countries import all or part of their domestic requirements, it would be useful to look at the economic implications of both international fertilizer shipping and inland fertilizer transportation.

Most developing countries have a large potential for reducing the c.i.f. price, port costs, and thus the fertilizer price paid by farmers. As shown in Figure 17, the fuel costs per metric ton of

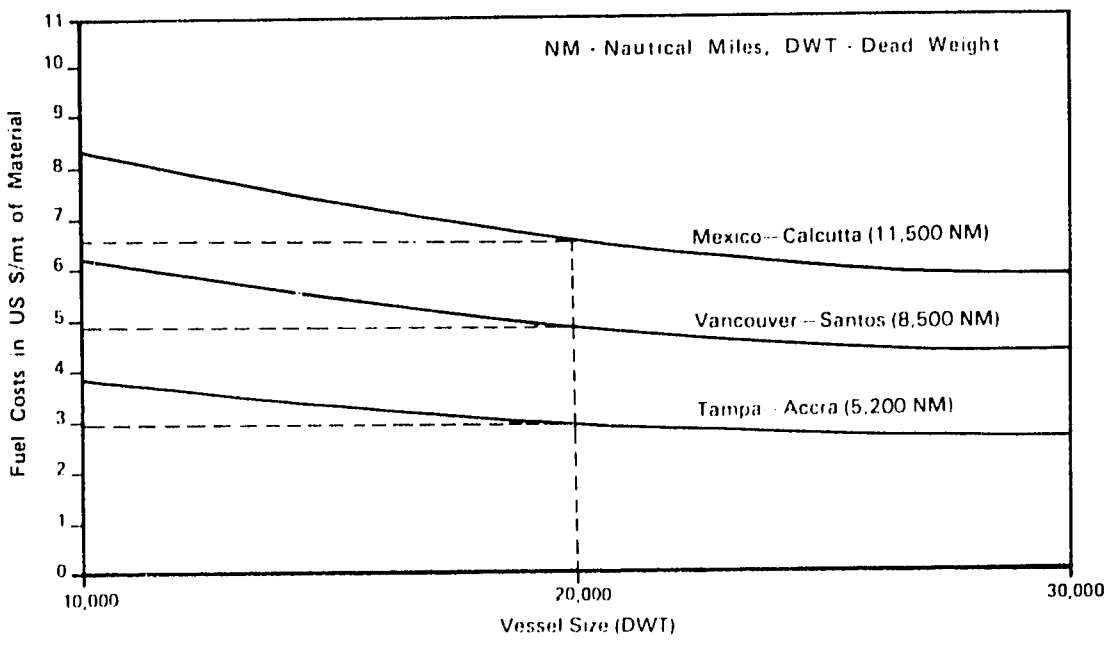

Figure 17. Fuel Costs by Different Vessel Sizes for Fertilizer Shipment.

fertilizer material decline as the vessel size increases. The developing countries, thus, can save through lower fuel costs and economies of scale by importing fertilizer in large shiploads. The total costs decline more than the fuel costs. However, many countries, especially in Africa, cannot realize these economies because of (1) small fertilizer requirements, and (2) port size limitations. In many cases, they have to resort to very small vessels, even smaller than 10,000 dwt. In some cases it may be possible to remove these constraints through cooperation in importing the needs of more than one country. For example, several landlocked and coastal countries in Africa might benefit from such an arrangement. Furthermore, fuel costs can also be reduced by providing preferential berthing facilities to ships carrying fertilizer, especially in many congested ports around the world. Every additional day in waiting results in substantial costs in the form of demurrage, which quite often can be eliminated.

The second component of transportation costs deals with in-country distribution of fertilizer. The landlocked countries, of course, have to pay additional international transportation costs before the fertilizer reaches its destination. The energy use and energy costs per unit of fertilizer transported would depend on the mode of transportation. The energy use estimates for different transportation modes are reported in Table 52. Clearly, moving fertilizer by truck is most energy intensive, and hence most expensive. Depending on the truck size, load factor, and type of fuel, transportation by truck may consume four to six times as much energy on a per ton-mile basis as railway transportation would. Yet, as reported in Table 53, with the exception of India, Bangladesh, Republic of Korea, and Burma, more than half of the fertilizer in Asia is moved by trucks. As long as the barge and/or

Table 52. Energy Intensity Estimates for Different Transportation Modes

Transportation Mode	Btu/mt-Mile[a]				
	A	B	C[b]	D	E
Ocean vessel	c	c	c	c	275
River barge	750	600	550	510	300
Pipeline	495	495	c	c	450
Rail	740	740	825	760	770
Truck	4,185	2,650	2,650	5,270	3,085
Air	46,285	c	69,425	42,090	c

a. A = Council of Agriculture Science and Technology (1973); B = Blouin and Davis (1975); C = Fallen-Baily and Byer (1979); D = Pimentel (1980); E = From Table 29.
b. The assumed load factors are 85 for barge, 94 for diesel rail, 59 for diesel truck, and 65 for air.
c. Not available.

Table 53. Percentage Share of Different Transportation Modes in the Movement of Fertilizer in Selected Asian Countries

Country	Year	Transportation Mode Rail	Truck	Water	Remark
Afghanistan	1976/77	-	90	-	Rest by porters, mules, and carts
Bangladesh	1977/78	42	21	31	-
Burma	1978/79	20	30	50	-
India[a]	1977/78	80	20	-	Primary transport
India[a]	1977/78	10	90	-	Secondary transport
Malaysia	1976	10	90	-	-
Nepal	1977/78	11	48	-	Rest by ropeway, lorries, mules, etc.
Pakistan	1976	18	52	-	Rest by bus, tractor, and carts
South Korea	1976	92	-	-	Rest by truck and water
Sri Lanka	1976	30	70	-	-
Thailand	1978	8	90	2	-

a. Refers to domestic production. For imported fertilizer, the share of rail transport is slightly higher than for domestically produced materials.

Source: ESCAP (1980).

railway facilities are available, every effort should be made to use them in fertilizer distribution. This can result in substantially lower transportation costs.

It has been argued, however, that truck transport is more efficient and reliable. Clearly, there is a possible trade-off. However, instead of resorting to less energy-efficient modes of transportation, the energy-deficit developing countries would be better off in the long run by debottlenecking the fertilizer transportation system and investing in barges and railroads, as major inland transport modes for fertilizer. As has been reported by Sikder (1980), on the basis of Indian experience, 1 hp can move 150 kg on road by truck, 500 kg on rail, and 4,000 kg on water. The reorganization of transportation patterns and transportation modes, supplemented by product exchange where possible, can result in lower energy use and lower transportation costs.

All forms of transport have some economies of scale. For example, large trucks, if fully loaded, are much more fuel efficient than small ones. However, the truck size is limited by the load-bearing capacity of the road system. Perhaps more important is providing the maximum amount of backhaul, which applies to all forms of transport except pipelines. However, one must always keep in mind that fertilizer must reach the farmer at the right time for application. Otherwise, any savings in terms of transportation costs can be cancelled by a loss in potential crop output.

CHAPTER 13

ENERGY SAVINGS THROUGH EFFICIENT FERTILIZER USE

An improvement in fertilizer use efficiency promises the greatest savings in energy use. Increased efficiency in fertilizer use will directly increase the efficiency of energy consumed in fertilizer manufacture and distribution. Since the demand for plant nutrients is rapidly growing, the energy saved by improving fertilizer use efficiency cannot be interpreted as savings per se. Rather, the saved fertilizer can be utilized to produce more food, feed, and fiber. In specific countries, such as South Korea, where nitrogen use is already very high, less fertilizer may be needed if the use efficiency is improved.

Alternatively, the country which depends basically on fertilizer imports may be able to reduce imports and, hence, requirements for foreign exchange. The economic implications, as discussed in Hignett (1980a) and Mudahar (1979a), could be substantial enough to justify research and policy efforts directed at improving fertilizer use efficiency. The underlying objective of these actions should be to maximize crop yields at a given level of fertilizer energy, or to minimize fertilizer energy needs in order to achieve a given level of crop yield, with appropriate considerations for the economics of fertilizer use. Since nitrogen fertilizer accounts for the major part of the energy use in the fertilizer sector, it is evident that the greatest opportunity for increasing crop yields at minimum energy cost is to use nitrogen fertilizer more efficiently.

Fertilizer Use Efficiency Levels

The efficiency of applied fertilizer is extremely low both in terms of nutrient recovery by the plants and in terms of productivity of nutrients recovered. The low efficiency problem is especially serious for the tropical and subtropical developing countries of the world. It has been well documented that no more than 25%-40% of applied nitrogen is recovered by plants, especially by rice under Asian conditions.[35] The rest is lost to the environment and results in air and water pollution. On the other hand, approximately 15%-20% of applied phosphate fertilizer is taken up by the crop to which it is applied.[36] However, unlike nitrogen, the

35. For example, see Craswell and Vlek (1979); Craswell and De Datta (1980); De Datta, Stangel, and Craswell (1980); Hignett (1980a); McCune (1981); Parish (1979); Parish, Hammond, and Craswell (1980); Savant, De Datta, and Craswell (1980); Stangel (1979); Stangel and Hignett (1979); and Vlek and Craswell (1979).
36. Additional details are available in Parish, Hammond, and Craswell (1980) and in Stangel and Hignett (1979).

rest of phosphate gets fixed in the soil and continues to become available to the succeeding crops in the next 10-20 years. The behavior of potash fertilizers appear to be somewhat between that of nitrogen and that of phosphate after their applications.

The estimates with respect to nutrient loss are generally based on experiments. These losses may be even higher under actual farmers' field conditions. There are a large number of biological, chemical, and physical factors that determine the mechanism of nutrient loss and the magnitude of loss through each mechanism. Furthermore, the mechanisms and magnitude of nutrient loss also vary across crops, soils, nutrient sources, management practices, and agroclimatic conditions. Any fertilizer technology and/or management practice which reduces nutrient loss under field conditions can go a long way to reduce fertilizer costs to the farmers and expand food production at the national level.

Ideally, the nutrient losses can be substantially reduced or even eliminated by perfectly matching nutrient availability with nutrient requirements of the crop throughout different stages of its growth. This goal may be worth striving for, but under field conditions it is difficult to achieve. This is mainly because both nutrient availability and requirements are difficult to ascertain with any degree of accuracy because of wide variations in agroclimatic conditions. While an exact match is seldom possible, it might be better to err on the side of supplying a higher share of the less energy-intensive nutrients.

There are several known mechanisms of nitrogen loss. These include volatilization, nitrification-denitrification, leaching, and runoff. Volatilization appears to be the major source of nitrogen loss for rice under the rainfed conditions prevalent in Asia. Nitrogen losses do occur through other mechanisms but the magnitude of losses through them is not very well known.

Urea is not only the major source of nitrogen in developing countries but it may continue to remain so in the next two decades. Although urea may be the cheapest source of nitrogen, it is also known to be least efficient. Consequently, and rightly so, most research efforts are being directed at improving the use efficiency of urea nitrogen.

It is often believed that average fertilizer productivity is higher in developing than in developed countries. The underlying logic is that fertilizer use levels in developing countries are very low and this results in much higher response. This may be true ordinarily but generalized statements cannot be made for all crops, crop technologies, and countries. One must remember that fertilizer productivity is determined by a large number of factors, including nutrient balance, fertilizer responsive crop varieties, irrigation and water control, plant protection techniques, intensity of weed problem, plant population, and crop management. The farmers, small or large, in developing countries do not have as easy

access to these complementary inputs and practices as do the farmers in developed countries. On the average, farmers in developing countries operate at low levels of crop production technology and management. Consequently, fertilizer productivity in these countries can be substantially improved by increasing the use of complementary farm inputs, improving farm management practices, and removing other soil fertility constraints. Furthermore, there is substantial scope for improved fertilizer productivity through improvements in fertilizer technology and proper management.

Efficiency Improvement Through Fertilizer Management

Regardless of the source of fertilizer nutrient, fertilizer use efficiency can be significantly improved through better fertilizer management. Four major aspects of better fertilizer management are (1) right dose of fertilizer, (2) proper balance among nutrients, (3) right time of application, and (4) right method of application. Each of these aspects is important in its own way. The right dose of fertilizer, for example, applied at a wrong time could be as wasteful as the wrong dose itself.

These basic management principles for improving fertilizer efficiency are not new. However, these principles are seldom applied under farmers' field conditions, especially in developing countries. This is due to (1) lack of knowledge on the part of farmers, (2) lack of knowledge or inability to communicate on the part of extension agents, (3) lack of appropriate research to generate relevant information about fertilizer management under varied agroclimatic conditions, and (4) lack of appropriate government fertilizer policies to assure adequate supply of right fertilizers at the right time, and to assure that farmers have access to the relevant information created through adequate investments in fertilizer research and extension.

Rice response to nitrogen derived from alternative sources, in differing forms of fertilizer, and the method of application is reported in Table 54. In the case of both ammonium sulfate and urea, the time and method of application are extremely important. The best split performs better than delayed-split in both cases. For ammonium sulfate, use of the best split results in 38% higher yield increase than use of the delayed split, whereas in case of urea the relative advantage is only 23%. The increase in yield is due to (1) better timing of fertilizer application and (2) proper incorporation of the first dose of fertilizer into the soil. The empirical evidence from other studies also seems to confirm the general thrust of these findings. There is need for more such studies, especially under farmers' field conditions for rice and other crops, and different agroclimatic conditions. However, split application of urea and ammonium sulfate at proper time intervals

and the deep placement of urea supergranules seem to reduce nitrogen losses and increase crop yields at a given level of fertilizer use.

A proper balance of plant nutrients is equally important in achieving higher yields (law of interaction). An overemphasis on one nutrient can result in a decline in productivity for that nutrient over time, especially when one or more of the other nutrients (primary, secondary, or micro) are missing or in short supply. Under ceteris paribus conditions, crop response to a given nutrient tends to decline with time when there is a lack of the minimum requirements (law of minimum) of other plant nutrients. More specifically, yields decline because of (1) the absence of the individual nutrient and (2) the lack of positive interaction between the missing nutrient and the applied nutrients.

Table 54. Paddy Response to Nitrogen From Alternative Sources, Differing Forms, and Various Methods of Application in the Philippines[a,b]

Nitrogen Source	Nitrogen Form	Method of Application[c]	Time of Application[d] (87 kg N/ha)	Grain Yield Total	Grain Yield Increment Over Control	Kilogram of Paddy Per Kilogram of Applied N
				- - - -(mt/ha) - - -		
Control	-	-	-	4.1	-	-
AS	Crystals	Delayed split, BU	2/3 21 DT + 1/3 PI	5.4	1.3	14.9
AS	Crystals	Best split, BI	2/3 Basal + 1/3 PI	5.9	1.8	20.7
Urea	Prilled	Delayed split, BU	2/3 21 DT + 1/3 PI	5.4	1.3	14.9
Urea	Prilled	Best split, BI	2/3 Basal + 1/3 PI	5.7	1.6	18.4
SCU	Forestry grade	Broadcast	Basal	5.8	1.7	19.5
Urea	Supergranule	Point placement	Basal	6.2	2.1	24.1

a. Based on field experiments at IRRI for IR36 rice variety during 1979 dry season at 87 kg/ha of nitrogen.
b. Derived from Craswell and De Datta (1980).
c. BI refers to broadcasted and incorporated, and BU refers to broadcasted and unincorporated.
d. DT refers to days after transplanting and PI refers to 5-7 days before panicle initiation.

Many developing countries, especially in areas experiencing the "Green Revolution," are already showing deficiency symptoms for zinc and sulfur. For example, as reported in Table 55, the average yield increase over control for rice is 62% due to N application alone, and 105% due to application of N, P, and K. As reported in Table 56, percentage uptake of applied nutrients increases in the presence of other nutrients. For example, the uptake of nitrogen increases from 48% when it is applied individually, to 65% when applied in combination with P, and to 73% when applied in combination with P and K. The same is true for phosphorus and potash applications. Proper nutrient balance thus improves recovery of the applied nutrients by plants and hence increases crop yields.

Table 55. Effects of NPK Fertilization on Grain Yield of Flooded Rice in the Philippines[a,b]

Treatment	Nutrients Applied N	P_2O_5	K_2O	Grain Yield[c] Maligaya	Bicol	Visayas
	- - - - -(kg/ha) - - - -			- - - - - - - - (mt/ha)- - - - - - -		
Control	0	0	0	3.4	3.5	2.6
N	140	0	0	5.6	4.6	5.2
NP	140	60	0	6.2	5.2	5.9
NK	140	0	60	5.6	5.7	5.0
NPK	140	60	60	6.6	6.9	6.0

a. Dry season data only.
b. Derived from De Datta and Gomez (1975).
c. Average of 5 crop years, each with three varieties replicated three times.

Table 56. Efficiency of Plant Nutrient Utilization Applied Annually on an Oat-Ryegrass Mixture, Louisiana, United States[a]

Treatment	Nutrients Applied N	P_2O_5	K_2O	% Utilization N	P_2O_5	K_2O
	- - - - -(lb/acre) - - - - -					
N	200	0	0	48	-	-
P	0	200	0	-	4	-
K	0	0	200	-	-	10
NP	200	200	0	65	15	-
NK	200	0	200	63	-	72
PK	0	200	200	-	4	21
NPK	200	200	200	73	11	63

a. Derived from Fisher (1980). The results are 5-year averages.

Nitrogen is one of 13 essential elements obtained from the soil; if any one of the other nutrients is deficient, the application of nitrogen alone will be less effective in increasing the yield than it would have been if all nutrient requirements had been met.[37] In case of severe deficiency of some other element such as phosphorus, sulfur, or zinc, there may be no response to nitrogen. So it is evident that the first concern should be to ensure that the supply of the less energy-intensive elements is adequate.

37. The 13 essential elements include nitrogen (N), phosphorus (P), potash (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn).

Most developing countries use a much higher percentage of nitrogen than do more mature fertilizer areas. There is little evidence that this emphasis on nitrogen is more profitable than a more balanced fertilizer program would be, particularly in the long run. Instead, many instances could be cited to show that nitrogen is frequently used inefficiently because of a deficiency of other elements. Certainly, from an energy conservation viewpoint, we need to search diligently for other nutrient deficiencies and correct them. This course of action is attractive because any miscalculation that results in an oversupply of phosphorus, for example, does not result in a loss; the excess remains in the soil and benefits future crops. On the other hand, when more nitrogen is applied than the crop can utilize, most of the excess is lost. So it is better in the long run to err on the high side of supply of those nutrients that will remain in the soil and increase its fertility rather than to supply too little.

There are several reasons for the heavy usage of nitrogen in developing countries.

First, farmers are impressed by the immediate visual response to nitrogen as indicated by the darker green color of leaves and the rapid vegetative growth. In contrast, the results of fertilization with other nutrients may not be immediately obvious, and the farmer may not associate the better yield at harvest with the phosphate and/or potash he supplied several months earlier. In fact, a large part of the benefit of most nutrients other than nitrogen may be in benefits to succeeding crops. The concept of building up the fertility of the soil is often lacking in developing countries.

