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Feeding fossil fuels to the soil An analysis of energy embedded and technological learning in the fertilizer industry

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Abstract

In this paper, we assess energy demand due to fertilizer consumption in the period 1961–2001. Based on historical trends of gross energy requirements, we calculated that in 2001, global energy embedded in fertilizer consumption amounted to 3660 PJ, which represents about 1% of the global energy demand. Total energy demand has increased at an average rate of 3.8% p.a. Drivers behind the trend are rising fertilizer consumption and a shift towards more energy intensive fertilizers. Our results show that despite significant energy efficiency improvements in fertilizer manufacture (with exception of phosphate fertilizer in the last 20 years) improvements in energy efficiency have not been sufficient to offset growing energy demand due to rising fertilizer consumption. Furthermore, we found that specific energy consumption of ammonia and urea developed in close concordance with the learning curve model, showing progress ratios of 71% for ammonia production and 88% for urea. This suggests an alternative approach for including technological change in energy intensive industries in middle and long-term models dealing with energy consumption and CO₂ emissions, while few learning curves exist for energy efficiency of end use technologies.

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Keywords: Fertilizer industry; Energy analysis; Learning curve

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1. Introduction

The growth of fertilizer use is an integral part of the technological revolution in agriculture that has generated major changes in production techniques, shifts in inputs and growth in output and productivity. Although several fertilizers have been known for over a century (e.g. superphosphate production by treatment of ground bones with sulfuric acid was patented in 1842), it is only in the last 50 years that growth in fertilizer consumption has really taken place (Fig. 1). In the year 2001, about 137 million tonnes of fertilizer nutrients were applied around the world. The growth in agricultural production has been enabled by the growth of yields that has been accompanied by an increasingly intensive use of land (FAO, 2000). With higher yields normally demanding higher fertilizer application rates, and with this trend expecting to continue for the next 30 years, debate is also intensifying over the interactions between increasing fertilizer application and the effects on ecosystem stability, biodiversity and processes of climate change.

Several analyses of the energy embedded in fertilizers can be found in literature, especially in the late 1970s and early 1980s (e.g. Achorn and Salladay, 1982; Disney and Aragan, 1997; Hignett and Mudahar, 1982; Honti, 1976; Lockeretz, 1980) when higher energy prices affected the price and supply of fertilizers. Interest in the topic seemed, however, to have decreased with the fall in energy prices. Only, from the beginning of the 1990s concern for climate change (related with the high use of fossil fuels needed to produce fertilizers) increased again the attention to energy consumption and energy efficiency in fertilizer production (Worrell and Blok, 1994). This also included the indirect energy use due to increase fertilization has proven to be a determining factor on calculating the net available energy benefits of biofuels (e.g. Pimentel, 2001; Patzek, 2004; Worrell et al., 1995).

If the interactions between fertilizer application and climate change are to be better understood, there is a need for studies that analyze the role that different factors (e.g. energy efficiency, increasing fertilizer consumption) have played in the development of energy use. There is, however, a remarkable lack of this kind of studies. In this context, the purpose of this paper is two-fold. First, to analyze the impact of improvements in energy efficiency during the manufacture of fertilizers in world energy demand (due to increased fertilizer

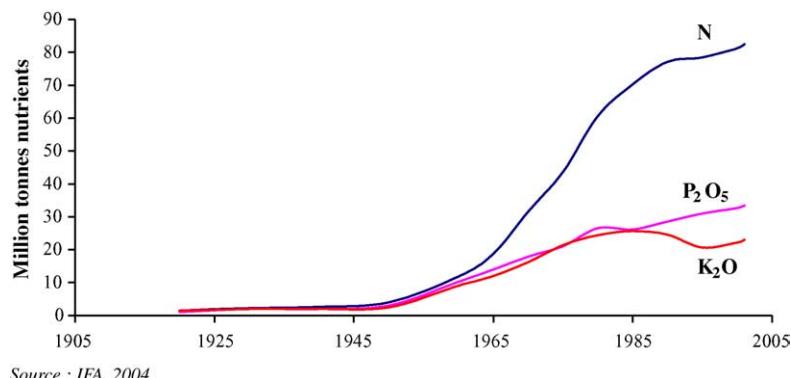


Fig. 1. Historical trends of world fertilizer consumption. Source: IFA, 2004.

Table 1
Composition of important fertilizers

Product	As percentage of final product (mass)		
	Nitrogen [N]	Phosphorus [P ₂ O ₅]	Potassium [K ₂ O]
Nitrogen fertilizers			
Ammonia	82	0	0
Ammonium sulphate	21	0	0
Ammonium nitrate	33–35	0	0
Calcium ammonium nitrate	25	0	0
Urea	46	0	0
Phosphate fertilizers			
Single superphosphate	0	16–20	0
Triple superphosphate	0	46	0
Monoammonium phosphate	11	52	0
Diammonium phosphate	18	46	0
Potash fertilizers			
Muriat of potash (potassium chloride)	0	0	60
Sulfate of potash	0	0	50
Complex fertilizers			
NP	15–25	15–25	0
NK	13–25	0	15–46
NPK	5–25	5–25	5–25

consumption), and second, to examine technological learning in the fertilizer industry. The paper is composed of two parts. In the first part, we develop historical trends of gross energy requirements by kind of fertilizer and assess the energy demand embedded in fertilizer consumption for the time period 1961–2001. Furthermore, we examine the role of fertilizer consumption, fertilizer mix and changes in energy efficiency in total energy demand. In the latter part, we explore whether technological development in the fertilizer industry can be analyzed using the concept of learning or experience curve to study energy efficiency development in the fertilizer industry.

2. Methodology

In this paper, energy and mass balances are made for the following fertilizers (see also Table 1): ammonia, ammonium nitrate (AN), calcium ammonium nitrate (CAN), urea, single superphosphate (SSP), triple superphosphate (TSP), mono-ammonium phosphate (MAP) and diammonium phosphate (DAP), muriat of potash (potassium chloride), PK 22-22 and complex fertilizers (NPK). In 2001, these fertilizers accounted for 83% of total nitrogen,¹ 91% of total phosphates, and 96% of total potash consumed in the world.

We distinguish between specific energy consumption (SEC) and gross energy requirement (GER). SEC is defined as the amount of energy used (as fuel, heat, electrical or

¹ The other 17% is made up by nitrogen solutions, calcium nitrate, sodium nitrate, ammonium chloride, calcium cyanamide and ammonium bicarbonate.

mechanical energy) to produce one unit of product. GER is defined as the amount of energy, which is sequestered by the process, including energy to produce the raw materials in the course of the production of a specific process (Worrell and Blok, 1994). For instance, we define the SEC of ammonium nitrate as the amount of electricity, heat and fuels used to convert ammonia and nitric acid to 1 tonne of AN, while the GER also includes the energy (electricity, heat and fuels) used to produce ammonia and nitric acid. In our analysis, we do not include the energy use for transportation of raw materials and distribution of fertilizers. The analysis of GER can be understood as a simplified LCA of the fertilizer industry focusing on energy use. Historical developments of SEC by product were calculated in this paper using fossil fuel and electricity data gathered from literature. GER were calculated using the SEC trends and literature data on input efficiencies by process. All energy data is expressed in lower heating value (LHV). We use metric units throughout this study.

