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Energy 30 (2005) 2487–2504
ENERGY
www.elsevier.com/locate/energy

Energy efficiency improvements in ammonia production—perspectives and uncertainties

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Received 20 December 2002

Abstract

The paper discusses the energy consumption and energy saving potential for a major energy-intensive product in the chemical industry-ammonia, based on technologies currently in use and possible process improvements. The paper consists of four parts. In the first part, mainly references to various ammonia production technologies are given. Energy consumption, emissions and saving potentials are discussed in the second part. Thereby, the situation in Europe, the US and India is highlighted and various data sources are compared. In the third part of the paper, a novel approach for modeling energy efficiency improvements is described that accounts for uncertainties and unobserved heterogeneity in the production processes. Besides new investments, revamping investments are also included in the modeling and the development of the production stock is accounted for. Finally, in the fourth part, this approach is applied to the modeling of energy efficiency improvements and CO_2 emission reductions in ammonia production. Thereby, considerable improvements in specific energy use and CO_2 emissions are found in the reference scenario, yet under the assumption of high oil and gas prices, a partial switch to coal based technologies is expected which lowers notably the CO_2 efficiency. Introduction of a CO_2 penalty under a certificate trading or other regime is on contrary found to foster energy efficiency and the use of low carbon technologies.

1. Introduction

Ammonia is a chemical base product and used for multiple purposes, including fertilizer production. Worldwide ammonia production capacity is indicated in Table 1 [1], which shows that the production capacity remains almost constant for the last 3 years in most of the regions of the world, except Asia.

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0360-5442/$ - see front matter © 2005 Published by Elsevier Ltd.
doi:10.1016/j.energy.2004.12.004

Table 1
Worldwide ammonia production capacities

Region	1999/00	2000/01	2001/02 (‘000 t ammonia)
North America	23,276	23,354	22,094
Latin America	9573	11,185	11,185
Western Europe	14,324	14,388	13,817
Eastern Europe	8641	8641	8641
Former Soviet Union	24,695	24,549	24,549
Africa	5069	4944	4944
Asia	71,032	72,948	75,463
Oceania	930	1157	1157
World	157,539	161,165	161,849

In fact, Asia is the largest ammonia producing region in the world with total production capacities of about 73×10^6 t, which is about the sum of the production capacities in North America, Latin America, Eastern Europe, Western Europe and former Soviet Union. One of the reasons for Asia’s high production capacity is the huge and still growing population in the region and the utilization of fertilizer to increase food production to meet the growing demand.

Production of ammonia is energy and resource intensive. In the works of several authors [2–6], energy losses in the process have been identified and possible alternatives for reduced energy consumption have been shown. However, despite significant progresses in this field have been made, especially during the last decade, there are still opportunities for further improvements.

The objective of the present study is to investigate the economic and technical potential for energy efficiency improvements in the intensive energy consuming ammonia manufacturing process in this paper and at what cost they may be activated.

The paper consists of four parts: in the first part, references to the various ammonia production technologies are given mainly. Then, in the second part, energy consumption, emissions and energy saving potentials as identified in previous research works [2–10] have been scrutinized through further contact with several companies and international organizations. In the third part of the paper, our modeling energy efficiency improvements—methodology is being discussed, followed by an overview of the modeling on investment decisions and stock development. Finally, in the fourth part, application of our modeling for the techno-economic analysis of energy efficiency development in the ammonia production has been discussed.

2. Ammonia production technologies

Ammonia is synthesized by reacting nitrogen with hydrogen. Nitrogen is obtained from air, while hydrogen is obtained mostly from catalytic reforming of natural gas and from other liquid and solid hydrocarbon fuels.

Ammonia plant has a typical capacity of 1000–1500 t/d, although new plants are now being designed to produce 3000 t/d or more (Krupp Uhde Dual Pressure Process) and are commonly integrated with other plants, particularly with urea plants, which make use of the CO_2, produced in the process.

Three types of processes are mainly used for ammonia production

1. Steam reforming of natural gas or other light hydrocarbons;
2. Partial oxidation of heavy fuel oil or vacuum residue;
3. Coal gasification.