Second, agricultural experiment stations often relate the economic response to a single crop rather than to a series of crops and make recommendations accordingly. When high-yielding varieties of cereal crops were first introduced, the main economic response was to nitrogen because there was often a sufficient supply of other elements in the soil. However, after a few years of more intensive cropping with nitrogen fertilizers and high-yielding cereal varieties, the soil supply of one or more other elements often became so exhausted that the response to nitrogen was no longer satisfactory. The farmer's reaction might be to use still more nitrogen. The visual response to nitrogen in vegetative growth was still evident, but the grain yield response was small. Agricultural experiment stations in most developing countries realized, sometimes belatedly, the need for more balanced fertilizer and amended their advice to farmers accordingly. Sometimes, however, it has been difficult to convince farmers of the need for balanced fertilization.

Third, national programs are often geared to supply more nitrogen than other nutrients. In some cases it has been difficult to produce or procure an adequate supply of the proper kind of fertilizers when the national program initially was geared to nitrogen supply.

The main emphasis in most agricultural research programs has been on the three primary nutrients N, P, and K. As a result deficiencies in other elements sometimes have not been detected or have not received proper attention. For example, widespread deficiencies in sulfur in developing countries led McCune (1981) to suggest that this element should be considered as equal in importance to the so-called primary nutrients. Few countries have taken effective steps to supply sulfur-containing fertilizer or even to define the extent of their need.

An increase in zinc deficiency is another example. Researchers in the Philippines have recently found that zinc was deficient in most of the soils used for irrigated rice grown in that country (Bautista et al., 1980). As an average of trials on 186 farms, the addition of 1 kg of zinc per hectare (5 kg of zinc sulfate) increased rice yields by 660 kg/ha. On 51 farms, doubling the amount of zinc (to 2 kg/ha) increased yields by 1,320 kg/ha over the no zinc plot. The delivered cost of 1 kg of zinc (5 kg of zinc sulfate) was $4, and the value of the increased rice harvest was $114 a value: cost ratio of 28. Zinc deficiencies are known to exist in many other countries (Brazil, India, and Thailand, for example), but few countries have taken effective action to identify and correct deficiencies of either this element or other micronutrient elements.

Probably the best system for supplying an effective mix of nutrients to the farmer is to market a range of compound fertilizer for basal application (at or before planting). For some crops, however, an additional application of a straight nitrogen fertilizer may be needed during the growing season. The compound fertilizers should contain proper proportions of N, P, and K to suit the needs of the various crops and soils, and should also contain other elements such as sulfur, magnesium, zinc, and boron when those elements are known to be needed. This is the system that is used in most developed countries.

For example, Austria, Japan, and the United Kingdom have the highest national average yields of maize, rice, and wheat, respectively (Von Peter, 1980). The pattern of fertilizer use in these countries is shown in Table 57. Compound fertilizers supply 35%-78% of the N, 73%-88% of the P_2O_5, and 82%-98% of the K_2O. They also supply other nutrient elements. Norway is an example of very high proportion of compound fertilizers; 94% of the N, P, and K used is in the form of compound fertilizers. Most of the compounds also contain the secondary elements, Ca, Mg, and S. Naturally, equally good results could be obtained with straight fertilizers, but it is not very likely that equally good yields would result if each farmer were left to decide for himself which nutrients he should use and how much of each he should apply.

Table 57. Share of Nutrients Supplied by Compound Fertilizers During 1978/79

Country	N	P_2O_5	K_2O	NPK[a]
	- - - - - - - - (%) - - - - - - - -			
Austria	35	73	82	62
Japan	78	76	83	79
United Kingdom	45	88	98	65
South Korea	42	85	74	60
India	16	80	44	23
Brazil	28	39	2	25

a. Weighted average.

Source: ISMA (1981).

Agricultural research should be intensified in an effort to define nutrient needs and identify the least energy-intensive combination of nutrients that will increase yields with due regard to economics. More emphasis should be placed on building up the fertility of the soil to reach and maintain high yields rather than to concentrate on heavy nitrogen fertilizations which tend to impoverish the soil. As a means of inducing farmers to adopt a more energy-efficient fertilizer program, more compound fertilizers and less straight nitrogen should be marketed. In countries where fertilizer prices are subsidized at the farm level, the subsidy can be used to promote more balanced fertilization.

In view of the difficulty of educating hundreds of millions of farmers in the efficient use of urea, the current tendency toward choosing urea as the dominant source of nitrogen should be reexamined. While urea is usually the lowest cost form of nitrogen delivered to the farmer, it is not necessarily the lowest cost form of nitrogen delivered to the crop. Ammonium sulfate or ammonium nitrate could well be less expensive per ton of increased grain yield. Maximum use should be made of nitrogen in the form of ammonium phosphate-based compound fertilizers. For example, a compound fertilizer such as 13-13-13 (ammonium phosphate-sulfate) might be useful for rice, while higher grade ammonium phosphate-nitrate grades (15-15-15) should be considered for other purposes. Provision should be made for supplying sulfur in either compound or straight fertilizer unless it is known that sulfur will not be needed.

As has been discussed by Hopper (1962) and Mudahar (1978), however, any dosage or nutrient balance which results in the highest crop yields may not maximize profit. In many developing countries, farmers have a tendency to use less than the recommended quantity of fertilizer, mainly because the recommendations may not be economic within the farmers' decision environment. As a result, it is extremely important to incorporate both agronomic and economic considerations surrounding the farmer's decision environment in making fertilizer recommendations.

Efficiency Improvement Through Fertilizer Technology

The fertilizer use efficiency can also be increased by modifying fertilizer materials in order to attain the proper timing and placement, and thus to partially compensate for fertilizer mismanagement. These twin objectives can be achieved by developing controlled release fertilizers which can easily be deep placed. The sulfur-coated urea (SCU) developed by TVA is controlled release and nonhygroscopic. As reported earlier in Table 54, forestry grade SCU results in higher rice yields than the best split ordinary prilled urea. Furthermore, labor costs for application can also be reduced However, the use of sulfur required for coating urea presents a problem for many developing countries because they generally lack adequate supplies of sulfur and/or because the use of sulfur increases the price of SCU over prilled urea by at least 50%/unit of N.

The placement of urea beneath the soil surface seems to reduce fertilizer losses from the applied nitrogen, and it does not interfere with biological nitrogen fixation by blue-green algae. Several approaches have been or are being attempted to accomplish deep placement. These approaches include development of mudballs, urea supergranules, and/or urea briquettes, along with the development of mechanical or manual applicators. As reported in Table 54, the point placement of urea supergranules results in the highest rice yield in experimental fields. The rice response to nitrogen use is reported to increase from 14.9 kg under farmer's practice (prilled urea application as delayed split, broadcasted, and unincorporated) to 24.1 kg under point placement of urea supergranules, which amounts to almost 62% increase.

Based on the empirical evidence available, the nitrogen efficiency for rice can be improved through (1) split application, (2) deep placement of fertilizer nitrogen in the active rooting zone of the plant and beneath the oxidized layers, (3) use of various coatings and inhibitors to control the release of nitrogen in the soil and to match more closely the nitrogen needs of the plant, and (4) use of nitrogen compounds which have low water solubility. The preliminary experimental results indicate that the sulfur-coated supergranules (SCSG) may be the most efficient nitrogen material because they combine the concept of deep placement with controlled release.

One might argue that we need not give high priority to improving use efficiency for phosphate fertilizers because (1) they use much less energy than nitrogen fertilizers do and (2) phosphate, unlike nitrogen, is not lost but rather gets fixed in the soil. Even though applied phosphate generally remains in the soil system, there is an urgent need to improve phosphate use efficiency. This is for at least two reasons. First, the current high analysis, highly water-soluble and citrate-soluble phosphates may be effective in tropical soils; however, crop utilization of phosphorus within any one season is extremely inefficient because

Table 58. Estimated Potential Savings in Energy and Nitrogen Through Improved Nitrogen Use Efficiency Duri g 1978/79

Region	Nitrogen Consumed	Nitrogen Uptake[a]	10% Efficiency Improvement[b]		25% Efficiency Improvement[b]		50% Efficiency Improvement[b]		100% Efficiency Improvement[b]	
			Nitrogen Savings	Energy Savings[c]	Nitrogen Savings	Energy Savings[c]	Nitrogen Savings	Energy Savings[c]	Nitrogen Savings	Energy Savings[c]
	- - - (10^6 mt) - - -		(10^5 mt)	(10^5 bbl)	(10^5 mt)	(10^5 bbl)	(10^5 mt)	(10^5 bbl)	(10^5 mt)	(10^5 bbl)
Developed market economies	21.3	8.52	0.85	10.85	2.13	27.20	4.26	54.40	8.52	108.80
North America	10.5	4.20	0.42	5.36	1.05	13.41	2.10	26.82	4.20	53.63
Western Europe	9.4	3.76	0.38	4.85	0.94	12.00	1.88	24.01	3.76	48.02
Oceania	0.2	0.08	0.01	0.13	0.02	0.26	0.04	0.51	0.08	1.02
Other DME	1.4	0.56	0.06	0.77	0.14	1.79	0.28	3.58	0.56	7.15
Developing market economies	10.2	4.08	0.41	5.24	1.02	13.03	2.04	26.05	4.08	52.10
Africa	0.5	0.20	0.02	0.26	0.05	0.64	0.10	1.28	0.20	2.55
Latin America	2.5	1.00	0.10	1.28	0.25	3.19	0.50	6.39	1.00	12.77
Near East	1.7	0.68	0.07	0.89	0.17	2.17	0.34	4.34	0.68	8.68
Far East	5.5	2.20	0.22	2.81	0.55	7.02	1.10	14.05	2.20	28.09
Centrally planned economies	20.0	8.00	0.80	10.22	2.00	25.54	4.00	51.08	8.00	102.16
Asian CPE	7.8	3.12	0.31	3.96	0.78	9.96	1.56	19.92	3.12	39.84
Eastern Europe & U.S.S.R.	12.2	4.88	0.49	6.26	1.22	15.58	2.44	31.16	4.88	62.32
Developed countries	33.5	13.40	1.34	17.11	3.35	42.78	6.70	85.56	13.40	171.12
Developing countries	17.9	7.16	0.72	9.19	1.79	22.86	3.58	45.72	7.16	91.43
World total	51.4	20.56	2.06	26.31	5.14	65.64	10.28	131.28	20.56	262.55
Value equivalent[d] (billion $)	28.27	11.31	1.13	0.79	2.83	1.97	5.65	3.94	11.31	7.88
Grain output (10^6 mt) from saved nitrogen at:										
1 kg N = 10 kg grain			21		51		103		206	
1 kg N = 15 kg grain			31		77		154		308	

a. Assuming that the average nitrogen uptake by plant is about 40%. This can be a weighted average over agroclimatic regions, crops, and N sources.
b. Refers to improvements in nitrogen use efficiency over 40%, with no reductions in crop yields.
c. In the form of crude oil by assuming that, on the average, 1 mt of N is equivalent to 12.77 bbl of crude oil.
d. The prices assumed are $550/mt of N and $30/bbl of crude oil.

of the rapid fixation which occurs in many tropical soils. According to Fisher (1980) (see Table 56), phosphorus efficiency could be as high as 60%, whereas in general, it is less than 15%. Second, farmers with extremely limited financial resources do not want to buy a fertilizer if no more than 20% of its nutrient value can be recovered in the first year. Because of various land ownership, tenancy, and financial problems, these farmers cannot afford to spend more money on phosphate fertilizers than they need immediately and consider the residual phosphate as "money in the bank."

The existing technology used to mine and beneficiate phosphate ores is extremely wasteful. It is common to discard up to 50% of the total phosphorus in the ore during beneficiation and processing. Unless new technology is developed to use many of the phosphate rock deposits currently unsuitable for commercial exploitation, the cost of phosphate fertilizers could increase sharply over the next few years. One way to reduce energy use in processing phosphate rock and, hence, lower phosphate fertilizer prices, is to use phosphate rock for direct application. It has been established that several highly reactive, finely ground phosphate rocks can approach the agronomic effectiveness of soluble P fertilizers in soils typical of the tropics, with high phosphorus fixation capacity. The dust problem of the finely ground rock can be reduced either by converting ground rock into minigranules or treating it with a dust suppressant.

Energy Savings Through Efficiency Improvements

Improving efficiency of fertilizer use greatly reduces fertilizer waste and, hence, saves fertilizer which can be applied to other crops. Improving efficiency of fertilizer use is essentially equivalent to improving efficiency of energy use in the form of fertilizer. The estimated potential energy savings through improvements in nitrogen use efficiency is reported in Table 58. For the world as a whole, doubling nitrogen efficiency (i.e., improving nitrogen recovery from 40% to 80%) could have potentially saved 20 million mt of nitrogen with a delivered value of approximately $11.3 billion during 1978/79.

In terms of energy, these nitrogen savings would have resulted in savings of energy equivalent to 262 million barrels of crude oil, worth at least $7.9 billion. Had the nitrogen that could have been saved been used either to expand fertilizer use intensity or applied on croplands previously not fertilized, the increase in grain output would have been at least 200 million mt. Clearly, the energy and economic implications of improvements in nitrogen use efficiency are too important to be ignored. The resulting payoffs of doubling nitrogen use efficiency are large enough to make any research effort worth undertaking.

CHAPTER 14

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The purpose of this chapter is to provide highlights of the study on energy and fertilizers. The main objectives of the study were (1) to examine the policy issues and linkages between the energy and fertilizer sectors; (2) to assess the implications of energy supply and prices on fertilizer production and prices; (3) to estimate energy requirements for manufacturing, packaging, transporting, and applying fertilizers; and (4) to evaluate policy options and prospects for improving energy efficiency in order to reduce the unfavorable impact of energy supply and prices on the fertilizer and, hence, on the agricultural sectors. Even though this study is focused on developing countries, it is expected to be useful for policymakers, planners, and researchers dealing with different aspects of the fertilizer sector around the world.

Energy and Fertilizer: Policy Problem

Fertilizer is a major factor in expanding agricultural output; its production, however, is highly energy intensive. This is especially true for nitrogen fertilizers, which are the most popular ones in developing countries. One 50-kg bag of urea, for example, requires as much energy as is contained in about 15 U.S. gal of gasoline.

The world population is expected to increase from 4.4 billion during 1980 to 6.3 billion by the year 2000. Furthermore, the share of developing countries in world population is expected to increase from 73% to 78% during this time.

The demand for food is increasing rapidly in response to population growth, income growth, and various government efforts to reduce the incidence of hunger and malnutrition. The prevalence of malnourishment is widespread in most developing countries.

Efficient and equitable distribution of available food supplies and implementation of various food subsidy and nutritional programs specially designed for the low-income consumers are extremely important to ameliorate the malnutrition problem. However, the total supply of food being distributed must be increased so that these programs can succeed.

Agricultural products other than food crops are also important to developing countries. Feed and fodder crops provide a major share of food for livestock. Export of agricultural products is the main source of foreign exchange in many countries. Fiber crops are needed for clothing and other necessities, and agriculture often supplies much of the noncommercial energy needs in rural areas.

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Despite the need to earn foreign exchange and expand feed and fiber production, however, the expansion in food production remains the primary goal of most developing countries. Unless the developing countries make a concerted effort to increase their own food production potential, the projected large food deficits and malnutrition cannot be avoided.

A large portion of incremental food production must come from an increase in crop yields. The use of chemical fertilizers is an extremely important component of the "package of inputs" and "package of practices" required to achieve an increase in crop yields and, hence, food production.

The fertilizer use level in developing countries is still very low. High fertilizer cost and lack of its availability are major factors for low levels of fertilizer use. Fertilizer production (especially nitrogen) and distribution are not only highly energy intensive but they also depend primarily on nonrenewable energy resources. Consequently, fertilizer supply and price are closely tied to energy supply and price.

The modernization of the agricultural sector in most developing countries was severely impeded by the quadrupling of fertilizer prices during the 1973-75 energy crisis. The recent increase in energy prices and the resultant increase in fertilizer prices are again threatening to sap the vitality from the budding "Green Revolution" in many of these countries. High fertilizer prices result in high food prices and thus jeopardize many national programs aimed at achieving food self-sufficiency and/or better standards of living.

It is therefore vital that fertilizer manufacture, marketing, and use be as energy- and cost-effective as possible, especially where the energy supply is scarce and expensive. This study was undertaken to better understand the relationships between the energy and fertilizer sectors. The knowledge of these relationships can then provide a basis for examining various policy options and designing strategies to improve energy efficiency and thereby minimize the adverse impact of increases in energy prices as well as accelerate the contribution of fertilizer to agricultural growth in the developing countries.

Energy for Fertilizer Sector in Perspective

Food, not commercial energy, is the basis of human survival. However, energy is necessary to produce fertilizer which, in turn, is necessary to produce food. Yet, ironically, the percentage of total commercial energy used in agricultural production is rather small. As reported in Table 59 for the world as a whole, fertilizer manufacture and distribution consume only about 1.5% of the total commercial energy, and approximately 3.5% is used in the entire

agricultural production sector. This energy is used mainly in the form of fertilizers, pesticides, irrigation, and fuel.

Table 59. Share of Total Commercial Energy Used in the Fertilizer and Agricultural Sectors

Region	% of Energy Used in Fertilizer Sector	% of Energy Used in Agricultural Production	Fertilizer Sector as % of Energy Used in Agricultural Production
Developed countries	1.3	3.4	40
Developing countries	2.7	4.0	68
World	1.5	3.5	45

Of the total commercial energy used in world agricultural production, 45% is used in the form of fertilizers. However, this value is about 68% in the developing countries. Despite the strategic role of agriculture in economic growth in developing countries, it does not seem to receive the priority for energy allocation that is commensurate with its contribution. Since a major part of the energy used at the farm level is in the form of fertilizer, any increase in energy price will inevitably adversely affect fertilizer price, fertilizer use, food production, and food prices.

The primary plant nutrients are nitrogen, phosphate, and potash. Commercial energy is used for manufacturing, packaging, transporting, and applying chemical fertilizers. The average energy requirements for fertilizer nutrients are reported in Table 60. The manufacture of nitrogen fertilizers is highly energy intensive (approximately 9 times that of phosphates and 11 times that of potash). This is due in part to the fact that in manufacturing ammonia, the basic material for all nitrogen fertilizers, the energy sources are used both as feedstock (about 55% of total) and as fuel (about 45% of total). The amount of energy required in fertilizer distribution is rather small. However, in the case of P_2O_5 and K_2O, more energy is used in their distribution than in their production.

Table 60. Average Energy Requirements for Fertilizer Nutrients[a]

Activity	U.S. Barrels of Oil Equivalent by Nutrients[b]		
	N	P_2O_5	K_2O
	(bbl/mt)		
Manufacturing	11.4	1.3	1.0
PTA[c]	1.4	1.6	1.2
TOTAL	12.8	2.9	2.2

a. The energy requirements for manufacture of individual nutrients are based on (1) weighted world average of all nutrient supply sources, (2) energy use survey for North America during 1979 and other appropriate sources, (3) high heating value estimates, and (4) total rather than battery-limit estimates.
b. One U.S. barrel of oil is equivalent to 6.12 GJ.
c. Packaging, transportation of raw materials and products, and application.

As reported in Table 61, 81% of the total commercial energy used in the world fertilizer sector during 1978/79 was for the manufacturing of N, P_2O_5, and K_2O and 19% for their distribution. As far as nutrients are concerned, nitrogen is by far the greatest energy consumer in the fertilizer sector. During 1978/79 the share of energy used in manufacturing and distribution of fertilizers was 82% for N, 11% for P_2O_5, and 7% for K_2O. Nitrogen accounted for 94% of the energy used in manufacturing all of the fertilizers consumed in developing countries.