Energy consumption is analyzed at the process boundary, and adjusted to a primary fuel equivalent basis. The primary fuel equivalent energy requirement of electricity was calculated based on historical efficiency development of power plants. Where steam data is given, energy values are converted into primary fuel assuming 85% boiler efficiency.

In order to single out the influence of increasing fertilizer consumption, changes in the mix of fertilizers use and changes in energy efficiency during fertilizer manufacturing on the total energy embedded in fertilizer consumption, we apply a statistical decomposition methodology. Statistical decomposition allows us to “give quantitative measures of the relative contributions of a set of pre-defined factors leading to the change in the aggregate indicator” (Ang and Liu, 2001) [for a detailed overview of the existing methodologies, see Ang and Zhang (2000)]. The method used in this paper is known as the log-mean divisia index method I (see Eqs. (1)–(6)).

$$D_{\text{tot}} = \frac{E_t}{E_0} = D_{\text{cons}} D_{\text{str}} D_{\text{int}} \quad (1)$$

$$D_{\text{cons}} = \exp \left\{ \sum_i \omega_i(t^*) \ln \left(\frac{Y_t}{Y_0} \right) \right\} \quad (2)$$

$$D_{\text{str}} = \exp \left\{ \sum_i \omega_i(t^*) \ln \left(\frac{S_{i,t}}{S_{i,0}} \right) \right\} \quad (3)$$

$$D_{\text{int}} = \exp \left\{ \sum_i \omega_i(t^*) \ln \left(\frac{I_{i,t}}{I_{i,0}} \right) \right\} \quad (4)$$

$$\omega_i(t^*) = \frac{L(E_{i,0}, E_{i,t})}{L(E_0, E_t)} \quad (5)$$

where

$$L(x, y) = \frac{y - x}{\ln(y/x)} \quad (6)$$

D_{tot} is the total change in energy embedded due to fertilizer consumption; D_{int} the effect of changes in energy efficiency during fertilizer manufacture; D_{str} the effect of changes in

fertilizer mix; D_{cons} the effect of increasing consumption of fertilizers; E_t the total primary energy consumption of fertilizer industry in year t , in Gigajoules; $E_{i,t}$ the energy consumption due to fertilizer i in year t , in Gigajoules; Y_t the total fertilizer consumption in year t ($=\sum Y_{i,t}$), in tonnes; $Y_{i,t}$ the consumption of fertilizer i in year t , in tonnes; $S_{i,t}$ the consumption share of fertilizer i in year t ($=Y_{i,t}/Y_t$); $I_{i,t}$ is the energy efficiency of manufacturing fertilizer i ($=E_{i,t}/Y_{i,t}$), in Gigajoules per tonne.

To analyze technological development in energy efficiency, we make use of the experience or learning curve concept. An experience curve provides a simple quantitative way of understanding technological progress. An experience curve is in essence “a relation between one of several, substitutable inputs and cumulative output” (IEA, 2000, p. 26). It most often is described by an exponential relationship between an input A and the cumulative output Z (Eq. (7)). The parameter b defines the slope of the curve and is generally referred to as the experience index. The progress ratio (PR) and the learning rates (LR) are calculated according to Eqs. (8) and (9). PR is the level at which input falls each time the cumulative output doubles. For instance, a PR of 85% (LR = 15%) implies that the input falls to 85% of its previous level for each doubling of cumulative output. Most published material on learning or experience curves relates costs to the cumulative production or use of a technology (e.g. Spence, 1981; Lieberman, 1989; Gruber, 1992; Junginger et al., 2005). However, in this paper, we relate specific energy consumption values to the cumulative production of the fertilizer. By analogy, our experience curve can be expressed as Eq. (10).

$$A = cZ^b \quad (7)$$

$$\text{PR} = 2^b \quad (8)$$

$$\text{LR} = 1 - 2^b \quad (9)$$

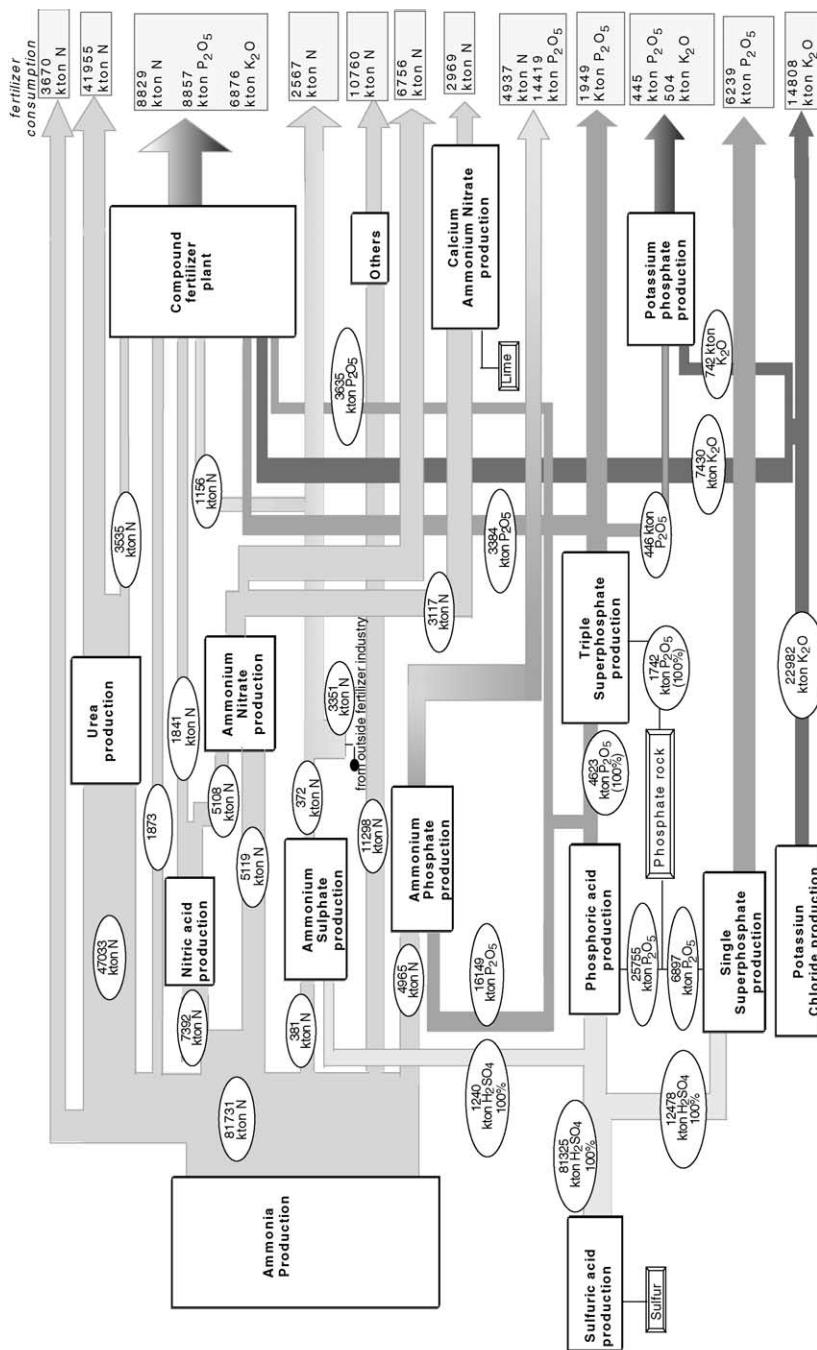
$$\text{SEC}_i = \text{SEC}_{i,0} \times \text{CP}^b \quad (10)$$

where SEC is the specific energy consumption of product i ; $\text{SEC}_{i,0}$ the specific energy consumption of the first unit produced; CP the cumulative unit production and b is the experience index.