However, the coal gasification process is no longer in use for ammonia production neither in Europe nor in the US. The process is neither economically nor environmentally friendly, though in time, with a high cost of natural gas or due to its scarcity, coal gasification process may become an attractive option.

The most widely used process is steam reforming of natural gas [1,2,5].

The Shell Process and the Texaco Process are two commercially proven partial oxidation routes for heavy feedstocks. Further, Lurgi has recently developed a partial oxidation process technology. These processes are described in [2].

3. Energy consumption, emissions and energy saving potentials

3.1. Energy consumption of existing plants

Steam reforming of hydrocarbons for ammonia production started in the 1930. Since then, the technology has been gradually improved and energy consumption decreased from an early level of more than 80 GJ/t to a BAT level of about 28 GJ/t today [2,11].

Partial oxidation process requires more energy and is more expensive than steam reforming. The advantage of partial oxidation is the flexibility in using feedstock: it can be used for any gaseous, liquid or solid hydrocarbon. The process can be economically viable when relatively cheap raw materials like oil residues or coal are used for conversion.

Different kinds of energy consumption data for ammonia production are available from different literature sources. For ammonia production in the US, the EU and India available data on energy consumption are shown in Table 2.

A comparison of the different data sources shows considerable variation in the data. For example an average value of 37.1 GJ (LHV)/t NH_3 in the year 1995 is reported for the US in [12]. Another study [13] gives for the period 1994–1996 regional averages within the US which are throughout above 39.3 GJ (LHV)/t NH_3. For 1998, the energy consumption for ammonia production is estimated at 36.7 GJ (LHV)/t NH_3 [14].

The average SEC in the European Union for the year 1989 is estimated at 35.5 GJ/t (LHV) and that varied between 28 GJ/t (LHV) in Spain and 40 GJ/t (LHV) in Belgium [8]. However, the energy consumption figure for Spain is at the level of BAT as indicated in the end of the nineties, e.g. by [2]. For the period 1994–1996, the average consumption in different regions in the EU is found to vary between 34.0 and 38.7 GJ/t according to [13]. The same source indicates for South Asia, i.e. India and neighboring countries, an average of 39.6 GJ/t, whereas according to [10] the Indian average is 45.6 GJ/t. In the case of India a considerable decrease is observed during the last two decades. This is partly due to the improvement within the different process alternatives, but also a consequence of the switch from partial oxidation processes using Heavy Fuel Oil and Coal to steam reforming processes

Table 2
Energy use for ammonia production in the United States, EU and in India

Year	Country	SEC (GJ/t, LHV) including feedstock					Source
		Natural gas	Naptha	Heavy fuel oil	Coal	Average	
1980	US	40.1					[5]
1985	US	38.7					[5]
1990	North America	37.7					[14]
1995	North America	37.1					[14]
1998	North America	36.7					[14]
1994–1996	US					39.3–41.3[a]	[13]
1979–1980	India					61.9	[10]
1986–1987	India					56.0	[10]
1991–1992	India	40.1	48.9	56.4	165.9		[10]
1994–1995	India	38.7	47.2	59.8			[10]
1995–1996	India					45.6	[10]
1994–1996	South Asia					39.6	[13]
1989–1990	EU					35.5	[6]
1994–1996	EU					34.0–38.7[b]	[13]

[a] Average figures for different regions in the US.
[b] Average figures for different regions in the EU.

fuelled with natural gas and/or naphtha. In the case of the US and the EU, the decrease in energy use is much less pronounced, albeit new plants are now reported to use not more than 28 GJ/t [2].