Table 61. Share of Energy Consumption in the World Fertilizer Sector by Activities and Nutrients, 1978/79

Activity	Nutrient Share, %			
	N	P_2O_5	K_2O	Total
Manufacturing	73	5	3	81
PTA[a]	9	6	4	19
TOTAL	82	11	7	100

a. Packaging, transportation of raw materials and products, and application.

Changing Structure and Outlook for the Fertilizer Sector

Fertilizer use has been rapidly increasing over time, especially in developing countries. Despite this, the average fertilizer use in developing countries is relatively low (approximately 14 kg/ha during 1979), amounting to 57% of the world average and 38% of the average in developed countries. Furthermore, as revealed by the $N:P_2O_5:K_2O$ ratio (5.8:2.2:1.0) during 1979, the fertilizer use in developing countries is dominated by nitrogen. This reflects a certain degree of imbalance in fertilizer use in developing countries, as compared with the nutrient needs of most crops. For comparison, the corresponding $N:P_2O_5:K_2O$ ratio in developed countries is about 1.7:1.1:1.0.

During 1979/80, 112 million mt of plant nutrients was supplied by chemical fertilizers. Of this amount, 31% was consumed in developing countries and the rest in developed countries. The share of world NPK consumption by developing countries is projected to increase to about 34% by 1984/85. The developing countries as a group meet at least 30% of their fertilizer requirements through imports. Countries with serious balance of payment and foreign exchange problems, especially those which import food and energy, are finding it exceedingly difficult to finance fertilizer imports. Some of these countries have chosen to expand domestic production of fertilizers even though this expansion cannot always be justified economically.

The world fertilizer industry, especially nitrogen fertilizer, is going through a process of readjustment. This readjustment is mainly a response to increases in energy prices. The production of nitrogen fertilizers is gradually shifting away from the traditional producers (e.g., Japan) toward the energy-rich countries, especially those rich in natural gas. The major raw material for phosphate fertilizers is phosphate rock, which is relatively widely distributed around the world. Morocco and the United States will still continue to dominate the world market for phosphate rock for some time, although many developing countries are planning to use indigenous resources. Since potash deposits are found only in a few countries, the world location and trade patterns are not expected to change very much in the near future. Canada and the U.S.S.R. will continue to be the major sources of potash for the world market. Among developing countries Jordan and Brazil are reported to have definite plans for potash production.

Energy and Growth in the Nitrogen Fertilizer Sector

Nitrogen dominates the fertilizer scene at all levels, including fertilizer use at the farm level and aggregate fertilizer production, consumption, and trade. The degree of dependence on nitrogen fertilizers is relatively greater in developing than in developed countries. This dependence on nitrogen fertilizers, many of which

are imported, makes the developing countries relatively more vulnerable to energy shortages and price hikes in the international market.

The fertilizer industry depends almost exclusively on ammonia as an intermediate in the manufacture of nitrogen fertilizers. However, among various nitrogen fertilizers, urea is by far the most commonly used form of solid nitrogen fertilizer (and ironically the most difficult to use efficiently). The proportionate share of urea in the nitrogen fertilizer production capacity in developing countries has increased from 34% in 1971 to 64% in 1979 and is projected to be 67% during 1985.

World ammonia production capacity increased from 50.7 million mt (in terms of N) in 1970 to 94.1 million mt in 1980. The share of total ammonia production capacity by developing countries increased from 17% during 1970 to 27% during 1980. The market outlook for ammonia production seems bright. However, the location and trading patterns are shifting away from traditional supply sources. During 1970 the United States and the U.S.S.R. accounted for 25% and 14%, respectively, of world ammonia capacity. However, during 1985 their respective roles in ammonia production are projected to reverse. Among the developing countries, China, India, Mexico, and Indonesia are emerging as major ammonia producers. It should be noted, however, that urea cannot be produced economically from imported ammonia because carbon dioxide is a necessary raw material that is available at almost no cost only at ammonia plants.

The sources of hydrogen in ammonia synthesis include natural gas, naphtha, fuel oil, coke oven gas, refinery gas, coal, and electrolytic hydrogen. During 1980, at least 71% of world ammonia capacity was estimated to be based on natural gas. This share is expected to increase still further. At the world level natural gas is clearly the dominant feedstock for ammonia production. However, the proportional share of feedstocks in ammonia capacity varies from region to region and from country to country. Natural gas is more often preferred because ammonia based on this feedstock is relatively less energy intensive and capital intensive than that based on other feedstocks. Also, the price of natural gas is usually lower than that of petroleum-based feedstocks. Considering the prevailing naphtha prices in the international market, it is cheaper to import ammonia and/or urea than to produce urea based on imported naphtha. Ammonia plants based on coal are not yet price competitive with plants based on natural gas.

As far as the availability of feedstocks is concerned, the outlook for ammonia production seems bright. There are large known reserves of natural gas and other hydrocarbons, which if used for nitrogen production alone, can last for centuries. However, the exploitation of these reserves and their allocation for fertilizer production depend on the price of nitrogen fertilizers and the opportunity cost of gas. Nevertheless, at current market prices and with modern exploration techniques, the prospects of

finding new reserves of natural gas seem rather good. Many "gas-rich" developing countries are already expanding their domestic capacity of nitrogen fertilizers. During 1981 the developing countries' share in estimated proven reserves of natural gas was 47%, and their share in estimated proven reserves of oil was 81%.

Impact of Energy Prices on Fertilizer Production Cost

Fertilizer price is one of the major determinants of fertilizer use at the farm level. Fertilizer prices in turn are heavily influenced by energy prices through an increase in fertilizer production costs. A long-range declining trend in fertilizer prices reversed itself in 1971. Peak-level prices during 1974/75 were at least four times the price levels for 1971. This rapid increase was caused mainly by the energy crisis. However, other economic factors also played an important role in determining the behavior of the international fertilizer market. The prices dropped during 1975 but stayed above the pre-1972 prices. During early 1979 the oil prices started increasing again, and this led to an increase in fertilizer prices through an increase in fertilizer production costs and freight rates. During the last 15 years, a period of major growth in the fertilizer industry, fertilizer prices have generally been following oil price movements. A further increase in energy prices will result in even higher prices for fertilizer and food.

An increase in natural gas prices results in higher ammonia production costs and, hence, higher urea production costs. However, the actual proportional impact of a given increase in natural gas prices on urea production costs depends on at least two other factors: (1) capital costs and (2) plant utilization rate. Higher capital costs and low utilization rates reduce the relative impact of energy price hikes at the expense of increasing total fertilizer manufacturing costs. The fertilizer plants in most developing countries generally have high capital costs and low utilization rates. The developing countries which are creating domestic nitrogen production capacity have their own natural gas reserves which are available to the fertilizer sector at rather low prices.

At a given price of natural gas, e.g., $3.50/Mcf, the energy cost component in urea production costs is estimated to be approximately 16%, 59%, and 34% in developed, developing, and remote sites, respectively. Since prevailing natural gas prices in some developing countries are much lower than those in developed countries, the energy cost component in urea production costs will be even lower (approximately 10%-20%). However, as long as the developed countries control the major share of the international market for nitrogen fertilizers, the f.o.b. and c.i.f. prices will be heavily influenced by the energy prices.

Energy Requirements for Fertilizer Manufacturing

Average energy requirements for manufacturing common nitrogen, phosphate, and potash fertilizers are summarized in Table 62. These estimates are based on an energy use survey in North America during 1979 and on information from other sources. Consequently, these estimates are representative of actual energy use by fertilizer plants in operation. However, one must be careful in generalizing these estimates for the developing countries because of the differences in technology, processes, management, and efficiency. As a result, the energy requirements in manufacturing fertilizers may be underestimated for developing countries. Furthermore, the energy requirements are based on high heating value (HHV) and total rather than battery-limits energy estimates.

Table 62. Average Energy Use for Manufacturing Selected Nitrogen, Phosphate, and Potash Fertilizers

Product		% Nutrients	Average Energy Input, GJ/mt Product	Average Energy Input, GJ/mt Nutrient
Nitrogen fertilizers (N)				
Ammonia		82	46.9	57.2
Urea: prilled		46	36.6	79.5
granular		46	35.0	76.1
Ammonium nitrate:	prilled	34	24.9	73.4
	granular	34	24.4	71.8
Ammonium sulfate:	synthetic	21	12.6	60.0
	byproduct	21	4.7	22.4
Phosphate fertilizers (P_2O_5)				
Ground rock[a]		30	1.2	4.0
Phosphoric acid		54	5.3	9.8
TSP, granular		46	4.3	9.4
DAP, granular		46	14.3[b]	8.6
MAP, granular		54	10.8[c]	8.3
SSP, nongranular		20	1.0	5.0
SSP, granular		20	1.7	8.5
Potash fertilizers (K_2O)				
Muriate:[d]	granular	60	2.9	4.8
	nongranular	60	2.3	3.8
	average	60	2.6	4.3
Muriate:[e]	average	60	4.6	7.7

a. For direct application, dried and finely ground.
b. Contains 18% N. Energy use is 57.2 GJ/mt of N.
c. Contains 11% N. Energy use is 57.2 GJ/mt of N.
d. For North America.
e. For Europe.

There is a substantial variation in the energy requirements for different fertilizers; it ranges from 79.5 GJ/mt of nutrient content for prilled urea (highest) to 3.8 GJ/mt for nongranular KCl (among the lowest). Both phosphate and potash fertilizers use very little energy; most of it is in the form of fuel, electricity, and steam. Since steam and electricity can be generated from any commercial fuel, the manufacture of phosphate and potash fertilizers presents a fairly wide latitude in choice of basic energy sources. On the other hand, nitrogen fertilizers are highly energy intensive and require energy sources both as feedstock (source of hydrogen for ammonia) and fuel (including steam). Most of the direct and indirect energy uses in the existing fertilizer sector depend primarily on nonrenewable hydrocarbons.

The production of urea requires more than 8 times as much commercial energy as TSP and 19 times as much as KCl. This is precisely the reason many countries that produce ammonia based on imported feedstocks find it difficult to continue operating their existing plants and plan to phase them out.

Energy Requirements for Fertilizer Distribution

After the chemical fertilizer is manufactured, commercial energy is also required to pack it in bags, transport it to the farm, and apply it to the crops. However, the total amount of energy required for fertilizer distribution and application is rather small relative to the energy needed for its manufacture. The major share of energy required for distribution is used in transportation of fertilizer products and raw materials.

Average energy use for fertilizer packaging, transportation, and application is 8.6 GJ/mt of N, 9.8 GJ/mt of P_2O_5, and 7.3 GJ/mt of K_2O. Of this amount, transportation accounts for 52%, 58%, and 63%; whereas, packaging accounts for 30%, 27%, and 21% for N, P_2O_5, and K_2O, respectively. In the case of P_2O_5 and K_2O, since their manufacture is relatively less energy intensive, packaging and transportation account for approximately 46% of the total energy needs on a nutrient basis.

Even though it is difficult to make any generalizations, two other features for fertilizer transportation stand out. First, trucks are the most common mode of transporting fertilizer, especially at the secondary level. Second, truck transportation is highly energy intensive. On the average, trucks use four times more energy than rail and almost nine times as much energy as waterways for transporting 1 mt of fertilizer for a distance of 1 mile.

Prospects for Saving Energy in Fertilizer Manufacturing

The probable maximum saving in energy use for new fertilizer plants using available technology is summarized in Table 63 for selected nitrogen and phosphate fertilizers. Even though, on a percentage basis, the potential energy saving for phosphate fertilizers is large as compared with that for nitrogen fertilizers, it is much smaller in an absolute sense. The saving shown in Table 63 is based on 1979 practice in North America as a reference point.

Table 63. Probable Maximum Saving in Energy Use for New Fertilizer Plants Using Available Technology for Selected Fertilizers

Process/Product	Energy Use Present (GJ/mt of nutrient)	Energy Use Future (GJ/mt of nutrient)	Energy Saving (%)
Nitrogen fertilizers (N)			
Ammonia	57.2	42.9	25
Urea: ammonia input	58.7	44.0	25
synthesis	12.0	6.7	44
finishing	8.9	3.5	61
urea total	79.6	54.2	32
Ammonium nitrate	73.4	50.7	31
Phosphate fertilizers (P_2O_5)			
Phosphate rock for phosphoric acid	3.1	1.5	52[a]
Phosphoric acid production	4.2	2.3	45[b]
Phosphoric acid concentration	2.9	0.0	100[c]
Sulfuric acid for phosphoric acid	-3.7	-5.0	35
Total for phosphoric acid[d]	6.5	-1.2	118
DAP production[e]	2.0	1.7	15
DAP total[e]	8.5	0.5	94
MAP total[e]	8.3	0.2	98
TSP total	9.4	2.6	72

a. Eliminate drying.
b. Less grinding.
c. Eliminate.
d. Net energy use from external sources.
e. Not including energy for N input.

Scattered data indicate that some developing countries where operating efficiency is low could save much more energy by improving their capacity utilization, particularly by avoiding frequent shutdowns of ammonia-urea plants. For example, operation of an ammonia plant at 60% capacity may use 25% more energy per ton of product than continuous operation at full capacity.

There do not seem to be any commercially feasible, technological breakthroughs in nitrogen manufacturing that would result in major energy saving in the near future. Most of the energy-saving innovations involving changes and modifications would result in only a small saving. However, the sum of numerous savings amounts to a substantial total of 25.1 GJ/mt of N as urea; in absolute terms this is the largest energy saving that can be foreseen in fertilizer manufacture. These marginal changes would involve large capital expenditures but they can be easily incorporated in new fertilizer plants; some of them can be used in existing plants.

Energy substitution innovations are limited but do exist for both feedstock and fuel. Some of these innovations are technically feasible but relatively expensive. However, the situation may vary from one country to another, depending upon the economics, raw material reserves, level of industrialization, and the size of the fertilizer market. Many countries with a domestic supply of raw material (coal for ammonia, for example) may find it a nationally attractive strategy from the security point of view to switch from imported to domestic feedstock, even if it does not save energy and is more expensive.

Similarly, many marginal changes can also result in an energy saving in manufacturing phosphate fertilizers. Some of these innovations include (1) use of undried (wet) rock; (2) wet grinding of rock or complete elimination of the grinding step; (3) use of the hemihydrate process in phosphoric acid manufacture, rather than the commonly used dihydrate process, to eliminate the need for concentrating the acid; and (4) generating of electric power from waste heat.

However, before making any changes in existing or even in new fertilizer plants which are supposedly more efficient, it is extremely important to ask, "How much energy is being saved and at what cost?" Saving a small amount of energy for the sake of saving it does not provide very strong economic justification for making large capital investments.

Energy Savings by Supplementing Chemical Nitrogen Sources

In rapidly modernizing and intensive agriculture it is not possible to completely replace nitrogen or other nutrients supplied by chemical fertilizers. However, there is a need to supplement nutrients supplied by chemical fertilizers with nutrients from organic and biological sources.

Some preliminary estimates indicate that two-thirds of the total nitrogen of the world is supplied by organic and biological sources; whereas, only one-sixth is supplied by chemical fertilizers.

Clearly, these large magnitudes of nutrients supplied by nonchemical sources cannot be easily ignored.

The use of organic fertilizers not only adds crop nutrients to the soil but also has a positive effect on crop yields through the interaction effect, water effect, micro-organism effect, and soil structure effect. Furthermore, if properly handled, it can also solve waste disposal problems and be a source of energy through bioconversion. However, one should be aware of the fact that organic fertilizers are bulky, are expensive to transport, could be a health hazard, and do compete in some cases with alternative uses either as fuel or as feed. Even in countries like China where the use of organic wastes as a source of plant nutrients has received the highest priority, the need to supplement organic wastes with chemical fertilizer has been recognized, as witnessed by China's recent additions of several large ammonia/ urea plants.

Biological fixation of nitrogen is another major source of nitrogen. Many organisms fix atmospheric nitrogen either in symbiosis with other plants or asymbiotically. However, the processes involved in fixing nitrogen biologically are not yet very well understood. Whatever is empirically known indicates that there is a large potential to fix substantial amounts of nitrogen biologically. Contrary to common belief, biological fixation of nitrogen is not always free and does not always save energy, particularly as related to cereal crop production. There may also be a trade-off between crop yields and biological fixation of nitrogen.

The available empirical evidence indicates that, under present fertilizer practices, there exists a negative correlation between nitrogen fixed biologically and the presence of nitrogen supplied by chemical fertilizers. The nitrogen fixed biologically can, however, be increased through more appropriate fertilizers and better fertilizer management practices.

Energy Savings Through Fertilizer Marketing

The fertilizer marketing systems in many developing countries are not very efficient. These systems need to be streamlined in order to reduce energy use, reduce marketing costs, and make the appropriate fertilizer available to farmers on time.

Fertilizer transportation is the major consumer of energy needed in fertilizer marketing. Since most transportation modes use hydrocarbons as fuels, the costs are very sensitive to energy prices. The approximate share of freight costs in c.i.f. fertilizer prices in India during 1980 is reported, as an example, in Table 64. The contribution of freight costs to c.i.f. prices is estimated to be 19% for urea, 21% for DAP, and 36% for KCl. Furthermore, from

1978 to 1980 the freight costs increased by 97% for urea, 102% for DAP, and 181% for KCl. Any increase in energy prices will be reflected in higher c.i.f. fertilizer prices. Since most developing countries import part or all of their fertilizer needs they are more vulnerable to such an increase. This situation would also be true for countries importing fertilizer raw materials and intermediates and for in-country transportation.

Table 64. Approximate Share of Freight Costs in c.i.f. Fertilizer Prices in India During 1980

Product	f.o.b. Price[a]	Freight Rate[b]	c.i.f. Price	% Share of Freight
	($/mt)			
Urea	208	49	257	19
DAP	225	61	286	21
KCl	107	60	167	36

a. The f.o.b. prices refer to bagged urea from Western Europe, DAP in bulk from the U.S. Gulf, and KCl in bulk from Canada.
b. The freight rates refer to those of Netherlands-India for urea, U.S. Gulf-India for DAP, and Vancouver-India for KCl.

Some ways to reduce energy consumption in fertilizer transportation are: (1) to import fertilizer in large shiploads and use larger conveyances whenever they are practical, (2) to provide preferential berthing facilities at ports for ships carrying fertilizer, (3) to maximize load factor, especially backhaul, (4) to use slower speeds when economical, (5) to make greater use of waterways and rail, (6) to move fertilizer in bulk, if practical, and (7) to use high-analysis fertilizers with due regard for secondary nutrients.

Energy Savings Through Efficient Fertilizer Use

An improvement in fertilizer use efficiency promises the greatest saving in energy use. The available empirical evidence indicates that not only is nutrient recovery from applied fertilizers low but also the productivity of nutrients recovered is low. For example, more than 60% of applied nitrogen is lost and may become a source of air and water pollution. Approximately 15%-20% of applied phosphate fertilizers is taken up by the first crop, and the rest is fixed in the soil to become available to succeeding crops in the next 10-20 years. The efficiency of potash fertilizers appear to be somewhat between that of nitrogen and that of phosphate after they are applied.