3. The fertilizer sector

The fertilizer sector is defined here as the chemical or physical transformation of raw materials into mineral fertilizers. Table 1 shows typical compositions of main fertilizer products in terms of three major nutrients: nitrogen, phosphorus and potassium.² Departing from world fertilizer consumption figures published by the International Fertilizer Association (2004) and input efficiencies by process, we have calculated nutrients flows for the year 2001 (Fig. 2). This figure illustrates the importance of ammonia in the fertilizer industry. A brief description of the processes named in Fig. 2 is given in Table 2. For

² Nitrogen is essential for growth and development in plants. Phosphorous is vital for adequate root development while potassium is central to the translocation of photosynthesis and for high yielding crops.



Note: This balance does not include the following fertilizer categories: basic slag, ground phosphate rock, dicalcium phosphate, phosphoric acid (applied direct), potassium magnesium sulphat and crude potash salts. They account for about 2% of the total nutrient consumed in the year 2001. The category named "Others" include: nitrogen solutions, calcium nitrate, sodium nitrate, ammonium chloride, calcium cyanamide, ammonium bicarbonate. We have assumed the following routes for the processing of compound fertilizers: 40% based on ammonium nitrate, phosphoric acid and potassium chloride, 40% from urea, triplesuperphosphate and potassium chloride. We also assumed that only 10% of the Ammonium sulfate is produced in the fertilizer industry, the rest is a by-product of caprolactam production and gas scrubbing.

Fig. 2. Global nutrient flows, 2001.

Table 2
Brief descriptions of production processes by kind of fertilizer

Product	Description	Main reactions	
Ammonia (NH_3)	Produced by the reaction between hydrogen and nitrogen at high pressure (Haber process). There are two main stages: the reforming stages (first and second reformer) and the converting stage (ammonia synthesis). Between these two stages, carbon monoxide is converted into carbon dioxide and removed from the process	$\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2$ } $\text{CH}_4 + 2\text{H}_2\text{O} \rightarrow \text{CO}_2 + 4\text{H}_2$ $2\text{CH}_4 + \text{O}_2 \rightarrow 2\text{CO} + 4\text{H}_2$ } $\text{CH}_4 + \text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2$ $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$ } $\text{N}_2 + 3\text{H}_2 \rightarrow 2\text{NH}_3$ }	Primary reformer
Urea (NH_2CONH_2)	Produced by reacting ammonia and carbon dioxide	$2\text{NH}_3 + \text{CO} \rightarrow \text{NH}_4\text{COONH}_2$ $\text{NH}_4\text{COONH}_2 \rightarrow \text{NH}_2\text{CONH}_2 + \text{H}_2\text{O}$	Secondary reformer
Nitric acid (HNO_3)	Produced by the oxidation of ammonia	$4\text{NH}_3 + 5\text{O}_2 \rightarrow 4\text{NO} + 6\text{H}_2\text{O}$ $2\text{NO} + \text{O}_2 \rightarrow 2\text{NO}_2$ $3\text{NO}_2 + \text{H}_2\text{O} \rightarrow 2\text{HNO}_3 + \text{NO}$	Water–gas shift Ammonia synthesis
Ammonium nitrate (NH_4NO_3)	Produced by reacting ammonia with nitric acid	$\text{NH}_3 + \text{HNO}_3 \rightarrow \text{NH}_4\text{NO}_3$	
Calcium ammonium nitrate ($\text{Ca}(\text{NO}_3)_2$)	Produced by mixing slurry of ammonium nitrate with a filler containing ground dolomite, ground limestone or with byproduct calcium carbonate	$2\text{NH}_4\text{NO}_3 + \text{CaCO}_3 \rightarrow \text{Ca}(\text{NO}_3)_2 + 2\text{NH}_3 + \text{CO}_2 + \text{H}_2\text{O}$	
Sulfuric acid (H_2SO_4)	Produced by the oxidation of sulfur	$\text{S} + \text{O}_2 \rightarrow \text{SO}_2$ $\text{SO}_2 + 1/2\text{O}_2 \rightarrow \text{SO}_3$ $\text{SO}_3 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4$	

Table 2 (Continued)

Product	Description	Main reactions
Ammonium sulfate ((NH ₄) ₂ SO ₄)	It is mainly a byproduct from manufacture of caprolactam and acrylonitrile, scrubbing coke oven gas or from other processes. It can also be produced directly by neutralizing ammonia with sulfuric acid or from a solution, which is obtained	2NH ₃ + H ₂ SO ₄ → (NH ₄) ₂ SO ₄
Phosphoric acid (H ₃ PO ₄) ^{a,b}	Produced from the reaction of phosphate rock and sulfuric acid	3Ca ₃ (PO ₄) ₂ ·CaF ₂ + 10H ₂ SO ₄ + 20H ₂ O → 10CaSO ₄ ·2H ₂ O + 2HF + 6H ₃ PO ₄
Superphosphates	Produced by reacting phosphate rock and sulfuric acid (single superphosphate) or phosphoric acid (triple superphosphate)	Ca ₁₀ F ₂ (PO ₄) ₆ + 7H ₂ SO ₄ + H ₂ O → 2HF + 3Ca(H ₂ PO ₄) ₂ ·H ₂ O + 7CaSO ₄ } SSP Ca ₁₀ F ₂ (PO ₄) ₆ + 7H ₃ PO ₄ + 10H ₂ O → 2HF + 10Ca(H ₂ PO ₄) ₂ ·H ₂ O} TSP
Ammonium phosphate	Produced by neutralizing phosphoric acid with ammonia	2NH ₃ + H ₃ PO ₄ → (NH ₄)HPO ₄ } DAP NH ₃ + H ₃ PO ₄ → NH ₄ H ₂ PO ₄ } MAP
Potassium chloride (potash) ^c	Occurs naturally in association with sodium or magnesium chloride	
Compound fertilizers	They are produced either by chemical or physical blending	

^a Pure phosphoric acid has the chemical form H₃PO₄ but is customary in the phosphate industry to express quantities of phosphate fertilizer in terms of the equivalent P₂O₅ content. Thus, 1 tonne of phosphoric acid (100%) is equivalent to 0.724 tonnes P₂O₅.

^b The process described is generally known as the classical or dehydrate process (DH). Two variations, which reduce the energy use are the hemihydrate and the hemidrivate dehydrate process. The main difference between these two processes and DH is that higher strength H₂SO₄ is used which results in direct production of H₃PO₄ at a strength of 50% P₂O₅, obviating the need for evaporative concentration.