How this energy use breaks down to different parts of the plant is indicated in Table 3. It is obvious that feedstock accounts for more than half of total energy use, in modern plants with total energy use of 28 GJ/t it is even almost three-quarter. The energetic consumption of natural gas occurs mainly in

Table 3
Estimated energy balance for ammonia plants in GJ (LHV)/t NH_3

Unit operation	US ammonia manufacturing (1996) [8]				Low energy ammonia plant [2]	
	Gas	Steam	Losses	Electricity	Gas	Losses
Reformer feed	20.4				22.3	
Reformer fuel	9.9				6.8	
Primary reformer		4.8				0.7
Secondary reformer		0.0				
Waste heat boiler		−5.6				
Shift + CO_2 removal		1.2		0.2		1.3
Methanator			0.3			
Synthesis loop		−2.0		0.2		1.7
Aux. boiler	4.5	−3.9			0.3	
Turbines/compressor		5.5				6.5
Miscellaneous			0.3	0.1		0.7
Flare	0.3					
Total	35.0	0.0	0.6	0.5	29.3	10.9

*Boiler efficiency is assumed to be 86%(LHV). Power generation efficiency is assumed to be 33%.

the reforming section. Steam is produced from gas both in the reforming section and in the auxiliary boiler and no steam imports are usually needed. In modern plant design, even a net steam export is possible

3.2. CO_2 emissions

During ammonia manufacturing CO_2 is produced as a bi-product and hence ammonia plants are often integrated with other plants, most commonly with urea plants using CO_2 as a feedstock.

The use of the rather pure CO_2 obtained from the steam reforming and CO_2 removal strongly affects the CO_2 balance of ammonia production. If the use did not lead to any CO_2 releases to atmosphere, emission levels could be as low as 0.43 t CO_2/t NH_3. However, if the CO_2 is used for urea production, it is released again to the atmosphere when the fertilizer is applied to the field. Also the use of CO_2 for the production of soft drinks, another frequent use, leads in the end to releases of CO_2 to the atmosphere. Therefore, in the following a complete release of CO_2 produced from feedstocks to the atmosphere is assumed [15]. The emissions of CO_2 then depend upon the type of hydrocarbon used for production of ammonia as well as technologies adopted. CO_2 emissions for different technologies in various countries are given in Table 4. The energy efficiency improvements observed in the past have consequently also reduced the total CO_2 emission. The average European CO_2 formation in ammonia plants is 2.2 t CO_2/t NH_3, while 30 years ago the net CO_2 emission was around 2.7 t CO_2/t NH_3 [7]. With a BAT energy consumption level of 28 GJ/t, an emission factor of 1.56 t CO_2/t NH_3 produced is obtained. This corresponds to the emission factor recommended for use by the IPCC, which hence seems to be rather optimistic for an average of existing plants [16].

3.3. Potentials for energy efficiency improvements

In the steam reforming process, the theoretical minimum energy consumption for ammonia manufacture is approximately 19.4 GJ/t NH_3 (LHV). By subtracting this value from the energy consumed in practice a theoretical energy saving potential is obtained. This is correct, if the chemicals are produced under ideal conditions. But commercial processes are not carried out at ideal conditions.

Significant energy savings have already been achieved in the past years by improvement of the steam reforming ammonia process. The high cost of natural gas in the production of ammonia has stimulated a drive towards decreasing the unit consumption of natural gas. The consumption has been decreased mainly through technology improvements and through efficiency increase in production. In the following the main possibilities for increasing the energy efficiency of existing plants are discussed.

Table 4
CO_2 emissions for different technologies in different countries based on fuel types

Fuel used	Technology	Year	Country/ region	SEC (GJ/t NH_3)	Emission factor (gCO_2/MJ)	CO_2 (t/t NH_3)
Natural gas	Steam reforming	1994–1996	US	41.3	55.7	2.3
		1994–1996	EU	34.9	55.7	1.9
		1994–1995	India	38.7	55.7	2.2
Heavy fuel oil	Partial oxidation	1994–1995	India	59.8	78.6	4.7
Coal	Partial oxidation	1991–1992	India	165.9	100.7	16.7

3.3.1. Reforming section

The conventional steam reforming process is carried out in a fired furnace either of the side fired or top fired type. In the reforming section energy savings can be achieved by several measures [2]

- Reduction of the flue gas temperature;
- Avoid heat loss by proper insulation of the reformer furnace;
- Increase of preheat temperatures for feed, steam and air used in the process;
- Increased operating pressure;
- Lower steam–carbon ratio;
- Shifting of partial reformer duty from primary to secondary reformer, using excess air or oxygen-enriched air in the secondary reformer;
- Installation of a pre-reformer.