The efficiency of applied fertilizers can be improved through appropriate fertilizer technology and management. The appropriate fertilizers, especially in the case of nitrogen, include (1) controlled-release fertilizers, (2) fertilizers amenable to deep placement, (3) more efficient forms of N, and (4) compound fertilizers. On the other hand, appropriate fertilizer management includes (1) right nutrient dosage, (2) proper nutrient balance, (3) right time of application, and (4) right method of application. For example, heavy applications of nitrogen alone are wasteful when other, less energy-intensive nutrients are limiting yields.

The potential economic benefits and saving in the form of energy are substantial enough to justify efforts to improve fertilizer use efficiency. The potential savings in fertilizer nitrogen and fertilizer energy through improved nitrogen use efficiency are summarized in Table 65. Doubling the efficiency of nitrogen use in the world can annually result in a saving of 20.6 million mt of nitrogen worth $11.3 billion, a saving of energy equivalent to 262 million barrels of oil worth $7.8 billion, or production of 200-300 million mt of additional grain. Greenhouse and field plot experimental results indicate that it is technically possible to at least double nitrogen use efficiency. The target of doubling N use efficiency is a challenging and worthwhile goal for everyone involved in the fertilizer sector.

Table 65. Potential Economic Benefits of Doubling Nitrogen Use Efficiency During 1978/79

Region	Nitrogen Saving[a]		Equivalent Energy Saving[b]	
	Million mt	Billion $	Million bbl	Billion $
Developed countries	13.4	7.4	171.1	5.1
Developing countries	7.2	3.9	91.4	2.7
World	20.6	11.3	262.5	7.8

a. Assuming existing average nitrogen use efficiency of 40%.
b. Energy in the form of crude oil.

Energy and Fertilizer: Policy Recommendations

Fertilizer is a major factor in expanding food production to meet the needs of the growing population and the rising expectations of developing countries. Appropriate fertilizer sector planning should receive a high priority. However, the plans should be designed and implemented carefully with as much emphasis on energy efficiency as is consistent with assuring adequate fertilizer supplies, increasing fertilizer productivity, reducing fertilizer prices, and other economic considerations.

The most promising means for saving fertilizer energy is the more efficient use of nitrogen at the farm level. Increased fertilizer use efficiency will not only save energy but will also improve fertilizer productivity and economics at the farm level. High fertilizer use efficiency can be attained by (a) better timing and placement of nitrogen fertilizers, (b) use of more efficient forms of nitrogen fertilizers, (c) use of greater proportions of the less energy-intensive primary fertilizer elements (phosphorus and potassium) where soil contains limited supplies of those elements, and (d) identification and correction of deficiencies with respect to secondary and micronutrients.

Appropriate fertilizer timing, placement, and nutrient balance often are not widely practiced by farmers. This is due to several reasons, including lack of recommendations, inadequate farmer education, late fertilizer deliveries, unavailability of the right kind of fertilizers, or delay in approval of fertilizer loans. Appropriate fertilizer programs need to be designed and implemented to correct these deficiencies. For example, balanced nutrient use could be ensured by supply of NP or NPK compound fertilizers of appropriate ratio, which contain the needed secondary or micronutrients.

Research dealing with improvement of fertilizer use efficiency should receive high priority, especially in the context of cropping systems and integrated nutrient management. Increased emphasis needs to be placed on continued research to update fertilizer recommendations, to improve fertilizer management practices, and to develop products that are easier to use efficiently--compound fertilizers, granular urea, and controlled-release fertilizers. In many cases urea may not be the most cost-effective nitrogen fertilizer; other nitrogen sources should be considered. Modified fertilizers need to be evaluated on a large scale for different crops, under farmers' field conditions, under varied agroclimatic conditions, and under different socioeconomic conditions and resource endowments. Further research is needed to determine strategies for economically expanding nitrogen supply through biological fixation and to make better use of biologically fixed nitrogen and crop residues or other organic materials.

As far as fertilizer manufacturing is concerned, the greatest energy saving is likely to come from operating existing plants more efficiently. For example, an operation of ammonia plants at 60% capacity (with frequent shutdowns) may use 25% more energy per ton of product than continuous operation at full capacity. An improvement in operational efficiency of fertilizer plants also results in higher fertilizer production and at lower per-unit production costs. Further study is needed to determine the implications of power interruptions on energy use, operating rates, fertilizer production, and fertilizer production costs.

For manufacturing nitrogen fertilizers, no single major technical breakthrough is in view that will drastically reduce the energy requirements. However, many energy-efficient innovations are

available which together promise potentially large energy savings in fertilizer manufacture. Some of these innovations can be added to existing plants, and most can be incorporated in new plants. However, these process modifications are not always economical and may adversely affect reliability. Careful consideration is needed to weigh prospective energy savings against possible adverse effects. There is need to study economic costs and benefits of various energy-saving technologies for countries with different raw material supply scenarios. Further evaluation should be made of the techno-economic feasibility of small-scale fertilizer plants for landlocked developing countries with small market and large potential for hydroelectric power generation or other natural resources.

The potential for saving energy in the transportation and distribution of fertilizer is likely to be small in the short run. Any efforts to save energy in fertilizer distribution should be approached with caution lest they interfere with the primary objective of getting the right kind of fertilizer to the farmer on time and in good condition. In fact, more energy use in fertilizer distribution could be cost-effective in some cases if spent on better, stronger, smaller bags, or more prompt delivery. In the long run, an energy saving could result from better planning, greater use of rail and waterways for transport, shipping in bulk when practical, importing few selected fertilizers in large shiploads, and using high-analysis and compound fertilizers.

Except when national security dictates it, no energy-saving innovation in the fertilizer sector will be adopted by individual decisionmakers if its use is not economical If fertilizer prices continue to increase as a result of energy price hikes, the policy-makers must ensure that economic returns to fertilizer use do not decline. In this context, there is need for research on the role, options, and implications of various economic incentive programs, including fertilizer subsidies. This should be done in the context of fertilizer-related national goals, including (a) improving the efficiency of fertilizer use, (b) achieving balanced fertilization, and (c) saving nonrenewable energy.

Appropriate information is a prerequisite for designing and implementing effective government policies. Those policies that are based on sound information and economic analysis with respect to their costs and benefits will have a relatively higher degree of success than those which do not have any scientific base. Energy use estimates should be based on country-specific energy surveys of fertilizer plants in operation in order to provide a more realistic basis for energy use analysis, potential for energy saving, and energy-related costs. Modified fertilizer technology needs to be evaluated with respect to its impact on energy costs and requirements in all phases of fertilizer manufacture, distribution, and use.

The national fertilizer programs will not succeed unless there is a strong commitment and active support on the part of the government to implement them. The government must take the lead in promoting energy-efficient manufacture, distribution, and use of fertilizer. This could be accomplished through appropriate incentives, interventions, education, research, regulation, or some combination of these actions. Developing countries that are deficient in food, fertilizer, foreign exchange, and energy must give a high priority to the design and implementation of fertilizer programs based on these recommendations if they expect to raise the standards of living of their people. International organizations that conduct research and provide technical assistance and financial aid can play a crucial role in facilitating the formulation and successful implementation of such national programs.

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APPENDIXES

List of Appendixes

Appendix	
A	Classification of Countries by Economic Classes and Regions
B	Energy Use Survey for Calendar Year 1979
C	Production Process Diagrams for Fertilizers and Intermediates

Appendix Tables

Appendix Table	
B-1	Natural Gas Source and Type of Contract
B-2	Average Energy Consumed to Produce Ammonia in Reciprocating Plants, 1,000 Btu/ton of Ammonia
B-3	Average Energy Consumed to Produce Ammonia in Centrifugal Plants, 1,000 Btu/ton of Ammonia
B-4	Average Energy Consumption in Fertilizer Production
B-5	Variability in Energy Consumption and Fertilizer Production
B-6	Energy Unit Equivalents

Appendix Figures

Appendix Figure	
C-1	Typical Ammonia Production Process Using Natural Gas Feedstock
C-2	Typical Phosphoric Acid Production Process
C-3	Typical Nitric Acid Production Process
C-4	Typical Sulfuric Acid Production Process
C-5	Typical Urea Production Process
C-6	Typical Ammonium Sulfate Crystallization Process
C-7	Typical Ammonium Nitrate Production Process
C-8	Den Process for Making Single, Double, or Triple Superphosphate

Appendix Figures
(Continued)

C-9	Typical Slurry Process for Making Granular TSP
C-10	Typical Ammonium Phosphate Production Process
C-11	Formulation of Alternative Nitrogen-Containing Chemical Fertilizers
C-12	General Diagram for Granular Compound Fertilizer Production
C-13	Typical Potash Refining Process

APPENDIX A

CLASSIFICATION OF COUNTRIES BY ECONOMIC CLASSES AND REGIONS[1]

The economic classes and regions into which the world is divided for the purpose of analytical studies are given below. This includes three economic classes and several regions.

Class I: Developed Market Economies

Region A—North America

Canada, United States.

Region B—Western Europe

Andorra, Austria, Belgium-Luxembourg, Denmark, Faeroe Islands, Finland, France, Federal Republic of Germany (including West Berlin), Gibraltar, Greece, Holy See, Iceland, Ireland, Italy, Liechtenstein, Malta, Monaco, Netherlands, Norway, Portugal (including Azores and Madeira), San Marino, Spain, Sweden, Switzerland, United Kingdom (including Channel Islands and Isle of Man), Yugoslavia.

Region C—Oceania

Australia, New Zealand

Region D—Other Developed Market Economies

Israel, Japan (including Bonin and Ryukyu Islands), South Africa.

Class II: Developing Market Economies

Region A—Africa

Algeria, Angola, Benin, Botswana, British Indian Ocean Territory, Burundi, Cameroon, Cape Verde, Central African

1. The classification of countries, and the list of countries included in each of the economic classes and regions is obtained from FAO's Fertilizer Yearbook 1980, FAO (1981a).

Republic, Chad, Comoros, Congo, Djibouti, Equatorial Guinea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Saint Helena, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, Spanish North Africa, Swaziland, Tanzania, Togo, Tunisia, Uganda, Upper Volta, Western Sahara, Zaire, Zambia, Zimbabwe.

Region B—Latin America

Antigua, Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador (including Galapagos Islands), El Salvador, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts-Nevis-Anguilla, Saint Lucia, Saint Vincent, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, Venezuela, Virgin Islands (UK), Virgin Islands (US).

Region C—Near East

Africa--Egypt, Libya, Sudan.

Asia--Afghanistan, Bahrain, Cyprus, Gaza Strip (Palestine), Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Kingdom of Saudi Arabia, Syria, Turkey, United Arab Emirates, Yemen Arab Republic, Democratic Yemen.

Region D—Far East

Bangladesh, Bhutan, Brunei, Burma, East Timor, Hong Kong, India, Indonesia, Republic of Korea, Lao, Macau, Malaysia, Maldives, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Thailand.

Region E—Other Developing Market Economies

America--Bermuda, Greenland, Saint Pierre and Miquelon.

Oceania--American Samoa, Canton and Enderbury Islands, Christmas Island (Australia), Cocos (Keeling) Islands, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, Johnston Island, Midway Islands, Nauru, New Caledonia, Niue, Norfolk Island, Pacific Islands (Trust Territory), Papua New Guinea, Pitcairn Island, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wake Island, Wallis and Futuna Islands.

Class III: Centrally Planned Economies

Region A—Asia

China, Democratic Kampuchea, Democratic People's Republic of Korea, Mongolia, Vietnam.

Region B—Eastern Europe and U.S.S.R.

Albania, Bulgaria, Czechoslovakia, German Democratic Republic (including East Berlin), Hungary, Poland, Romania, U.S.S.R.

All Developed Countries

Includes developed market economies and Region B of centrally planned economies.

All Developing Countries

Includes developing market economies and Region A of centrally planned economies.

APPENDIX B

ENERGY USE SURVEY FOR CALENDAR YEAR 1979[1]

Natural Gas Sources for Ammonia Production

Anhydrous ammonia production during the survey year was 13,762,000 tons.[2] Since natural gas is the main source of feedstock for ammonia production, a breakdown of natural gas supply sources is reported in Table B-1.

Average Energy Consumption in Anhydrous Ammonia Production

Average energy consumption depends on whether the ammonia plant uses reciprocating or centrifugal compressor technology. The survey is based on 2,402,000 tons of ammonia produced by reciprocating plants and 11,450,000 tons of ammonia produced by centrifugal plants. The average energy consumption in reciprocating plants is reported in Table B-2 and in centrifugal plants is reported in Table B-3.

Average Energy Consumption in Fertilizer Production

Average energy consumption for various fertilizers based on different fertilizer technologies is reported in Table B-4. Average energy consumption is further divided into different sources, including natural gas, fuel oil, electricity, and imported steam.

Variability in Energy Consumption in Fertilizer Production

In order to provide a perspective on the variability of energy consumption in production of different fertilizers, using different technologies, the average, median, and interquantile range of energy consumption in fertilizer production is reported in Table B-5.

1. This is a revised (June 1980) version of the Energy Use Survey conducted by Tyson, Belzer, and Associates, Inc., on behalf of TFI, Washington, D.C.
2. All tonnage (short tons) data refer to tonnage of participants in the survey, not to industry-wide tonnages.

Companies Participating in the Survey

The listing of companies participating in the TFI Energy Use Survey is provided below.

Agrico Chemical Company
Agway, Inc.
Allied Chemical Corporation
American Cyanamid Company
Atlas Powder Company
Beker Industries Corporation
Borden Chemical
CF Industries, Inc.
Chevron Chemical Company
Columbia Nitrogen Corporation
Cominco American
Conserv
Estech General Chemicals Corporation
Farmland Industries, Inc.
First Mississippi Corporation
Freeport Minerals Company
Gardinier, Inc.
Gold Kist, Inc.
Grace, W. R. & Company
Gulf Oil Chemicals Company
Hawkeye Chemical Company
Ideal Basic Industries
International Minerals & Chemical Corporation
Mississippi Chemical Corporation
Mobil Chemical Company
Monsanto Agricultural Products Company
Occidental Chemical Company
Olin Corporation
Potash Corporation of Saskatchewan
Scott, O. M. & Sons
Simplot, J. R. Company
Sunniland Corporation
Terra Chemicals International, Inc.
Texas Farm Products Company
Triad Chemical
Union Oil Company
USS Agri-Chemicals
Vistron Corporation
Wycon Chemicals

Assumption Regarding Energy Equivalents

The units of energy equivalents for converting items in the Energy Use Survey to Btus as specified by U.S. Department of Energy, Federal Register, February 27, 1980, are reported in Table B-6.

Product Definitions

The Energy Use Survey was based on the following fertilizer products definition. All the units refer to short tons of product except for phosphoric acids which are as short tons of P_2O_5.

1. Anhydrous Ammonia--82% N ammonia product.

2. Urea

   a. Total liquid--Synthesis section product reported as 100% urea.

   b. Prilled--Product from prilling operation, including concentration of synthesis product.

   c. Granulated--Product from granulation operation, including concentration of synthesis product.

3. Ammonium Nitrate

   a. Liquor--Include energy for production of nitric acid and for the neutralizer. Report as 100% AN liquor.

   b. Prilled--Product from prilling operation, including concentration of liquor.

   c. Granulated--Product from granulation operation, including concentration of liquor.

4. Phosphate Rock

   a. Mining and reclamation--Energy for mining ore and for mine reclamation.

   b. Beneficiation (wet)--Exclude energy value of flotation agents (e.g., kerosene).

   c. Calcining--Self-explanatory.

   d. Rock drying--Self-explanatory.

5. Wet Process, Phosphoric Acid, Filter Grade--Report as filter grade (dihydrate and/or hemihydrate) without concentration and as tons of P_2O_5.

   a. Wet-rock feed--Include rock grinding.

   b. Dry-rock feed--Include rock grinding.

   Wet Process, Phosphoric Acid, Merchant Grade--Report as merchant grade (54% P_2O_5) including only the energy between filter grade and merchant grade. Report as tons of P_2O_5.

6. Superphosphoric Acid--Include only superphosphoric acid, 68% P_2O_5 or higher, as tons P_2O_5. Include only the energy between filter-grade wet-process phosphoric acid and superphosphoric acid.

7. Sulfuric Acid--100% H_2SO_4 basis.

8. Normal Superphosphate--26% P_2O_5 or less; run-of-pile, granular, and enriched.

   a. Unground rock--Production from unground phosphate rock.

   b. Ground rock--Production from ground phosphate rock.

9. Concentrated Superphosphate--Superphosphates with over 26% P_2O_5. Include grinding of rock used in the process.

   a. Run-of-pile.

   b. Granular (slurry)--Self-explanatory.

   c. Granular (reclaimed from run-of-pile)--Self-explanatory.

10. Diammonium Phosphate--18-46-0, 21-53-0, and 16-48-0 only.

11. Monoammonium Phosphate, Granular--N-P_2O_5-O, combinations of 1:3 ratios or larger, such as 11-48-0, 13-39-0, 12-50-0.

12. Potash (shaft mining only).

   a. Standard muriate

   b. Coarse muriate

   c. Granular muriate

13. Mixed Fertilizers

   a. Granulation

   b. Bulk blends

   c. Mixed fluids

Table B-1. Natural Gas Source and Type of Contract

Interstate Source	%	Intrastate Source	%	Total, %
Firm	33.3	Firm	55.8	89.1
Interruptible	5.9	Interruptible	5.0	10.9
TOTAL	39.2		60.8	100.0

Table B-2. Average Energy Consumed to Produce Ammonia in Reciprocating Plants

Source	Feedstock Energy	Reformer Process Energy	Other Process[a] Energy	Total
	(1,000 Btu/ton of ammonia)			
Natural gas	21,521	12,957	582	35,060
Electricity	-	632	4,460	5,092
Fuel oil	-	204	86	290
Imported steam	-	-	1,416	1,416
Other	276	-	-	276
Total	21,797	13,792	6,544	42,134

a. Energy such as electrical, import steam, fuel for turbine and engine driven compressors of pumps, etc.

Table B-3. Average Energy Consumed to Produce Ammonia in Centrifugal Plants

Source	Feedstock Energy	Reformer Process Energy	Other Process[a] Energy	Total
	(1,000 Btu/ton of ammonia)			
Natural gas	22,368	14,542	2,181	39,091
Electricity	-	-	708	708
Fuel oil	-	215	(178)	37
Imported steam	-	-	408	408
Other	-	102	-	102
Total	22,368	14,859	3,119	40,346

a. Energy such as electrical, import steam, fuel for turbine and engine driven compressors of pumps, etc.