^c Strictly, potash has the chemical form of K₂O, but in the fertilizer industry potassium chloride (KCl) is referred to as potash and is normally recorded in by its K₂O equivalent: 1 tonne of KCl is equivalent to 0.632 tonnes K₂O.

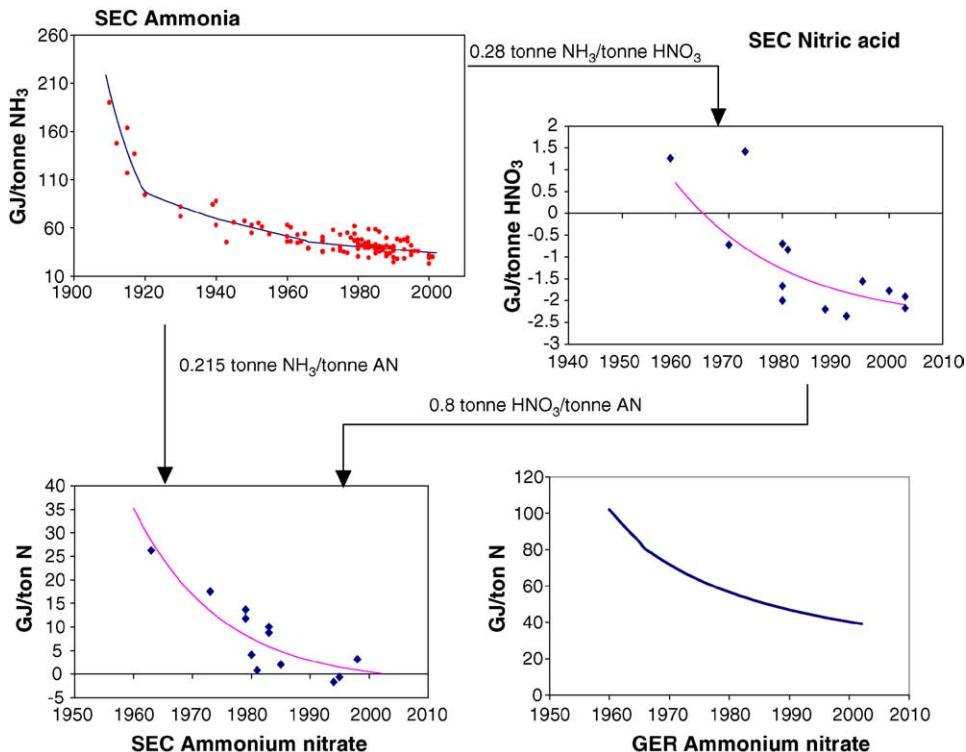


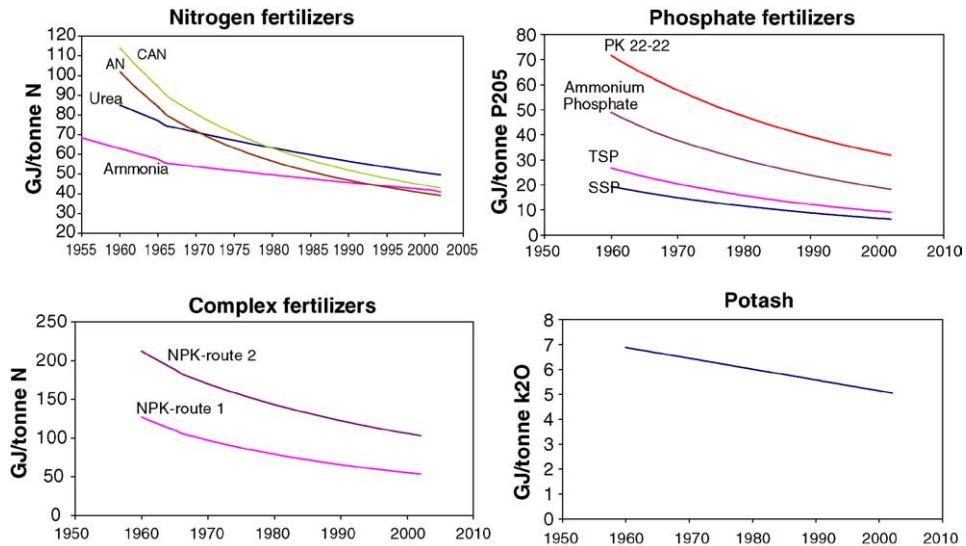
Fig. 3. SEC and GER involved in the production of ammonium nitrate (AN).

a more extended description of each process, we refer to Kirk-Othmer (1993), European Community (2004) and Wiesenberger (2002).

4. Energy embedded in fertilizer consumption

The first step to calculate the energy embedded in fertilizer consumption is to obtain historical trends in SEC for each fertilizer. The trends are then used to calculate GER using input efficiencies by process. In order to illustrate the procedure used, Fig. 3 shows how the GER trend for ammonium nitrate (AN) was obtained: from SEC trends for the production of ammonia, nitric acid and AN. Each point in the graphs represents typical SEC values for the average of plants in a given year. The points were obtained from a literature review (about 50 sources) and include data for different geographical regions. In this way, the trends characterize the average developments of SEC in the world. Feedstocks requirements needed to calculate GER are shown on top of the arrows. The values represent stoichiometric requirements and are constant during the period studied.³ Negative values of the SEC for

³ Deviations from the stoichiometric requirements reported in the literature were found to be of less than 10%, which justifies to use stoichiometric values in this analysis.



Note: The GER includes the heat content of feedstock (i.e. the heat content of natural gas in the production of ammonia and of sulfur in the production of sulfuric acid). Trends for NPK refer to a fertilizer 17-17-17. Route 1 stands for a fertilizer based on AN, Phosphoric acid and Potash while route 2 stands for a fertilizer based on Urea, TSP and Potash. In both cases all energy has been allocated to the Nitrogen content. In the case of ammonium phosphate and PK 22-22 energy has been allocated to the P₂O₅ content.

Fig. 4. Historical gross energy requirements by type of fertilizer.

nitric acid appear because (a) all chemical reactions in the production of nitric acid are exothermic and (b) plants have improved heat utilization, and consequently, modern plants export heat. Note that the technological development in ammonia production is the most important factor in the GER of AN and in fact, of all nitrogen fertilizers.

Fig. 4 shows the historical developments in GER obtained by kind of fertilizer. By using the GER per tonne of nutrient and the world consumption as reported by the International Fertilizer Association (2004), we calculate world energy use by the fertilizer sector (Fig. 5).