The installation of a pre-reformer and an upgrade of the convection section is reported to yield about 1.4 GJ/t NH_3 in energy savings [17]. Another revamp project [18] reports energy savings of 5 GJ/t through modified coils and installation of a gas turbine. The reduction of the steam to carbon ratio is found to provide approximately 0.8 GJ/t according to [19], whereas according to the same source the recuperation of flue gas waste heat may yield 0.4 GJ/t in savings. A whole bundle of energy saving measures [18,20] including a lowering of the steam to carbon ratio and increased radiation heating in the reformer decreases energy use by approximately 3 GJ/t. The installation of a gas turbine leads to a decrease in energy use by 3.5 GJ/t according to [21].

These examples indicate the possible energy efficiency improvements in revamp projects strongly depend on the vintage and status of the existing plant. For India [9], estimates that a typical energy efficiency revamp of a plant would reduce specific energy consumption for plants installed before 1980 by 5.02–13.4 GJ/t and for plants installed between 1981 and 1990 by about 3.3–4.2 GJ/t, depending on the feedstock used. Plants installed after 1991 are considered to be highly efficient and there is little scope for energy efficiency improvement.

Emerging technologies, which may be used to reduce further the energy use in the reforming section include the use of Gas Heated Reformers (GHR), which are tubular exchangers. In the GHR, the secondary reformer outlet gases supply the reforming heat. Kellogg's Reforming Exchanger System is an example of GHR technology.

Also hydrogen separation is viewed as a promising technology. In reforming, experiments have been performed, using a palladium membrane to remove the product hydrogen. These experiments have resulted in a significant increase in methane conversion [8]. A related option is isobaric manufacturing: if the methane conversion can be increased by hydrogen separation, the process can be operated at higher isobaric pressures. Overall, in the reforming section, it is estimated that 3–5 GJ/t NH_3 of the energy losses in the primary reformer (steam reforming process) can be avoided [22]. The investment costs for such advanced steam reforming are estimated at 65 Euro/GJ saved per year [23].

3.3.2. Shift section

The most important objectives for this section are a low-pressure drop and efficient heat recovery from the process gas. The water–gas shift reaction is favorable for producing carbon dioxide, which is used as a raw material for urea production. New types of HT shift catalysts allow lower steam to carbon ratio in the reforming section, thus avoiding hydrocarbon formation by Fischer–Tropsch reaction at low vapor partial pressure [2]. However, the net energy savings of these improvements cannot be yet quantified.

3.3.3. Carbon dioxide removal section

The removal of carbon dioxide has been performed via solvent absorption and distillation since the inception of ammonia technology processes. This section of the ammonia plant consumes a huge quantity of energy. Such high-energy consumption is due to thermally inefficient distillation, dissipation of huge amounts of low-level heat into the cooling water via the product carbon dioxide, and pressurization and depressurization of absorbents. Considerable energy savings have been achieved, using new solvents and processes like BASF aMDEA or Benfield LoHeat, etc. [19] indicates a saving potential of 0.4–1.4 GJ/t NH_3, whereas [24] and [12] estimate overall energy savings of 1 GJ/t NH_3 and 1.1 GJ/t NH_3, respectively, through the use of advanced solvents, pressure swing absorption or membranes for an efficient removal of CO_2 from the synthesis gas. Costs for investment are estimated at 15 Euro/GJ saved annually [23].

3.3.4. Final purification of synthesis gases

The process has been improved by removing the water and carbon dioxide traces to a very low level by using molecular sieves. The conventional methanation process can result in the loss of hydrogen. Minimizing this loss is of prime concern when examining the process used to purify the synthesis gas. Pressure Swing Absorption (PSA) provides here an effective means for reducing those losses.

3.3.5. Ammonia synthesis and separation

Several developments in ammonia synthesis have been made in the past, these developments include improved converter designs as well as improved catalysts. The converter design development through use of indirect cooling instead of quenching, which allows the recovery of reaction heat as high pressure steam, is a significant break through in process development.