Table B-4. Average Energy Consumption in Fertilizer Production

Product	Production 1,000T	Natural Gas	Electricity	Fuel Oil	Imported Steam	Total
		(1,000 Btu/ton)				
Urea						
Total liquid	4,791	1,516	864	187	2,188	4,755
Prilled	1,487	222	636	1	2,640	3,499
Granulated	2,438	463	479	3	1,231	2,176
Ammonium Nitrate						
Liquor	5,038	541	568	(3)	392	1,498
Prilled	2,601	113	443	45	1,913	2,514
Granulated	528	643	315	75	1,025	2,058
Phosphate Rock						
Mining & reclamation	58,814	-	249	12	-	261
Beneficiation (wet)	34,944	-	347	9	-	356
Calcining	2,771	447	282	173	-	902
Rock drying	35,078	178	37	186	1	402
Wet Process, Filter-Grade Phosphoric Acid (P_2O_5)						
Wet rock feed	2,515	-	1,462	17	1,660	3,139
Dry rock feed	5,524	66	1,650	30	1,852	3,598
Wet Process, Merchant-Grade Phosphoric Acid (P_2O_5)	3,706	22	681	62	4,567	5,332
Superphosphoric Acid (P_2O_5)	940	1,296	428	-	972	2,696
Sulfuric Acid	22,985	23	162	27	(1,343)	(1,131)
Normal Superphosphate						
Unground rock	295	-	215	6	-	221
Ground rock	246	278	212	-	-	490

(Continued)

Table B-4. Average Energy Consumption in Fertilizer Production (Continued)

Product	Production 1,000T	Natural Gas	Electricity	Fuel Oil	Imported Steam	Total
		(1,000 Btu/ton)				
Concentrated Superphosphate						
Run-of-pile	440	143	170	19	19	351
Granular (slurry)	2,755	505	527	287	180	1,499
Granular (reclaimed from run-of-pile)	222	423	414	21	13	871
Diammonium Phosphate	9,179	223	344	70	173	810
Monoammonium Phosphate, Granular	1,537	492	440	-	79	1,011
Potash (shaft mining)						
Standard, coarse, and granular	8,193	1,230	964	1	-	2,195
Mixed Fertilizers						
Granulation	5,059	372	380	121	28	901
Bulk blends	566	109	35	10	-	154
Mixed fluids	1,961	309	140	2	90	541

Table B-5. Variability in Energy Consumption in Fertilizer Production

Product	Average	Median	Interquartile[a] Range
	(1,000 Btu/ton)		
Ammonia			
Reciprocating	42,134	42,666	40,015-47,830
Centrifugal	40,346	39,740	38,300-42,730
Urea			
Total liquid	4,755	4,752	3,345-5,515
Prilled	3,499	2,501	1,407-3,626
Granulated	2,176	b	b
Ammonium Nitrate			
Liquor	1,498	1,002	242-2,383
Prilled	2,514	2,234	1,666-3,430
Granulated	2,058	b	b
Phosphate Rock			
Mining & reclamation	261	284	188-473
Beneficiation (wet)	356	356	210-625
Calcining	902	b	b
Rock drying	402	406	387-444
Wet-Process, Filter-Grade Phosphoric Acid (P_2O_5)			
Wet rock feed	3,139	b	b
Dry rock feed	3,598	2,408	2,009-4,494
Wet Process, Merchant-Grade Phosphoric Acid (P_2O_5)	5,332	5,444	4,071-8,881
Superphosphoric Acid (P_2O_5)	2,696	b	b
Sulfuric Acid	(1,131)	(867)	(1,883)-270
Normal Superphosphate			
Unground rock	221	b	b
Ground rock	490	b	b
Concentrated Superphosphate			
Run-of-pile	351	b	b
Granular (slurry)	1,499	1,251	1,075-2,619
Granular (reclaimed from run-of-pile)	871	b	b
Diammonium Phosphate	810	881	667-1,308
Monoammonium Phosphate, Granular	1,011	b	b
Potash (shaft mining)			
Standard, coarse, & granular	2,195	b	b
Mixed Fertilizers			
Granulation	901	829	568-1,362
Bulk blends	154	b	b
Mixed fluids	541	b	b

a. Mid-50% range of values reported. Thus, 25% of values are higher and 25% are lower.
b. Insufficient number of participants.

Table B-6. Energy Unit Equivalents

Types of Energy	Btu
1 ft^3 natural gas	1,020
1 Mcf natural gas	1,020,000
1 kWh	10,000
1 gal residual fuel oil (No. 6 equivalent)	149,690
1 gal propane	91,620
1 lb steam	1,000

APPENDIX C

PRODUCTION PROCESS DIAGRAMS FOR FERTILIZERS AND INTERMEDIATES

The purpose of this appendix is to develop typical production process diagrams for important fertilizers and intermediates. This includes ammonia using natural gas, phosphoric acid, nitric acid, sulfuric acid, urea, ammonium sulfate, ammonium nitrate, den process for superphosphates (single, double, and triple), slurry process for TSP, ammonium phosphate (MAP and DAP), alternative N fertilizers, granular compound fertilizers, and potash. These process diagrams are complete but somewhat simplified technically.

These diagrams serve at least three purposes: (1) provide a complete description of the process for manufacturing common fertilizers; (2) identify various inputs, outputs, and raw materials needed to manufacture fertilizers and intermediates; and (3) identify energy using components of the manufacturing process and possibilities for saving energy.

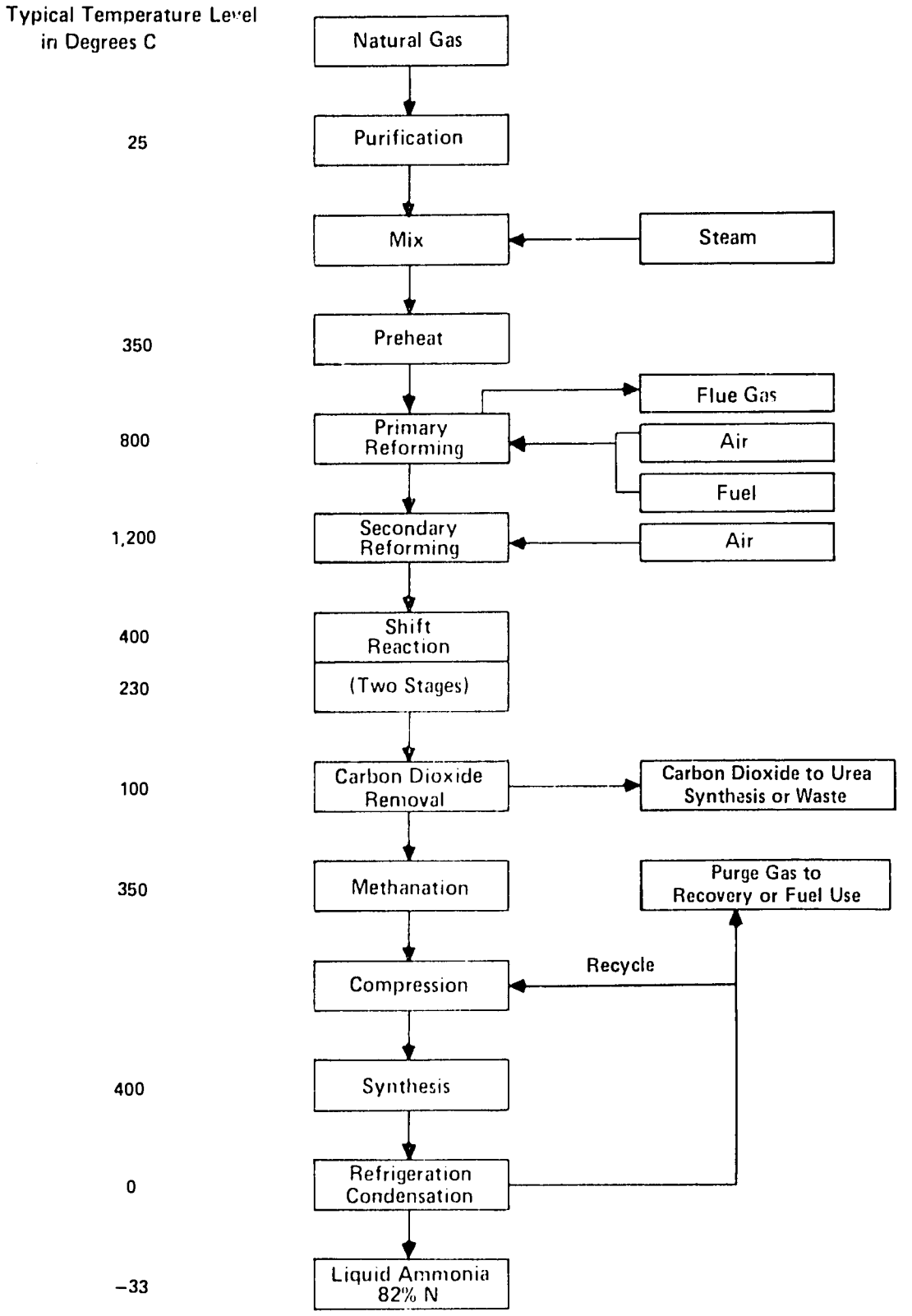
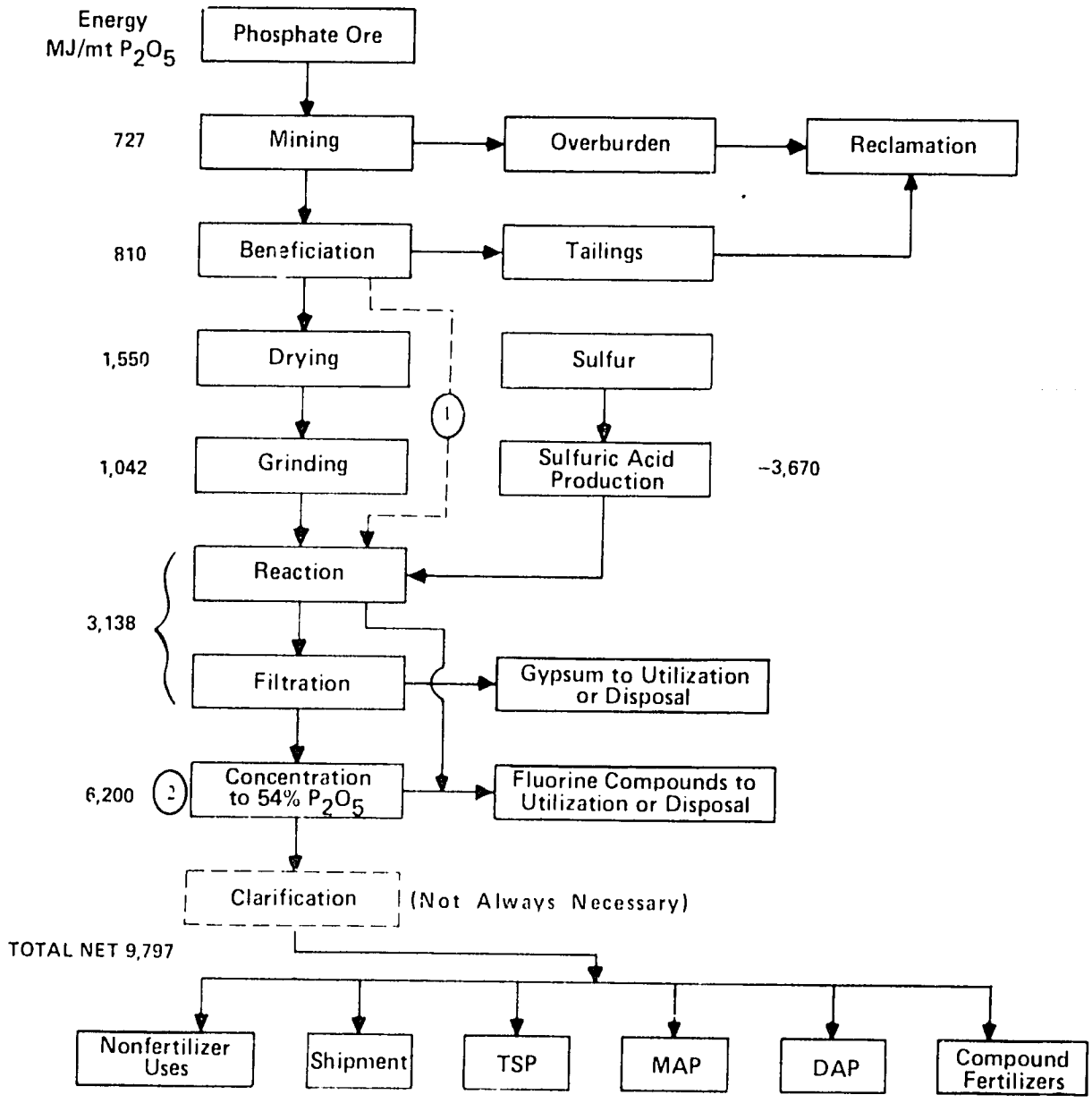


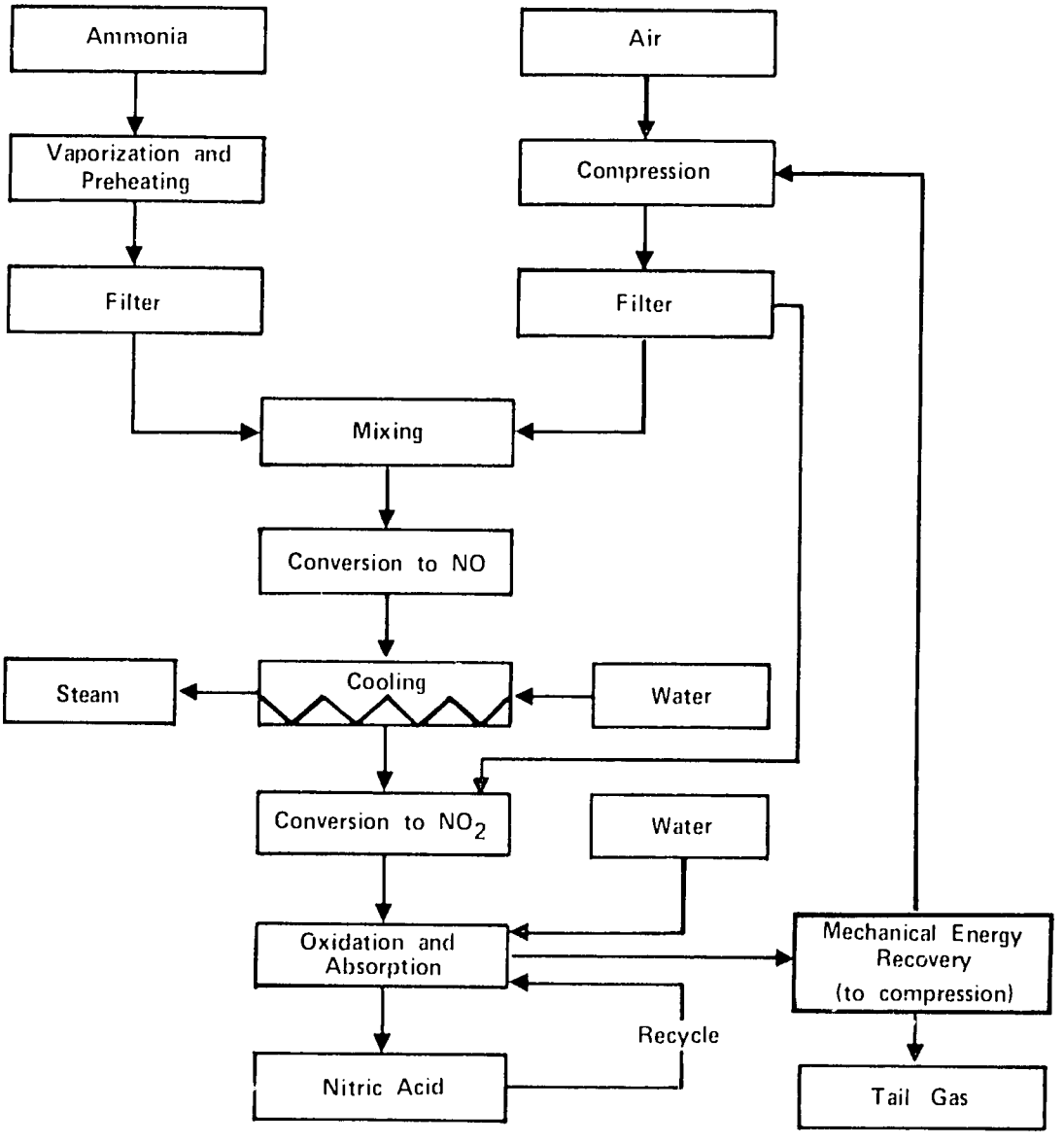
Figure C-1. Typical Ammonia Production Process Using Natural Gas Feedstock.



Energy-Saving Options:

1. In Some Processes, Drying or Grinding or Both Can Be Omitted.
2. For Some Uses 40% P_2O_5 Concentration is Sufficient, Saving Over Half of the Energy for Concentration. In Hemihydrate Processes, Concentration Can Be Omitted or Greatly Reduced.

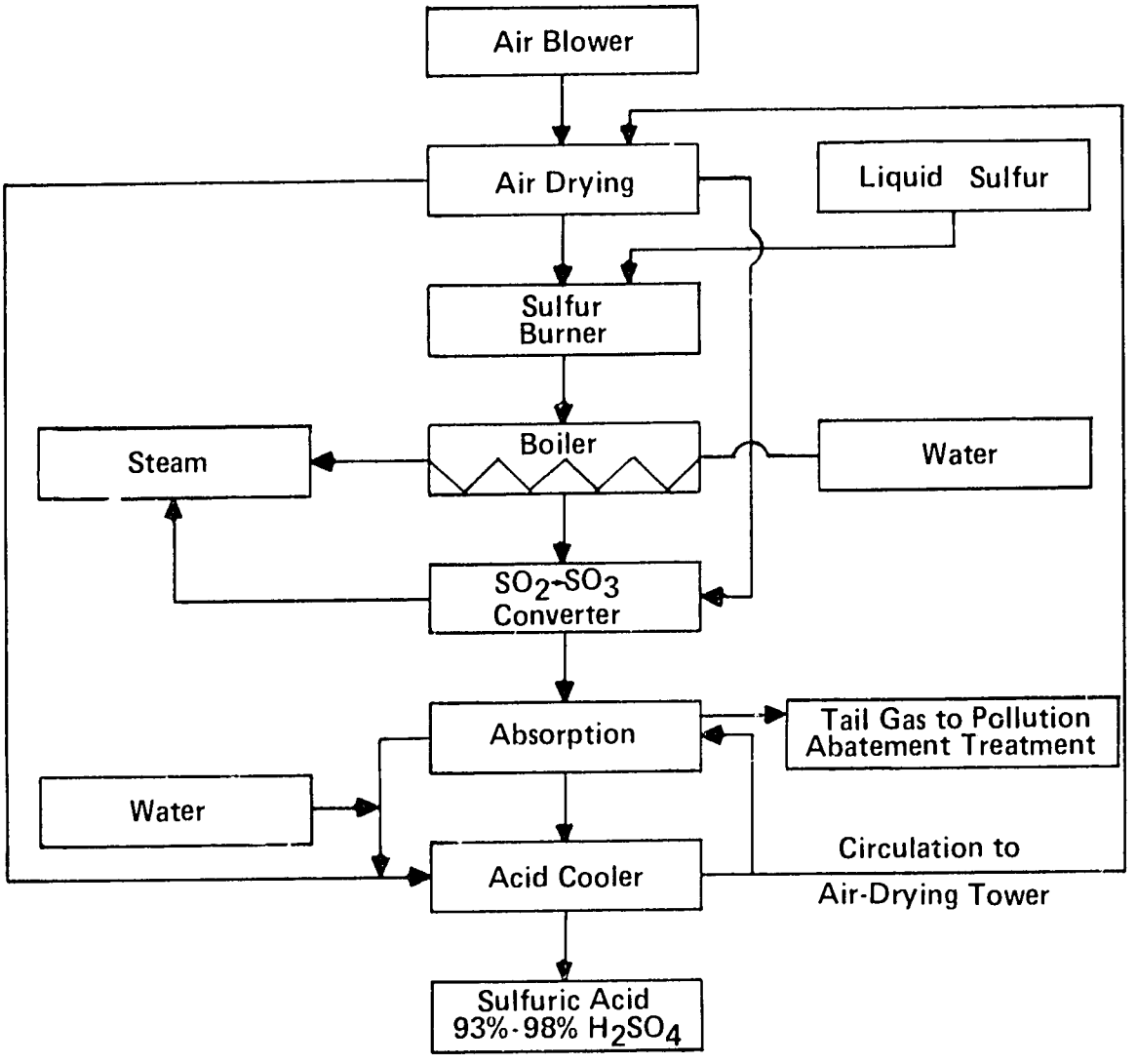
Figure C-2. Typical Phosphoric Acid Production Process.