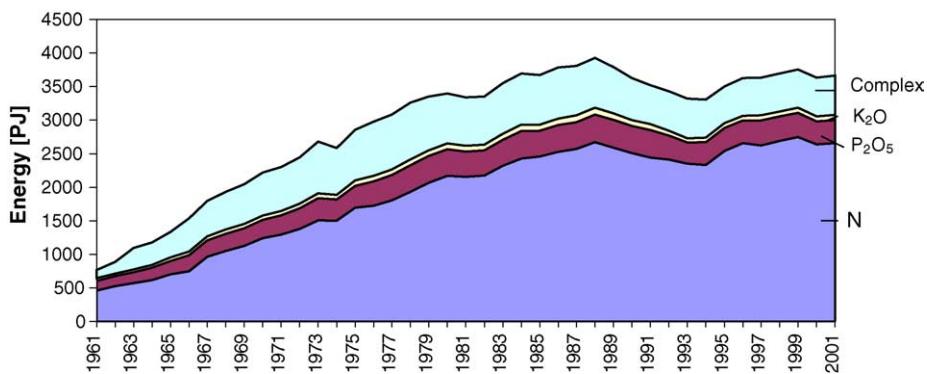


Fig. 5. World historical consumption of primary energy for fertilizer production.

According to our analysis, in the year 2001, energy embedded in world fertilizer consumption was about 3660 PJ, of which 72% was for the production of nitrogen fertilizers, 10% for phosphate fertilizers, 16% for complex fertilizers and only 2% for potassium fertilizers. The highest average annual rate of energy demand was shown by nitrogen fertilizers followed by compound fertilizers (4.5 and 3.9% p.a., respectively). Energy for phosphate fertilizer increased at a rate of 2.1% p.a., while the rate for potassium fertilizers was 1.7% p.a. Total energy demand increased by about 3.8% p.a. in the period 1961–2001 (this rate is the result of an increase of about 6% p.a. between 1961 and 1988 and a decrease of 0.3% p.a. between 1989 and 2001). The fall in energy demand shown between 1990 and 1994 is due to a steep decrease in fertilizer consumption (and production) in Central and Eastern Europe and Central Asia. The fall in consumption by 70% is directly linked to the changes of the economic and political systems in the region (Malinowski, 2000), and although since 1995 the agricultural systems began to recuperate from the crisis (and fertilizer consumption began to increase), fertilizer consumption has not yet reached the peak levels of 1989.

In order to understand the development in embedded energy due to fertilizer consumption between 1961 and 2001 (Fig. 5), we have applied a decomposition methodology to each nutrient for the time period 1961–1981 and 1981–2001. The results allow us to assess the effect of improved energy efficiency in fertilizer manufacture (D_{int}), increasing consumption of fertilizers (D_{cons}) and changes in the fertilizer mix used (D_{str}) in the change in total energy embedded (D_{tot}). For nitrogen, the fertilizers (i) taken into account are: direct application of ammonia, ammonium nitrate, calcium ammonium nitrate and urea. Phosphate fertilizers are single superphosphate, triple superphosphate, ammonium phosphate and PK 22-22. The results for the world are depicted in Fig. 6. There are three major findings from these results. The first is not surprising: growth in fertilizer consumption has been the main driver of increasing energy consumption. The second finding is that the fertilizer mix has moved towards more energy-intensive fertilizers per tonne of nutrient, which has led to an increasing energy demand. This trend is especially significant for phosphate fertilizers (i.e. from superphosphates towards ammonium phosphates). The third implication is that although significant improvements in energy efficiency have been able to offset the increased energy consumption as a result of changes in the fertilizer mix (with exception of phosphate fertilizers in the period 1981–2001), they were not sufficient to offset the impact of increased fertilizer consumption. In the case of nitrogen fertilizers, the impact of changes in energy efficiency was higher in the period 1961–1981 than in 1981–2001.

5. Technological improvement in the nitrogen fertilizer industry: learning curves

The results shown so far point out significant improvements in energy efficiency. In this section, we further examine the nitrogen fertilizer industry, since it accounts for over 70% of the total energy demand. As mentioned earlier, the decrease in GER values of nitrogen fertilizers has been driven by the decreasing SEC of ammonia production. It is not our intention to assess all process changes that have contributed to a reduction of the specific energy consumption in the nitrogen fertilizer industry, since this has already been well documented (e.g. Appl, 1997; Quartulli and Buividas, 1976). Instead, we look at technological development as a learning process. Most published material on experience

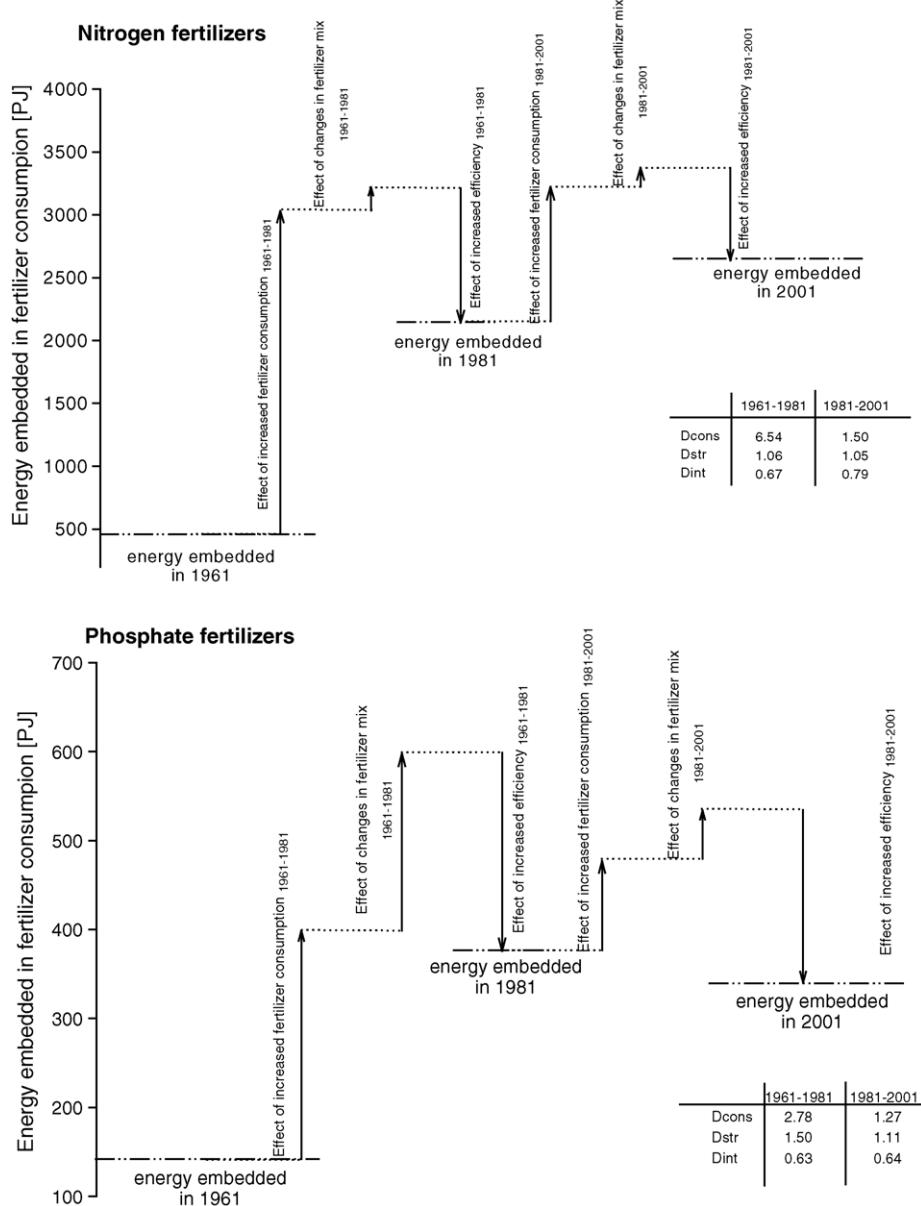


Fig. 6. Effect of increasing consumption, fertilizer mix and energy efficiency on the world energy use due to fertilizer consumption between 1961 and 2001.