As far as catalysts are concerned, It is reported that the KAAP catalyst is 40% more active than iron catalysts [11]. Yet, a lower ammonia synthesis pressure reduces the energy demand of the ammonia synthesis only slightly by 0–0.5 GJ/t NH_3 according to [23]. Earlier communications based on manufacturer information indicate higher savings [12] in the order of 1–2 GJ/t NH_3, but this information has to be treated with care. These savings can be achieved by the use of improved catalysts and by adjustments to the power system and the recycle loop. Investment costs are estimated at 25 Euro/GJ saved per year, but costs for operation and maintenance increase by 1 Euro/GJ saved annually [23].

Furthermore, minimizing the amount of ammonia in the recycle gas is important. Usually the ammonia concentration of the recycle is 3–4%, but reducing this amount to 1.5% can increase plant capacity by about 2.5%. A recovery of ammonia and hydrogen from the purge gas may save about 0.002 GJ/t NH_3 according to [25].

3.3.6. Machinery and process automation

Developments in compressor and turbine manufacturing has lead to higher efficiencies. Process automation can also contribute to energy saving. Ref. [26] reports savings of 0.7 GJ/t NH_3 for a specific revamp project whereas according to [12] process automation can save about 0.6 GJ/t NH_3.

3.3.7. Process integration

A further important option to improve the energy efficiency is a better *process integration* of heat exchange reformers and co-generation of heat and power. However, whether this is feasible, strongly depends on the specific situation on the site. According to [27] this could yield a maximal improvement of the SEC of 3–4 GJ/t NH_3 with estimated costs for implementation of 10 Euro/GJ saved per year.

4. Methodology for modeling energy efficiency improvements

The previous descriptions have highlighted that there is considerable uncertainty on the potential for energy efficiency improvements especially as far as existing ammonia plants are concerned. This should be taken into account explicitly when assessing the future potential for energy-efficiency improvements. Additionally one has to account for both the possible investment in new plants and the revamp of existing plants. This leads to the following model of energy efficiency, consisting of three main parts:

- modeling of investments in new plants,
- modeling of investments in plant revamps,
- modeling of stock development.

These model parts are briefly described in the following (cf. also [28]), before discussing the application to the case of ammonia production.

4.1. Modeling investment decisions for new plants

Investment decisions in energy-intensive processes such as the ammonia production are influenced by a multitude of factors. Analyzing all relevant factors in detail would require extensive theoretical and empirical (case) studies, which are hardly achievable. In the following therefore the focus is on the relative cost and benefits of different investment alternatives. Based on empirical evidence and previous theoretical work in economics, it is assumed that these costs and benefits at least to a certain extent determine the investment decisions. In our context, an appropriate total cost (and benefit) measure for comparing investment alternatives i is the annuity A_i

$$A_i = aI + \sum_j p_{E,j} q_{E,i,j} + C_{M,i} + C_{0,i} - B_{NM,i} \quad (1)$$

with

A_i annuity of the investment in technology i
a annuity factor (dependent on the lifetime l of the investment and the interest rate r)
I investment cost
j index for energy carriers
p_E price of energy
$q_{E,i,j}$ quantity of energy carrier j consumed in technology i
$C_{M,I}$ material costs for technology i

$C_{o,I}$ other costs (annualized) for technology i
$B_{NM,I}$ money equivalent of non-monetary benefits of technology i

Usually, an investor will choose the investment alternative with the lowest annuity (corresponding to the lowest lifetime costs).

If the annuity of the investment alternatives is not known exactly by the modeler, but only up to some error ε (e.g. due to unknown site-specific conditions, varying energy prices, etc.), one may use the so-called discrete choice modeling approach developed in economics notably by year 2000 Nobel prize laureat Daniel McFadden [29]).