Notes:

1. Tail gas may require pollution abatement treatment unless extended absorption is used.
2. Some processes operate with relatively low pressure in NO conversion and further compression before absorption.

Figure C-3. Typical Nitric Acid Production Process.



Notes: 1. Tail gas treatment may consist of ammonia scrubbing or addition of a second converter and absorber.
2. Steam is used to drive blowers and pumps, and up to 1.3 GJ/mt of H_2SO_4 is available for use elsewhere.
3. Sulfuric acid may also be made from pyrite, smelter gas, or gypsum.

Figure C-4. Typical Sulfuric Acid Production Process.

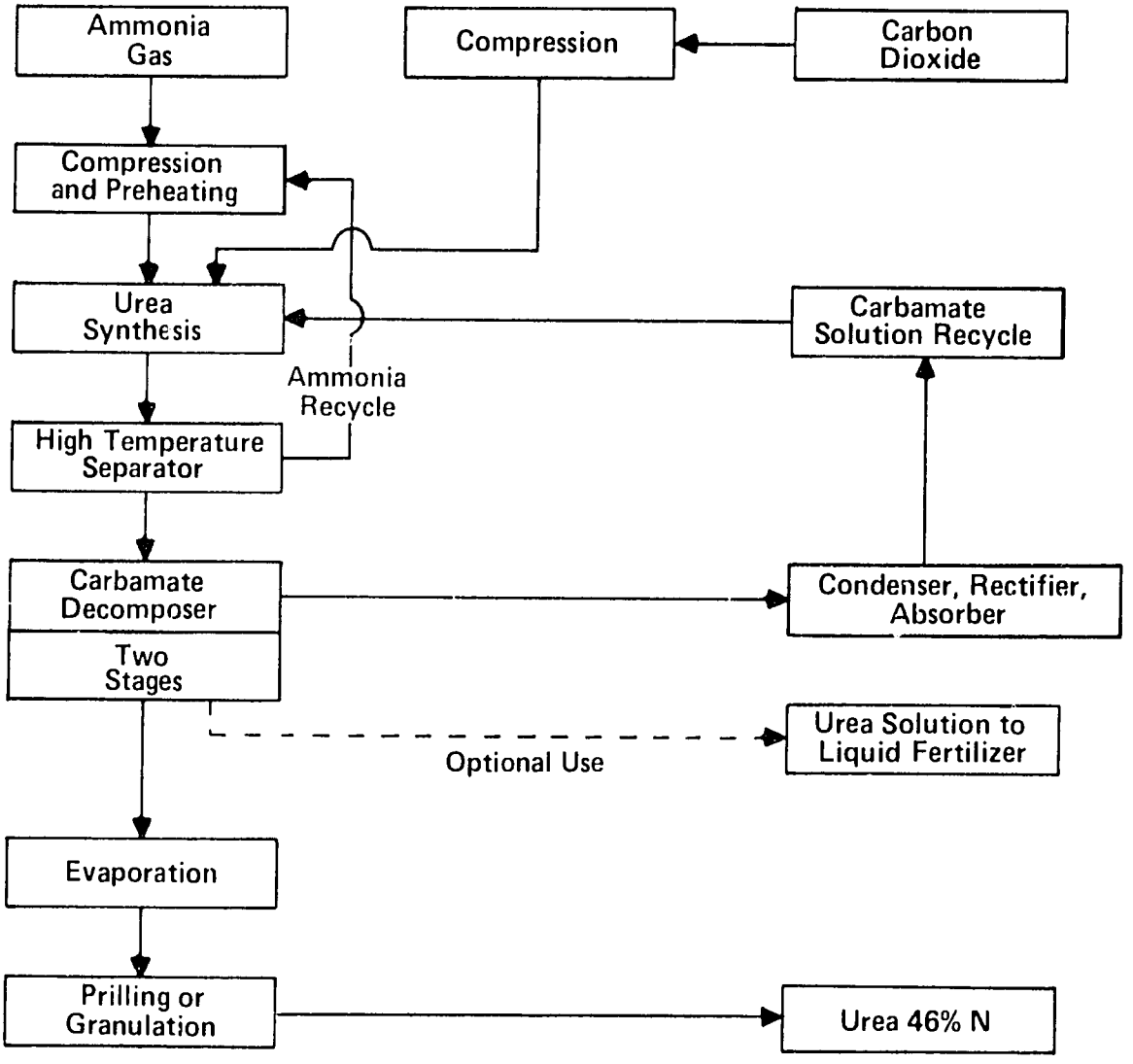
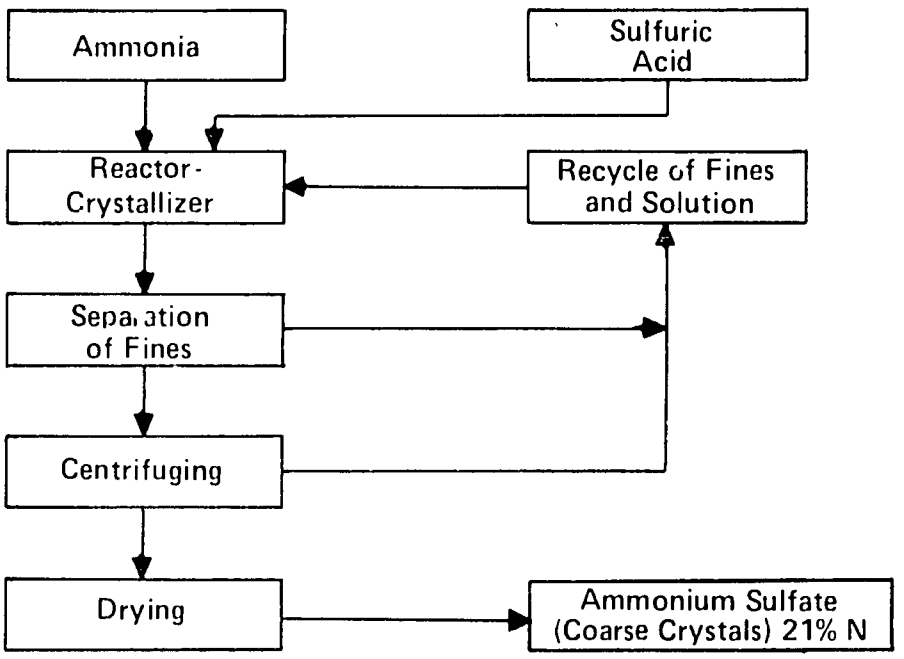


Figure C-5. Typical Urea Production Process.



Process Variations:

1. Fine crystals may be produced for use in compound fertilizer or for granulation for direct application.
2. Byproduct ammonia recovered from coke-oven gas may be used.
3. Byproduct ammonium sulfate solution from caprolactam production or other sources may be used.
4. Ammonium sulfate solution may be produced by reaction of calcium sulfate with ammonium carbonate solution; calcium carbonate is a byproduct.

Figure C-6. Typical Ammonium Sulfate Crystallization Process.

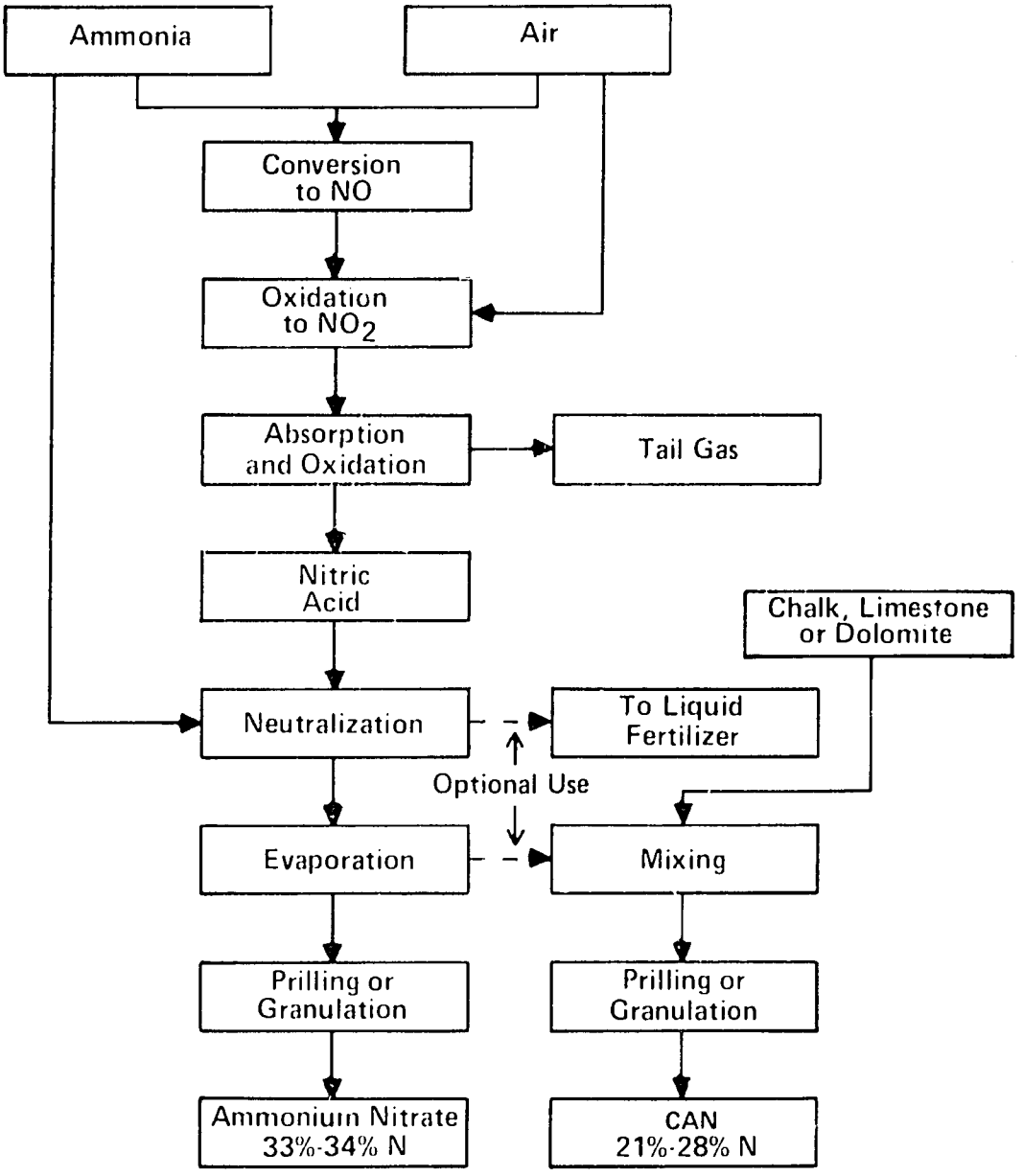
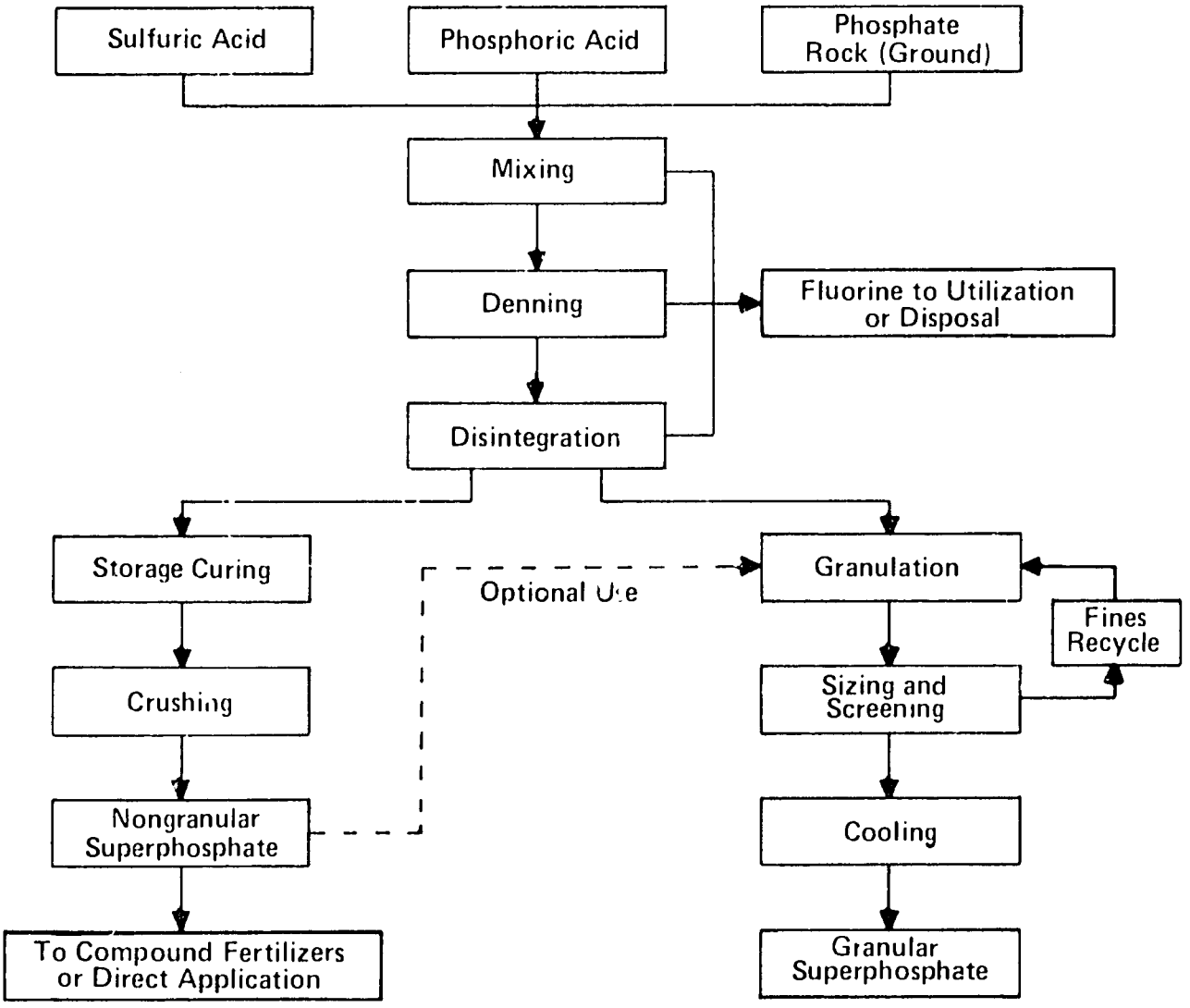


Figure C-7. Typical Ammonium Nitrate Production Process.



Usual Grades: Single 18%-22% P_2O_5
Double 25%-35% P_2O_5
Triple 44%-48% P_2O_5

Figure C-8. Den Process for Making Single, Double, or Triple Superphosphate.

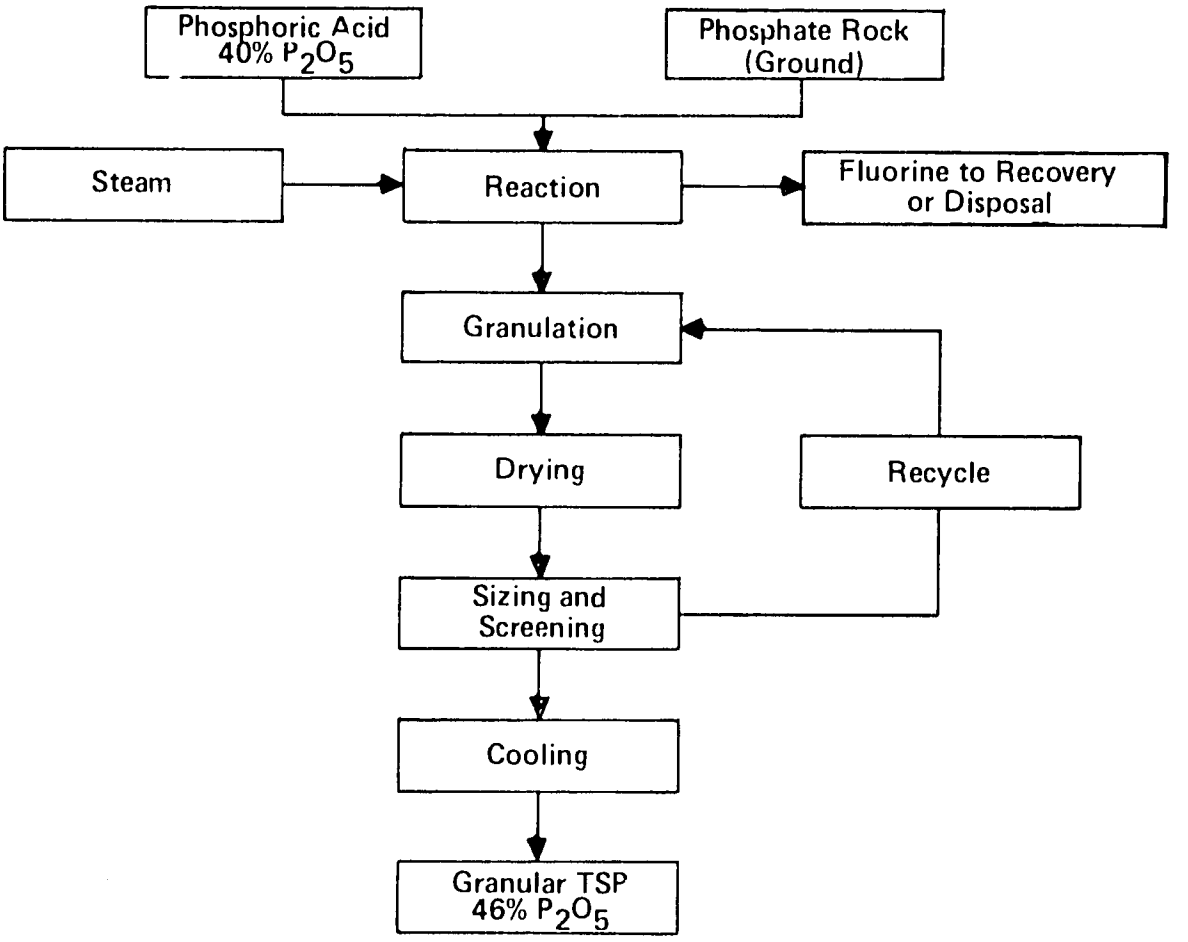
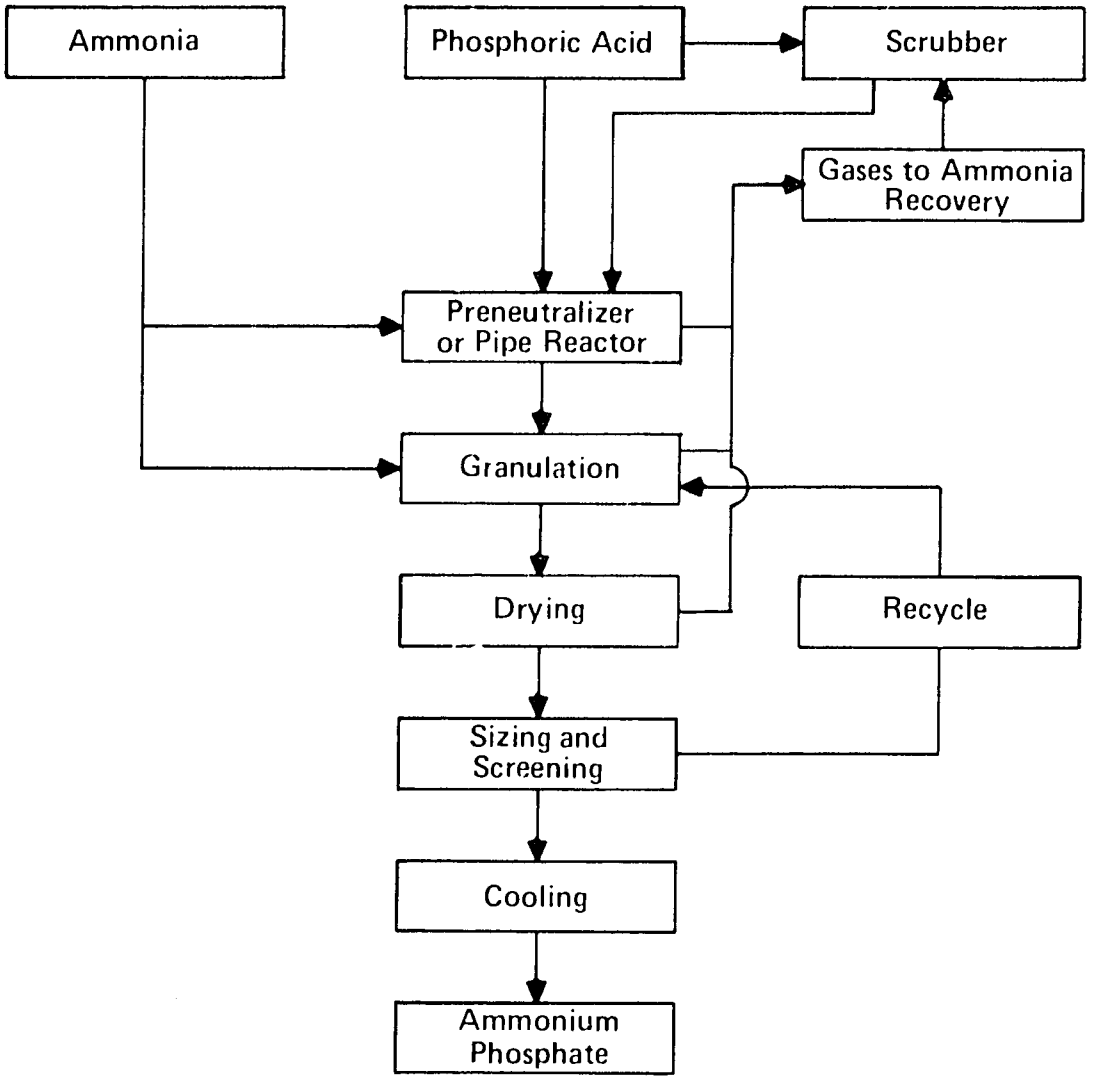