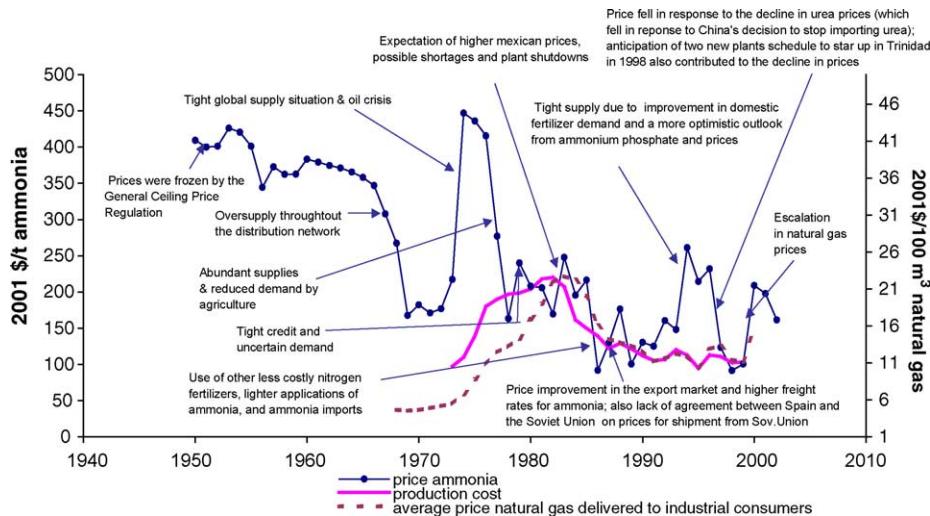


Fig. 7. Historical trends in the price of ammonia, production cost of ammonia and natural gas in the US, with explanatory notes for changes in ammonia prices. *Data sources:* ammonia prices: US Mineral yearbooks (several years); natural gas prices: Energy Information Administration (2001); production costs of ammonia: Vrooman (2004) and Mudahar and Hignett (1987b).

or learning curves relates prices to the cumulative production or use of a technology.⁴ The mathematical equations behind the experience curve were described in Section 2. In this paper, we relate the historical trends in specific energy consumption of various nitrogen fertilizers to cumulative production. Natural gas costs represent around 70–90% of the ammonia production costs and (including the gas cost in ammonia production and the additional process gas costs needed for the production of urea) natural gas represents around 70–75% of urea production costs (Hydro Company, 2003; Appl, 1997; UNIDO, 1967). Hence, it is reasonable to assume that decreasing total energy consumption per unit of product has been a main driver of technological change in the nitrogen fertilizer industry. Several reports confirm this point (e.g. Swaminathan and Sukalac, 2004; Mudahar and Hignett, 1987a; Marsal, 1986; Slack and James, 1973). Furthermore, by working with SECs instead of prices per unit of product we avoid problems associated with fluctuations of fertilizer prices that reflect market conditions, and not necessarily are related to technology productivity changes. As an example, in Fig. 7, we plot historical trends for the US price of ammonia, production costs of ammonia and natural gas prices (all deflated to 2001 values). The figure shows the strong influence of market forces and price of natural gas on the prices and production costs of ammonia. As a consequence, the correlation factor between costs or prices and cumulative output is too weak ($R^2 < 0.4$) to make any strong conclusion about learning rates in US ammonia production.

⁴ Strictly speaking, learning curves apply to production cost rather than price. However, given that production costs are generally not publicly available, price data tend to be used as a surrogate measure of cost.

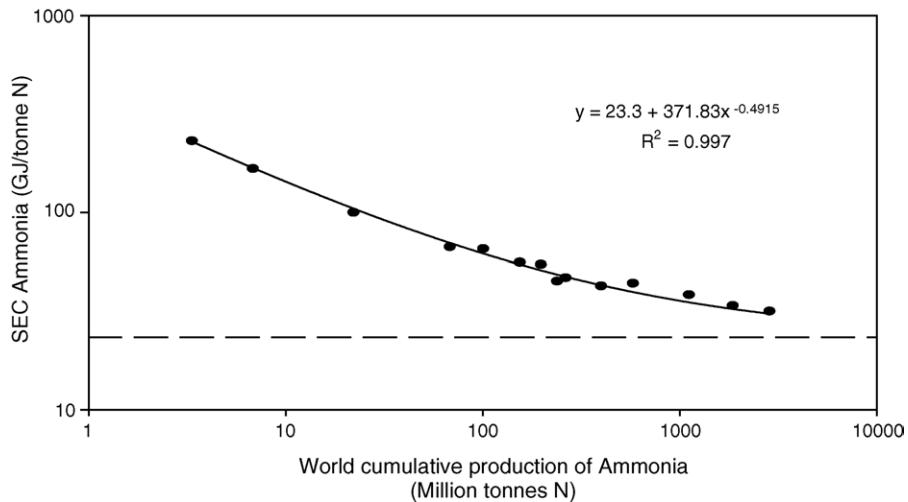


Fig. 8. Changes in SEC values for ammonia. Best available technologies.

A main difference with experience curves based on prices is the existence of a physical limit: specific energy consumption figures cannot be below the theoretical minimum energy requirements, for instance, in the case of ammonia 23.3 GJ/tonnes N (LHV). Therefore, the equation for the experience curve (Eq. (10)) can be rewritten as follows:

$$\text{SEC}_i = \text{SEC}_{\min} + \text{SEC}_{i,0} \times \text{CP}^b \quad (11)$$

where SEC_{\min} is the thermodynamically minimum energy requirement; SEC the specific energy consumption of product i ; $\text{SEC}_{i,0}$ the specific energy consumption of the first unit produced; CP the cumulative unit production; b is the experience index.

Fig. 8 plots the experience curve for specific energy consumption obtained for world ammonia production between 1913 and 2001. The experience curve in Fig. 8 is based on Best Available Technologies values (BAT). The progress ratio found for ammonia production is 71% ($R^2 = 0.997$).⁵ We compare the learning curve plotted in Fig. 8 with a learning curve obtained by using average SEC values. Results are depicted in Fig. 9. The progress ratio found for the average development in SEC in the period 1913–2001 is 77% ($R^2 = 0.925$). The potential for energy savings in ammonia production is still significant. Based on the current progress ratios, it will take a 3.3 doubling of the 2001 cumulative production (3066 million tons) for the world's SEC average to reach BAT performance levels of 2001 (≈ 32 GJ/tonnes N). We estimate that at the current rate of annual production growth, a cumulative production of 12,000 million tonnes will be reached in the year 2045. Calculations on fertilizer requirements until the year 2030 made by FAO (2000), assume, however, a slowdown in the growth of world population and crop production and an improvement in fertilizer use efficiency, which would result in growth rates of nitrogen fertilizers between

⁵ If the SEC_{\min} is not taken into account (Eqs. (6)–(10)), the progress ratio is 81% ($R^2 = 0.951$).