Figure C-9. Typical Slurry Process for Making Granular Triple Superphosphate.



Common Grades:

18-46-0 DAP
11-55-0 > Variations of MAP
10-48-0
13-54-0 > Mixtures of DAP and MAP
16-48-0

Note:

For making DAP, 54% P_2O_5 acid may be used in the preneutralizer or pipe reactor and 30% P_2O_5 acid in the scrubber. The average concentrations may be about 40% P_2O_5

Figure C-10. Typical Ammonium Phosphate Production Process.

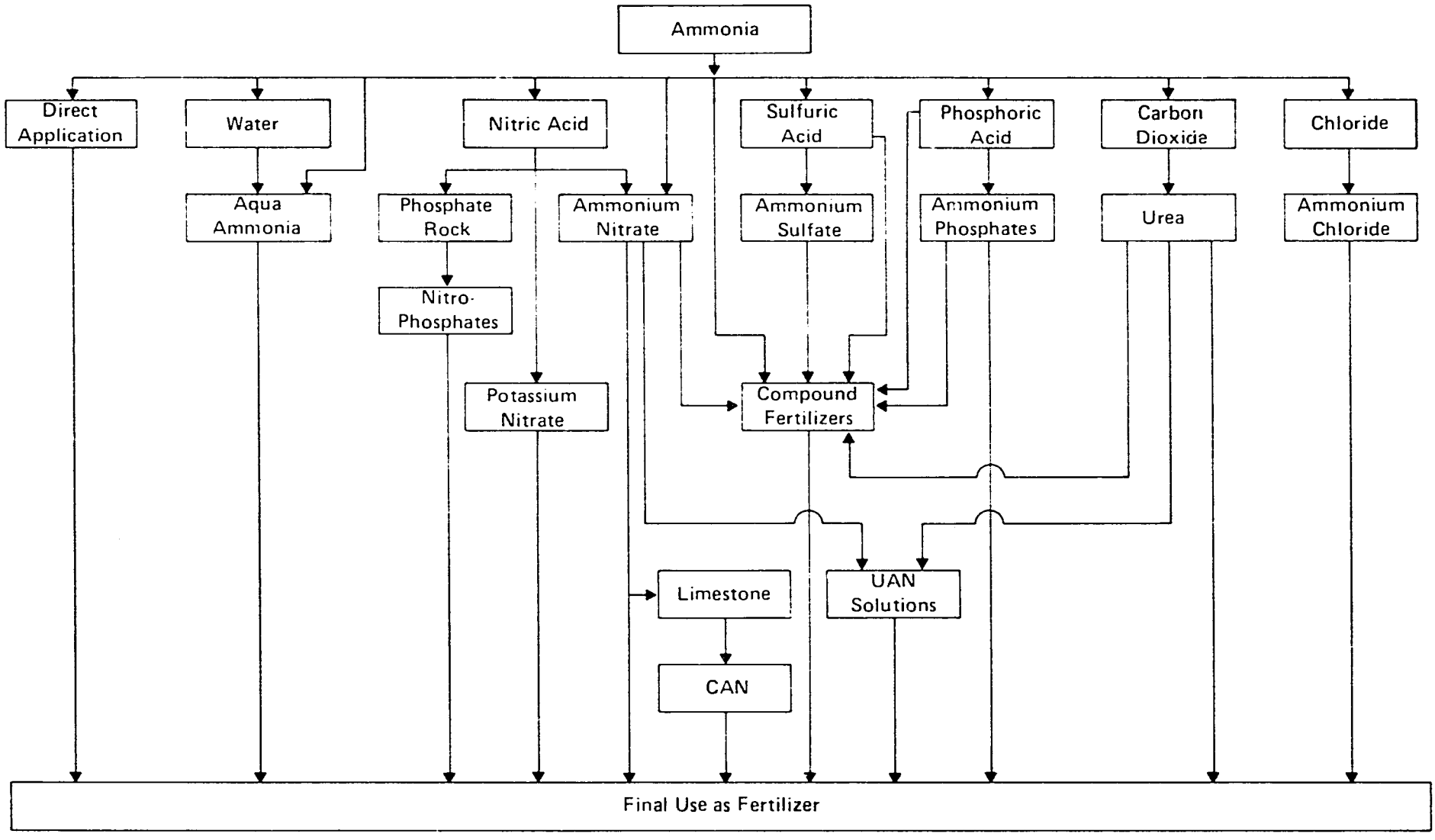


Figure C-11. Formulation of Alternative Nitrogen-Containing Chemical Fertilizers.

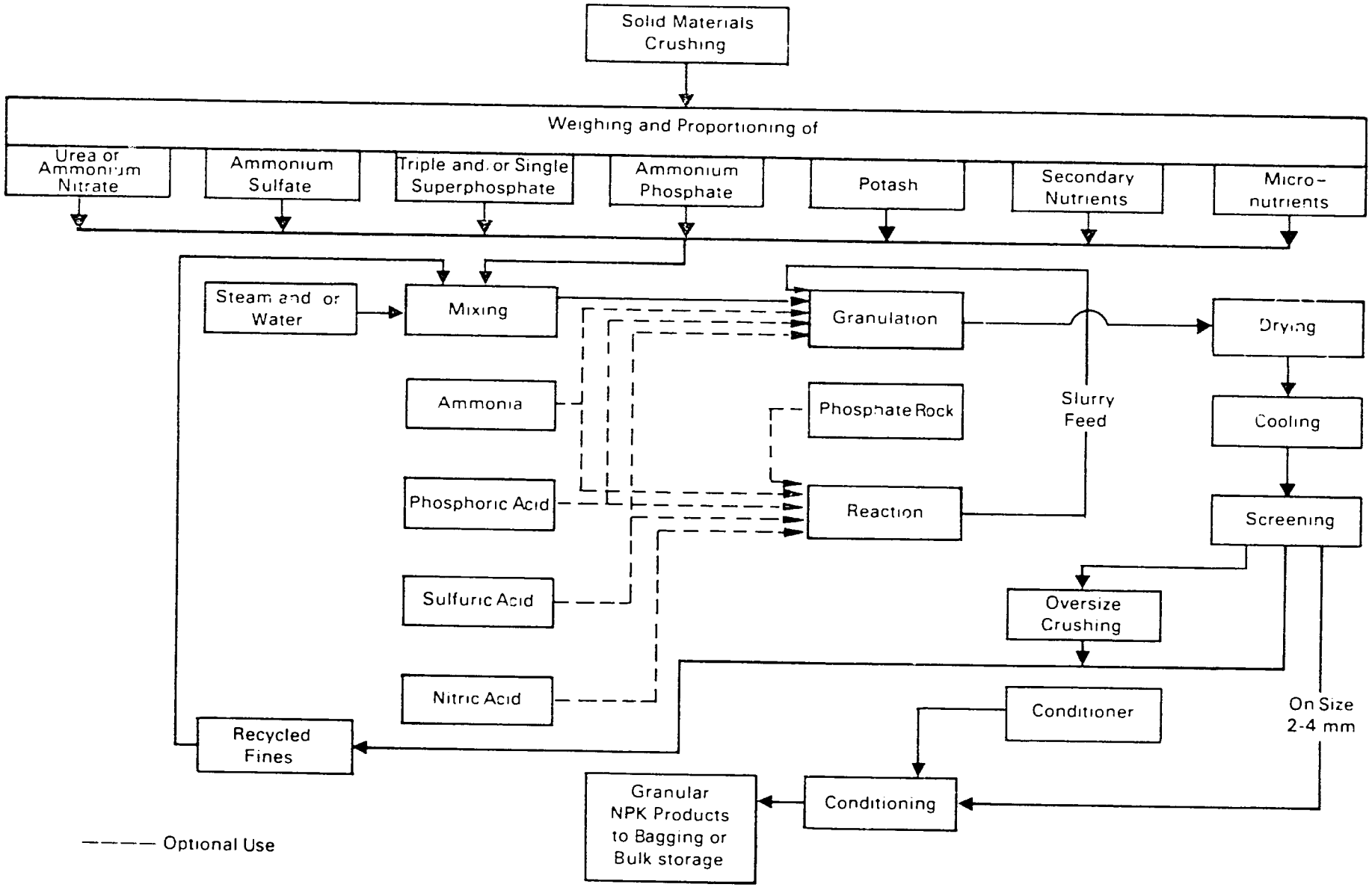
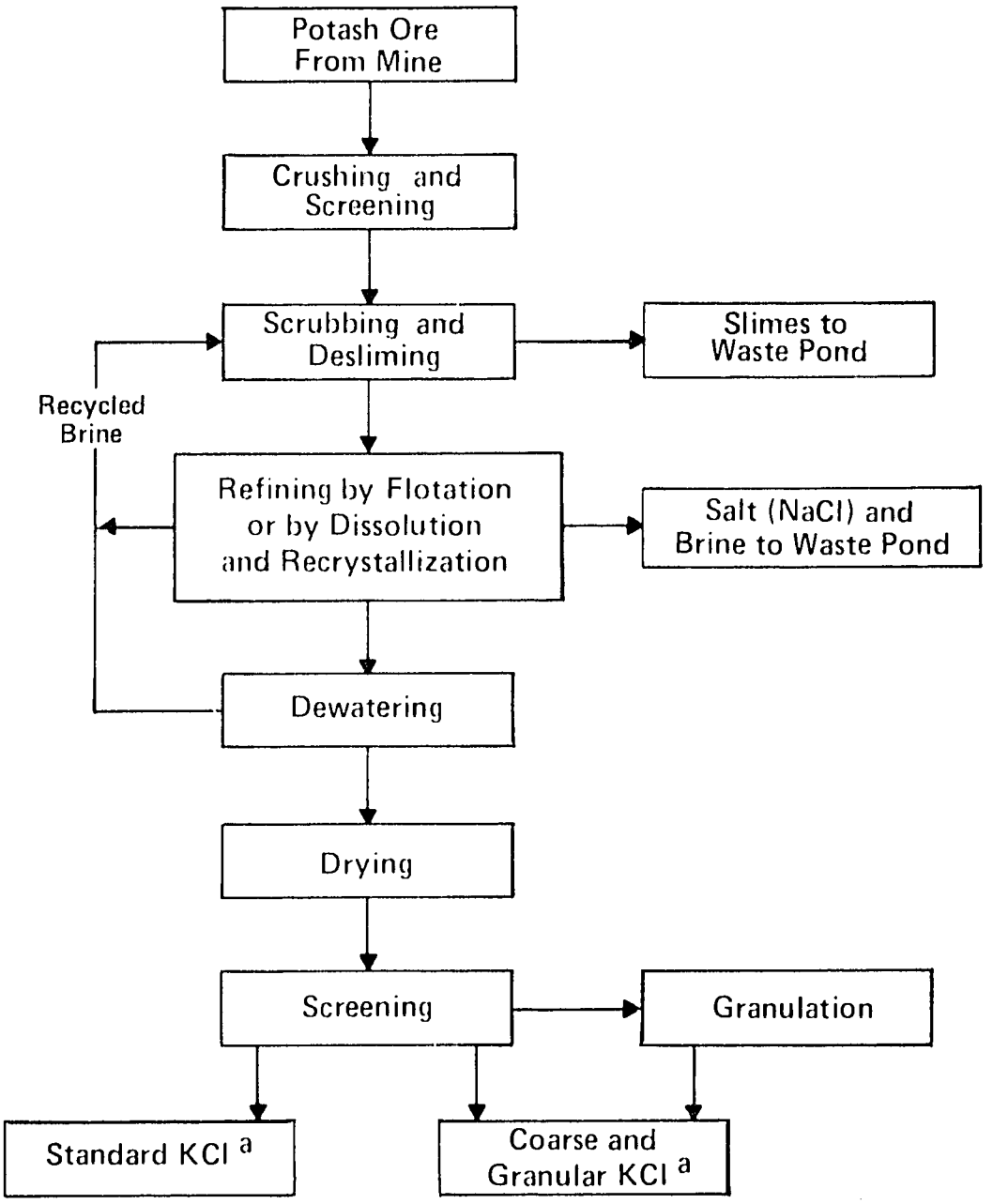


Figure C-12. General Diagram for Granular Compound Fertilizer Production.



[a]KCl=Muriate of Potash, 60%-62% K_2O

Typical Particle Sizes:		
	Standard	0.15-0.70mm
	Coarse	0.70-2.00mm
	Granular	1.00-3.30mm

Figure C-13. Typical Potash Refining Process.

GLOSSARY

Fertilizer Forms

Fertilizer--Broadly speaking, any material, organic or inorganic, natural or synthetic, that is placed on or incorporated in the soil to supply plants with one or more of the chemical elements necessary for normal growth. Since this study deals with commercial or "chemical" fertilizer, the term "fertilizer" is used to mean a manufactured product containing a substantial amount of one or more of the primary nutrients--nitrogen, phosphorus, and potassium--unless otherwise noted. The manufacturing process usually involves chemical reactions but may consist of refining or physically processing naturally occurring materials such as potassium salts or sodium nitrate.

Fertilizer Grade--The guaranteed nutrient content expressed in percentages of N, P_2O_5, and K_2O in that order. In most countries the grade, when used for commercial purposes, includes only that amount of nutrient found by prescribed analytical procedures, thereby excluding any nutrient present in a form that is deemed to be unavailable for plant nutrition. For example, a grade of "10-15-18" indicates a fertilizer containing 10% N, 15% P_2O_5, and 18% K_2O as found by prescribed analytical procedures.

Straight Fertilizer--A fertilizer containing only one of the three primary nutrients--nitrogen, phosphorus, or potassium.

Compound Fertilizer--A fertilizer that contains two or more of the primary nutrients. It may also contain secondary nutrients and micronutrients.

Mixed Fertilizer--Essentially synonymous with "compound fertilizer."

Complex Fertilizer--A compound fertilizer that is formed by mixing ingredients that react chemically, as opposed to a mechanical mixture of two or more fertilizers.

High-Analysis Fertilizer--A fertilizer containing a high percentage of nutrients, usually more than 30%.

Low-Analysis Fertilizer--A fertilizer containing a low percentage of nutrients, usually 30% or less.

Nitrophosphate--A complex fertilizer containing nitrogen and phosphorus made by a process of which one step consists of chemical reaction of nitric acid with phosphate rock. This material is also called "nitric phosphate."

Polyphosphates--Salts of polyphosphoric acids. In fertilizer parlance the salts usually are ammonium salts. Polyphosphate salts contain more than one phosphorus atom per molecule. The phosphorus atoms are linked to each other through oxygen atoms.

Fertilizer Intermediate--A manufactured fertilizer product, such as ammonia, phosphoric acid, or nongranular ammonium phosphate, that is intended primarily for further processing. Most of these "intermediates" can also be, and often are, used directly as fertilizers. For example, ammonia can be used directly as a fertilizer or used as an intermediate to make nitrogen fertilizers such as urea, ammonium nitrate, and ammonium phosphate.

Granular Fertilizers and Urea Forms

Granular Fertilizer--Fertilizer in the form of particles sized between an upper and lower limit or between two screen sizes, usually within the range of 1-4 mm, often more closely sized. In the United States, a common size specification is 6-16 or 7-14 mesh, Tyler (1.0-3.3 or 1.2-2.7 mm). In most other countries the preferred size is 2-4 mm (about 5-9 mesh, Tyler). In general, the term "granular" does not imply any particular means for preparing the sized material. The desired size may be obtained by agglomerating smaller particles; by crushing and screening larger particles; by control of crystal size in crystallization processes; by separating a screen fraction of crushed, beneficiated ore; or by prilling a material. However, it is often customary to specify the method by referring to the product as "prilled," "compacted," and "crystalline."

Prilled Urea--Urea in the form of near-spherical particles, usually about 1.0-2.5 mm in diameter, made by solidification of free-falling droplets in air. Ammonium nitrate and some compound fertilizers often are prilled.

Granular Urea--see granular fertilizer.

Forestry-Grade Urea--Coarse granular urea measuring 4-8 mm in mean diameter.

Urea Supergranules--Usually closely sized large granules with an average weight of 1, 2, or 3 g/granule. The mean diameter ranges from about 11 mm for 1-g granules to 17 mm for 3-g granules.