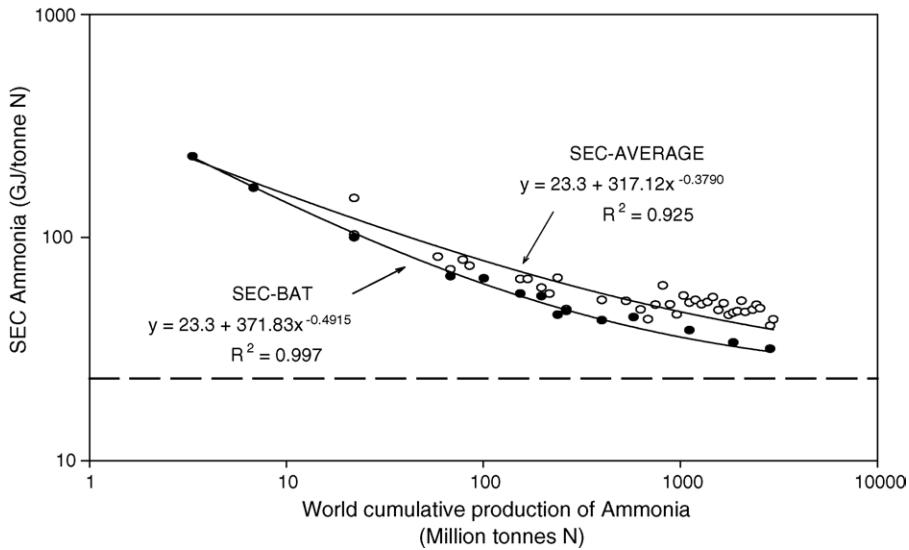


Fig. 9. Trends in SEC and cumulative production of ammonia, BAT and average technologies. Data in LHV.

0.7 and 1.3% p.a. (compared with an average annual rate of 3% over the last 40 years). With these assumptions, a cumulative production of 12,000 millions tonnes would be reached in the years 2065 or 2055, respectively.

We performed a similar analysis for urea. Fig. 10 shows the learning curves for BAT and average SEC development. The progress ratios found were for SEC_{BAT} 88% ($R^2=0.856$)

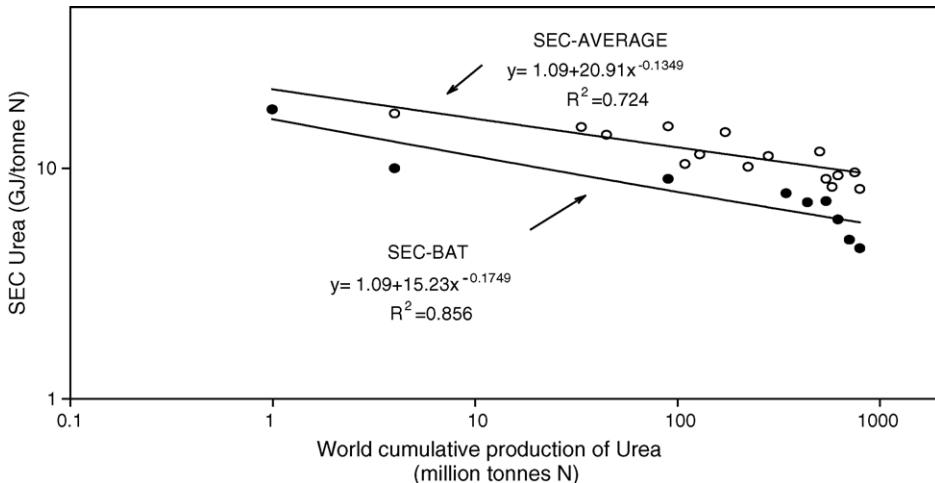


Fig. 10. Trends in SEC and cumulative production of urea, for BAT and average developments in technologies.

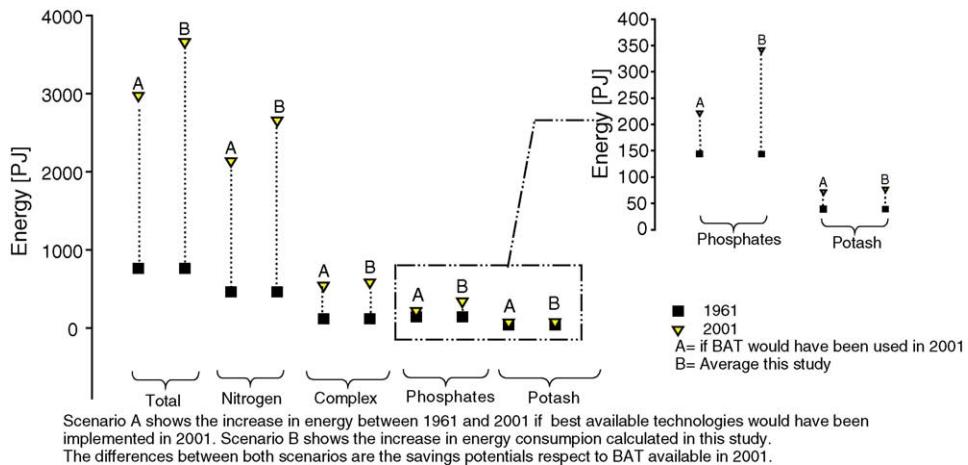


Fig. 11. Comparison of the effect of best available technologies in global energy embedded in fertilizer consumption by kind of fertilizer, with a zoom for phosphate and potash fertilizers.

and for SEC_{average} 91% ($R^2 = 0.724$). Contrary to the ammonia curves were the gap between BAT and average SECs seems to be closing up, there is no indication of this happening for urea production.

We attempted to perform the same kind of analysis for other fertilizers (AN, CAN, SSP, TSP, DAP, MAP). We found that despite a decline in SEC throughout the years (Fig. 4), correlation factors between SEC and cumulative production are too low ($R^2 < 0.65$) pointing out weak dependences among the variables. This result is not totally unexpected. Firstly, most of the processes for the manufacture of these fertilizers are relatively simple (e.g. mixing and blending), and thus the space for improvement may be more limited. Secondly, because energy plays a minor role in production costs for these processes, increased energy efficiency may not be a main driver of technological development.

6. Discussion and conclusions

This paper departed from two main goals: to assess world energy demand due to fertilizer consumption and the impacts of increasing energy efficiency on total energy demand, and examining technological development using the learning curve concept. We calculate that primary energy demand for the year 2001 was about 3660 PJ, which represents about 1% of the world total energy demand in 2001. Recent data on energy consumption related to fertilizers has been published by Kongshaug (1998),⁶ estimating the global energy consumption due to fertilizer consumption in 1998 at 3832 PJ, compared to 3629 PJ in 1998 in

⁶ We have adjusted the data provided in Kongshaug (1998) to the number of fertilizers used in this study.

this study. This is a difference of 5%. Kongshaug does not publish global energy consumption figures for earlier years so it is not possible to compare trends in the development of energy consumption.

When analyzing the drivers of increasing energy demand for fertilizer production (about 3.8% p.a. for the period 1961–2001), we found that although improvements in energy efficiency have been able to counterbalance the effect of changes in fertilizer mix towards more energy intensive fertilizers, they have not been able to offset the impact of increased fertilizer consumption. A comparison with BAT developments (Fig. 11) reveals a saving potential for the year 2001 of about 19% (687 PJ of energy). This potential is found mainly in the nitrogen fertilizer industry (Fig. 11). For instance, we calculate the energy embedded due to nitrogen fertilizer consumption in 2001 at 2660 PJ. However, if BAT would have been used, the energy embedded in 2001 would have been 2140 PJ, which would place the energy demand due to nitrogen fertilizers in 2001 below the level seen in 1980 (2160 PJ). In other words, the implementation of BAT would have counterbalanced the effects of raising fertilizer consumption and changes in fertilizer mix in the last two decades (Fig. 6).

As far as we know, no attempts have previously been done to use the concept of learning curves to development of industrial energy efficiency. The results presented in Figs. 7–9 reveal that over the long term, developments in specific energy consumption for ammonia and urea decline in close concordance with the learning curve concept. This is an important result since middle and long-term models of energy consumption and CO₂ emissions face the difficulty of how to consider technological changes. The use of progress ratios can provide an alternative to include technological change into scenario developments. Another consequence of our findings is that for energy intensive industries for which classical learning curves (i.e. based on prices or costs) cannot be developed due to high dependences on market prices and strong fluctuations of raw material prices (e.g. ammonia, see Fig. 7), the analysis of SEC as a main indicator of technological development can provide a way out to analyze rates of technological change for energy intensive processes (i.e. those processes for which energy is a major cost factor).

The results in this paper are only the first step into understanding learning in energy efficiency development. It would be interesting to test if the results found in this study for urea and ammonia apply as well to other industrial energy intensive processes. Furthermore, if the results are going to be used for more than developing business-as-usual scenarios, for instance, if progress ratios are to be changed by policy measures, the dynamics behind the learning curve need to be better understood.

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References

- Ang BW, Liu F. A new energy decomposition method. Perfect in decomposition and consistent in aggregation. *Energy* 2001;26:537–48.
- Ang BW, Zhang FQ. Survey of index decomposition analysis in energy and environmental studies. *Energy* 2000;25:1149–76.
- Achorn FP, Salladay DG. Optimizing use of energy in the production of granular ammonium phosphate fertilizers. Report TA/82/5. Paris: International Fertilizer Association; 1982.
- Appl M. Modern production technologies. Nitrogen. London, UK: CRU publishing; 1997.
- Disney R, Aragan H. The choice of technology in the production of fertilizers. A case study of Ammonia and Urea. *World Dev* 1997;5(9–10):853–66.
- Energy Information Administration (EIA). Historical natural gas annual, 1930–2000. Washington, DC, USA: EIA; 2001.
- European Community. Best available technologies in the large volume inorganic chemicals, ammonia, acids & fertilizer industries. Draft report, EC, available online at: <http://eippcb.jrc.es/pages/FActivities.htm>; 2004.
- Food and Agriculture Organization (FAO). World agriculture: towards 2015/2030—a FAO perspective. Rome, Italy: FAO; 2000.
- Gruber H. The learning curve of semiconductor memory chips. *Appl Econ* 1992;24:885–94.
- Hignett TP, Mudahar MS. Energy consumption in North American fertilizer plants and potential savings. Report TA/82/3. Paris, France: International Fertilizer Association; 1982.
- Honti P. The nitrogen industry. Budapest: Akadémiai Kiadó; 1976.
- Hydro Company. Agri Fertilizer Industry Handbook. Hydro; 2003.
- International Energy Agency (IEA). Experiences curves for energy technology policy. Paris, France: OECD/IEA; 2000.
- International Fertilizer Association (IFA). IFADATA Statistics, CD-Rom. Paris, France: IFA; 2004.
- Junginger M, Faaij A, Turkenburg W. Global experiences curves for wind farm. *Energy Policy* 2005;113–50.
- Kirk-Othmer. Encyclopedia of chemical technology, vol. 10. fourth ed. John Wiley & Sons; 1993.
- Kongshaug G. Energy consumption and greenhouse gas emissions in fertilizer production. In: IFA Technical Conference; 1998.
- Lieberman MB. The learning curve, technological barriers to entry and competitive survival in the chemical process industries. *Strat Manage J* 1989;10(5):431–47.
- Lockertz W. Energy inputs for nitrogen, phosphates and potash fertilizers. In: Pimentel D, editor. Handbook of energy utilization in agriculture. FL, USA: CRC Press; 1980.
- Marsal JDR. Energy saving in fertilizer plants. Report TA/86/14. Paris, France: International Fertilizer Association; 1986.
- Malinowski M. Fertilizer situation central and east Europe. In: 26th IFA Enlarged Council Meeting, International Fertilizer Association; 2000.
- Mudahar MS, Hignett TP. Energy requirements in the fertilizer sector. In: Helsel ZR, editor. Energy in plant nutrition and pest control. Amsterdam, the Netherlands: Elsevier; 1987a. pp. 25–61.
- Mudahar MS, Hignett TP. Energy efficiency, economics and policy in the fertilizer sector. In: Helsel ZR, editor. Energy in plant nutrition and pest control. Amsterdam, the Netherlands: Elsevier; 1987b. pp. 1–23.
- Patzek TW. Sustainability of the corn-ethanol biofuel cycle. Berkeley, USA: University of California; 2004.
- Pimentel D. The limits of biomass utilization. In: Meyers R, editor. Encyclopedia of physical sciences and technology. USA: Academic Press; 2001. p. 159–71.
- Quartulli OJ, Buividas LJ. Some current and future trends in ammonia production technology. *Nitrogen* 1976;100:60–5.
- Slack AV, James R. Ammonia (in fourth parts). New York: Marcel Dekker Inc; 1973.
- Spence AM. The learning curve and competition. *Bell J Econ* 1981;12:49–70.
- Swaminathan B, Sukalac KE. Technology transfer and mitigation of climate change: the Fertilizer industry perspective. In: IPCC Expert Meeting on Industrial Technology Development, Transfer and Diffusion; 2004.
- United Nations Industrial Development Organization (UNIDO). Fertilizer industry. Unido monographs on industrial development monograph No. 6. Vienna, Austria: UNIDO; 1967.

- Vrooman H. Demand destruction for natural gas in the US nitrogen industry. In: National Energy Modeling System, Annual Energy Outlook, 2004 Conference; 2004.
- Wiesenberger H. State of the art for the production of fertilizers with regard to the IPCC directive. Austria: Federal Environmental Agency; 2002.
- Worrell E, Blok K. Energy savings in the nitrogen fertilizer industry in the Netherlands. Energy 1994;19(2):195–209.
- Worrell E, Meuleman B, Blok K. Energy Savings by efficient application of fertilizer. Resour Conserv Recycl 1995;13(3–4):233–50.