Urea Briquettes--Urea formed into shaped particles by pressure in a machine constructed for that purpose. The briquettes may be various shapes such as almond shape. Weight per briquette may be in the range of 1-3 g.

Urea Mudballs--Mudballs which measure 3-5 cm in diameter and contain approximately 1-3 g of urea. Mudballs are formed by hand. A thumb is inserted into the mudball and withdrawn. Urea is then placed in the thumb hole and covered.

Sulfur-Coated Urea--Urea granules (or prills) that have been coated with sulfur for the purpose of controlling the rate of dissolution in the soil. The sulfur coating is applied by spraying molten sulfur on the surface of the granules in specially designed equipment. After coating with sulfur a small amount of a wax-like sealant may be applied to seal pores or cracks in the sulfur coating, followed by a clay conditioner to make the product free flowing. A typical product contains about 80% urea (36.8% N), 16% sulfur, 2% sealant, and 2% conditioner.

Minigranules--Granules measuring approximately 0.15-0.5 mm, which is smaller than the usual size.

Energy Types

Chemical Energy--Energy released (or absorbed) by chemical reactions, usually in the form of heat but sometimes in the form of electrical energy, as in electrolysis.

Electrical Energy--Energy in the form of electricity which may be converted to mechanical, thermal, or chemical energy.

Mechanical Energy--Energy required to operate machinery such as compressors, pumps, conveyors, elevators, and cranes. Mechanical energy may be derived from electricity, steam, or fuel-fired engines.

Thermal Energy--Energy in the form of heat.

Commercial Energy--Refers to renewable or nonrenewable energy resources that are commercially produced, distributed, or traded. This includes fossil fuels; electricity; nuclear fuel; conversion of wind, water, and solar energy to mechanical or electrical energy; and conversion of forest products and agricultural wastes to solid or gaseous fuels.

Noncommercial Energy--Refers mainly to renewable energy resources that are not commercially produced, distributed, or traded. This includes crop residues, animal wastes, and wood when used as fuel.

Natural Gas--A gas consisting mainly of methane (a compound of carbon and hydrogen), which occurs in underground deposits. It originates from the decomposition of organic matter, mainly vegetation, which has been buried by geological action in prehistoric times. Natural gas usually contains small percentages of higher hydrocarbons such as ethane and various impurities--carbon dioxide, hydrogen sulfide, nitrogen, and sometimes helium. When used for commercial purposes, the gas is purified by removing carbon dioxide and hydrogen sulfide to prevent pipeline corrosion and toxic effects.

Formation of methane from decaying organic matter is a continuing process and occurs in swamps, deep lakes, sanitary landfills, and sewage treatment plants. However, the term "natural gas" is commonly limited to gas formed in previous geological eras. LNG is liquified natural gas. It is liquified by cooling to about -164°C.

Associated Gas--A term applied to natural gas that occurs in petroleum deposits. The gas may be dissolved in the petroleum at the high pressures that occur in deep deposits and is withdrawn with the petroleum from oil wells. When the pressure is released, methane and other gaseous hydrocarbons separate from the liquid portion of the petroleum. On the other hand, there are numerous deposits of natural gas that do not contain petroleum; this gas is called "nonassociated gas."

Petroleum Gases--Usually refers to hydrocarbons, other than natural gas, that are gases at atmospheric pressure and therefore separate from petroleum when the pressure is released. These gases include propane, butane, or a mixture of the two, which is separated from petroleum and later liquified by compression. Liquified petroleum gas (LPG) is transported under pressure for use as industrial or domestic fuel. LPG is also transported in nonpressure vessels when cooled to about -30°C. When used as a domestic fuel delivered in steel cylinders, it is sometimes called "bottled gas." Ethane is also a petroleum gas which may be allowed to remain in the "natural gas" or it may be separated for use as a chemical feedstock where there is a demand for it.

Refinery Gas--Commonly refers to gaseous products from petroleum refining. Its composition may vary widely depending on the refining process and the type of petroleum. However, it usually contains a high percentage of hydrogen and smaller percentages of gaseous hydrocarbons.

Coke-Oven Gas--Gas that is evolved when coal is converted to coke in a byproduct coke oven. The main gaseous components are hydrogen, methane, and carbon monoxide. It also contains numerous condensable hydrocarbons, such as benzene and tar, which are removed by refining and used to make a wide range of chemicals. Coke-oven gas also contains a small percentage of ammonia which is recovered during refining, usually in the form of ammonium sulfate, and sold for fertilizer use.

Petroleum and Industrial Liquids

Liquid Petroleum Products--A range of liquid hydrocarbon products that are derived from refining of petroleum. These products are used mainly as fuels but also as chemical feedstocks and lubricants. They are commonly classified by weight (specific gravity or density), although they also vary in volatility, viscosity, purity, and other respects. The primary method of refining is distillation. As petroleum is heated the more volatile liquids are vaporized first and collected by condensation. The result is a range of liquids that include, in approximate order of increasing density, naphtha, kerosene, jet fuel, diesel fuel, and fuel oils numbered from 1 (lightest) to 6 (heaviest).

Since the lightest liquids are the most valuable, a variety of refining processes other than simple distillation are used to maximize the yield of lighter fractions. These processes include "cracking" (splitting large molecules into smaller ones) and hydrogenation.

Crude Oil--A term applied to unrefined petroleum.

Fuel Oils--Fuel oils refer to liquid fuels derived from petroleum. The following table shows typical specific gravities and heating values of several grades. No. 4 oil is widely used as fuel for drying or calcining phosphate rock or drying fertilizers when natural gas is not available. No. 6 oil has a high viscosity and can be used only when facilities for preheating it are available. It is likely to contain 2% or more sulfur; therefore, pollution control facilities may be required when it is burned to generate steam or electricity. No. 6 oil is commonly used to drive oceangoing ships, and it is also used as feedstock in some ammonia plants.

Heating Value and Specific Gravity of Typical Liquid Fuels Derived From Petroleum

Liquid Fuels	Specific Gravity	Heating Value (HHV) Btu/lb	Btu/U.S. gal	GJ/U.S. gal
Motor fuels[a]				
Gasoline	0.70-0.74	20,360	119,000-126,000	0.126-0.133
Kerosene	0.82	19,750	135,150	0.143
No. 1 diesel	0.87	19,240	139,700	0.145
No. 2 diesel	0.92	19,110	146,700	0.155
No. 4 diesel	0.96	18,830	150,600	0.159
Fuel oils[b]				
No. 1	0.83	19,940	137,000	0.145
No. 2	0.87	19,570	141,000	0.149
No. 4	0.93	18,900	146,000	0.154
No. 5	0.95	18,650	148,000	0.156
No. 6	0.99	18,265	150,000	0.158

a. R. E. Bolz and G. L. Tuve (Eds.). 1973. Handbook of Applied Engineering Science. C.R.C. Press, Cleveland, Ohio.
b. G. R. Fryling. 1967. "Combustion Engineering," Combustion Engineering, Inc., 227 Park Avenue, New York, New York 10017.

Naphtha--The lightest liquid product and also the purest and most expensive. Its specific gravity is about 0.686. It is widely used for making gasoline, for making plastics such as polyethylene and polypropylene by cracking and polymerization, and for making ammonia.

Fertilizer Manufacturing Terms

Beneficiation--Treatment of an ore to separate the desired mineral from worthless minerals, usually by physical means. As applied to phosphate ores, beneficiation is a treatment or series of treatments that separate the phosphate-containing mineral from other minerals such as sand and clay.

Calcining--Heating of a mineral, e.g., phosphate rock, to expel volatile and combustible ingredients such as combined water, carbon dioxide, and organic matter.

Electric-Arc Process (for producing nitrogen fertilizer)--A process in which air is passed through an electric arc (an electrical discharge between two or more electrodes), thereby causing some of the nitrogen and oxygen in the air to combine to form nitric oxide. The air containing nitric oxide (a gas) is cooled, and the nitric oxide is converted to nitric acid by reaction with water and some of the oxygen remaining in the air. The nitric acid usually is used to make calcium nitrate fertilizer by reaction with limestone; it can also be used to make sodium nitrate by reaction with soda ash (sodium carbonate) or for making various military or industrial chemicals.

Electrolysis and Electrolytic Hydrogen--Basically, the separation of a compound into its elements by passing an electric current through the compound or a solution containing it (electrolysis). Water is separated into its elements--hydrogen and oxygen--by passing an electric current through the water in an electrolytic cell. A soluble chemical (usually caustic potash) is added to the water to make it electrically conductive, but the additive does not participate in the reaction. Direct current must be used. The hydrogen is collected at one electrode and oxygen at the other. The hydrogen produced by electrolysis can be used to make ammonia by combining it with nitrogen that is extracted from air. Electrolytic hydrogen also is produced as a byproduct when a salt (sodium chloride) solution is electrolyzed to produce caustic soda and chlorine.

Haber-Bosch Process--A process for producing ammonia by reaction of hydrogen and nitrogen in the presence of a catalyst at elevated temperature and pressure. Since the reaction is incomplete, the process involves separation of the ammonia from the unreacted gaseous mixture of hydrogen and nitrogen and recycling the mixture to the catalytic reactor. The term does not imply any specific method for producing the hydrogen and nitrogen for the process.

Cyanamide Process--A process for making a nitrogen fertilizer consisting mainly of calcium cyanamide. The process involves production of calcium carbide from coke and burned lime in an electric furnace. The calcium carbide is crushed and then reacted with pure nitrogen at elevated temperature. The resulting product contains calcium cyanamide together with some impurities and may be applied directly to the soil as a fertilizer. Alternatively, it may be further processed to make ammonia.

Centrifugal Compressor--A machine that compresses gases by means of centrifugal force.

Reciprocating Compressor--A machine that compresses gases by means of pistons.

Cryogenic Recovery of Hydrogen (from ammonia plant purge gas)--Separation of hydrogen from other gases (mainly argon and methane) by cooling to a very low temperature at which argon and methane are converted to liquids.

Steam Stripping--A method for removing volatile ingredients such as ammonia from water or other solvent by contacting the solution with steam in equipment designed for that purpose.

IDR (Isobaric Double Recycle)--A process in which most of the unreacted ammonia and carbon dioxide are separated from the urea solution in two steps at the same high pressure as the reactor and recycled to the reactor thereby avoiding the need for energy for compression. In all urea manufacturing processes, ammonia and carbon dioxide react at high temperature and pressure, but the reaction is incomplete. Therefore, the urea must be separated from the remaining reactants which are recycled.

OTEC (Ocean Thermal Energy Conversion)--Generation of electricity from temperature difference in ocean water at different depths. The surface of ocean water is warmed by solar radiation. The warm water tends to remain near the surface while cold water (which is heavier) remains at greater depth. Thus there may be as much as 25°C difference between the upper and lower levels of ocean water in some locations near the equator. This temperature difference can be converted to electricity by a bimetallic circuit with one junction in a stream of cold water and the other in the warm water. The electricity is generated as direct current at relatively low voltage; therefore, it is well suited for use in electrolysis.

Exothermic Reaction--A chemical reaction that generates energy, usually as heat.

Endothermic Reaction--A chemical reaction that absorbs energy. The required energy may be supplied as heat or by electricity as in electrolysis.

Rankine Cycle--In general, it refers to a method for converting thermal energy (heat) to mechanical or electrical energy. The method consists of alternately vaporizing and condensing a fluid. The fluid is vaporized and optionally superheated at a relatively high pressure and temperature, absorbing heat. The vapor under pressure is used to drive an engine (such as a turbine) which may drive an electric generator. The vapor leaving the turbine is cooled and condensed to a liquid at a relatively low temperature and pressure. The condensed liquid is then pumped back to the vaporizer, completing the cycle. In the most common example of the Rankine cycle, the liquid is water and the vapor is steam. However, the water-steam cycle requires a high temperature for efficient conversion of heat to electrical energy. In the example cited in the study (Van Weenan and Tielrooy, 1980), the liquid is trichlorofluomethane, which vaporizes at a lower temperature than water and therefore is capable of utilizing waste heat at a lower temperature level.

Neutralizer--A vessel or device in which an acid reacts with an alkaline chemical. Usually, in fertilizer technology, a vessel in which ammonia reacts with phosphoric, sulfuric, or nitric acid.

Hemihydrate Process--A process for producing phosphoric acid in which the byproduct calcium sulfate forms crystals containing one-half molecule of water for each molecule of calcium sulfate. Hemihydrate processes operate at a higher temperature than dihydrate processes and produce a more concentrated phosphoric acid.

Dihydrate Process--A process for making phosphoric acid in which the byproduct calcium phosphate forms crystals containing two molecules of water for each molecule of calcium sulfate (commonly called "gypsum").

Slurry Process--A process in which a fertilizer is first produced as a slurry (a fluid mixture of solids and solution). The slurry is further processed to a solid by drying and granulation.

Den Process--A process for the manufacture of superphosphate in which phosphate rock is mixed with sulfuric acid and the mixture, while still fluid, is transferred to a fixed or movable container called a "den." The mixture is retained in the den for a period of time ranging from 20 minutes to 2 hours during which time the mixture solidifies and hardens due to chemical reactions. The mixture is then removed from the den as a damp solid to storage or further processing.

Falling Curtain Process--A process for granulating urea (and possibly other fertilizers) in which molten urea is sprayed on a cascading stream of solid urea particles thereby increasing their size to that desired. The process takes place in a specially constructed rotating drum. Seed particles of solid urea are added as necessary and undersized granules are recycled.

Pipe-Cross Reactor--A process for making fertilizers containing ammonium phosphate and ammonium sulfate in which phosphoric acid, sulfuric acid, and ammonia are injected continuously into a pipe where they react at high temperature forming a melt and water vapor. The melt is discharged into a granulator where it is granulated with addition of potash, if desired, and the water vapor is swept out of the granulator by an airstream. The main advantage of the process is the utilization of the heat of reaction rather than fuel for making a dry, granular fertilizer.

Mining Techniques

Frasch Mining--A method for recovering sulfur from underground deposits by pumping superheated water into the deposit to melt the sulfur which is then pumped to the surface. The hot water is pumped into the deposit through an "injection well" and molten sulfur is recovered from the same well while the water, after passing through the sulfur-bearing formation, is removed through one or more "bleed wells."

Shaft Mining--A method for mining underground deposits by constructing one or more shafts (usually vertical) to provide access to the deposit for men and machines to extract the ore. The shafts also are used to hoist the ore to the surface for further processing.

Solution Mining--A method for mining water-soluble underground ores, such as potash, by injecting water or brine into the deposit through a well. The water dissolves potash salts, and the resulting solution is withdrawn from another well. The injected water usually is heated to increase the solubility and to provide a more concentrated solution.

Fixation of Nitrogen

Nitrogen Fixation--Conversion of uncombined (elemental) nitrogen from the atmosphere into a compound of nitrogen by causing the nitrogen to combine with other elements.

Biological Fixation of Nitrogen--Fixation of atmospheric nitrogen by living organisms.

Symbiotic Fixation of Nitrogen--Fixation of atmospheric nitrogen by micro-organisms (bacteria or algae) which live in symbiotic relationship with the plants. These micro-organisms supply nitrogen to the plants. These organisms, on the other hand, receive nutrition and energy from the plant in the form of carbohydrates.

Asymbiotic Fixation of Nitrogen--Fixation of nitrogen by micro-organisms in soils or water without any direct association with plants.

Rhizobia--Bacteria found in nodules on the roots of certain plants (normally legumes) that are capable of fixing atmospheric nitrogen.

Ozonization--Conversion of oxygen molecules (O_2) in air to ozone (O_3) in the earth's upper atmosphere by solar radiation. The "ozone layer" of the earth's atmosphere begins at a height of 8-10 miles above the earth's surface. Ozone is a highly reactive form of oxygen, and it is known that oxides of nitrogen (NO and NO_2) are formed in the ozone layer although there is some uncertainty as to what reactions occur. The oxides of nitrogen react further with oxygen and moisture and eventually reach the earth's surface as nitrates or nitrites dissolved in rainwater.

Nitrogen Loss Mechanisms

Volatilization--Generally, refers to conversion of a liquid to a gas. As used in this study it refers to loss of nitrogen from the soil or floodwater (in flooded rice field) due to volatilization of ammonia that is formed by chemical changes of nitrogen fertilizers (urea or ammonium salts) in the soil or floodwater.

Nitrification--Conversion of nitrogen compounds in the soil to nitrates by microbiological processes. The term usually refers to soil reactions that convert nitrogen, originally applied as urea or ammonium salts, to nitrates. However, the nitrogen in organic compounds is also subject to nitrification. Nitrification occurs only when there is a supply of oxygen, such as from the air. Nitrification usually is beneficial since most crops prefer to take up soil nitrogen in the nitrate form.

Denitrification--Conversion of nitrates to nitrites and ultimately to elemental nitrogen and nitrous oxide in the soil. Flemental nitrogen and nitrous oxide are gases which are lost to the atmosphere. The reaction occurs only in anaerobic conditions (absence of oxygen) such as in waterlogged soil.

Miscellaneous Terms

Biomass--Generally refers to nonfossil organic matter, such as wood, straw, leaves, and manure, derived from plants and animals.

Caprolactam--An organic chemical that is used to produce nylon.

Cultivar--A specific variety of a cultivated crop.

Feedstock--A raw material used for manufacturing a product, such as ammonia or plastic film and fiber used for making bags. The term usually is applied to raw materials derived from petroleum or coal.

Filter Acid--As used in this study, it refers to phosphoric acid (usually 28%-30% P_2O_5) derived directly from the filtration step as opposed to acid that has been concentrated by evaporation.

Atmospheric Pressure--The pressure exerted by the earth's atmosphere, which is about 14.7 psi at sea level.

Battery Limits--A term used to define an operational unit within a manufacturing plant, usually for the purpose of defining the responsibility of the engineering and construction firm which supplies that unit.

Fertilizer Capacity--The amount of fertilizer that a fertilizer plant or a group of plants is presumed to be capable of producing when not limited by market demand, supply of raw materials, technical difficulties, or extraneous factors. Capacity may be expressed in mtph, mtpd, or mtpy. Annual capacity usually is considered to be 330 times daily capacity. When part of the output is used for nonfertilizer purposes, the fertilizer capacity is the total capacity less the estimated nonfertilizer use.

Economy of Scale--The extent to which the cost per unit of output of an operation such as fertilizer manufacturing can be lowered by increasing plant size.

Law of Diminishing Returns--The input-output relationship that for a given fertilizer response function each successive additional unit of fertilizer use results in a relatively smaller amount of incremental crop yield.

Law of Interaction--The principle of interaction refers to the relationship among a given set of plant nutrients and their impact on crop yield. For example, positive interaction implies that the additional crop yield in response to an application of a given amount of N and P_2O_5 applied together is more than the sum of additional crop yields when these nutrients are applied separately.

Law of the Minimum--The concept that crop growth is limited by that nutrient which is in minimum supply relative to crop needs. Application of nutrients other than the most deficient is ineffective in increasing crop yields unless the deficiency is remedied. For example, crops may respond poorly or not at all to nitrogen when phosphorus is extremely deficient. There are 13 elements that are essential to plant growth (not including those supplied by air and water), and deficiency of any one of them can limit crop yields. The law of the minimum may be expanded to include other crop growth factors such as moisture, light, and temperature.