Thereby it is assumed, that the annuity A_i includes besides the known, deterministic part given in Eq. (1) also a stochastic error ε_i which captures unobserved variations e.g. in plant size, energy prices, etc. This leads to the formulation:

$$A_i = aI + \sum_j p_{E,j} q_{E,i,j} + C_{M,i} + C_{o,i} - B_{NM,i} + \varepsilon \tag{2}$$

The error terms ε_i may be unknown only to the external modeler (e.g. plant specific costs), or it might also be stochastic for the decision-maker himself (e.g. on site performance). If ε_i follows a so-called extreme-value- or Weibull-distribution, the so-called multinomial logit model is obtained. The cumulative distribution function for ε_i is in this case:

$$F(\varepsilon_i) = \exp(-e^{-\beta\varepsilon_i - \gamma}) \tag{3}$$

with:

β distribution parameter
γ Euler's constant (0.577…)

The expected value of ε_i is zero in this case and its standard deviation $\pi/(\sqrt{6}\beta)$.

This leads to the following equation for the market share m_i of an investment alternative i:

$$m_i = \frac{e^{-\beta A_i}}{\sum_j e^{-\beta A_j}} \tag{4}$$

In order to obtain a more easily understandable uncertainty parameter we use the transformation

$$\beta = \frac{1}{\alpha A_0} \tag{5}$$

and obtain

$$m_i = \frac{e^{-A_i/(\alpha A_0)}}{\sum_j e^{-A_j/(\alpha A_0)}} \tag{6}$$

with

m_i market share of the investment in technology i
A_i (deterministic) annuity of the investment in technology i

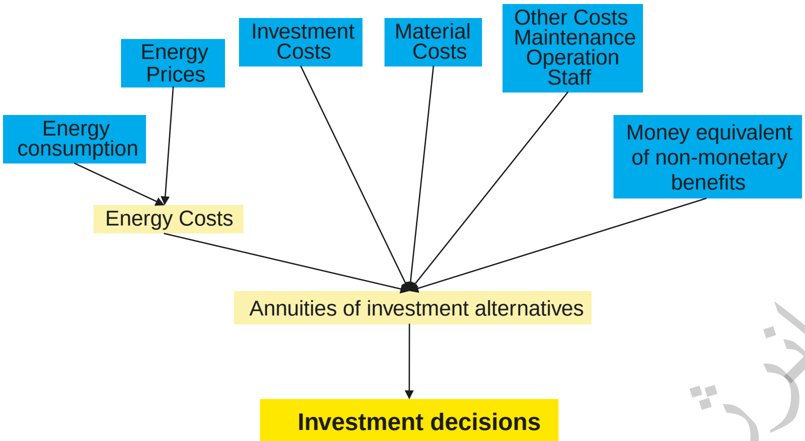

Fig. 1. Overview of modeling of investment decisions.

A_0 lowest annuity among the possible choices
α uncertainty parameter

α now describes the uncertainty on annuities as a share of the lowest investment annuity observed (alternatively also the average could be used). The standard deviation of the error term ε_i is then $\alpha\pi/\sqrt{6}A_0$ or roughly a fraction 1.28 α of the reference annuity A_0.

Of course, also alternative specification of the error term such as a normal distribution (multinomial probit model) or a generalized extreme value distribution (nested multinomial logit model) are possible (cf. [29]). However, the chosen logit model has the advantage that it provides a treatable analytical formulation for the market shares. The property of the so-called 'independence of irrelevant alternatives', which is sometimes perceived as a drawback of multinomial logit models, is not much a problem here, since the choice alternatives can be chosen to represent clearly distinct technologies.

The calculation procedure for the investment choice is also summarized in Fig. 1. The required input data are indicated in blue, the calculation results are shown in yellow.

4.2. Modeling revamp investments

The modeling of the revamp investments is done along the same lines as the modeling of investment alternatives for new plants. Yet, the reference alternative is in this case not to invest at all. Consequently, annuities are expressed based on differences compared to the reference alternative:

$$A_i = a\Delta I_i + \sum_j p_{\mathrm{E},j}\Delta q_{\mathrm{E},i,j} + \Delta C_{\mathrm{M},i} + \Delta C_{0,i} - \Delta B_{\mathrm{NM},i} + \varepsilon_i \tag{7}$$

Since the reference alternative has an annuity of 0, also another formulation of the uncertainty parameter is preferable. Since the expected energy savings represent a major uncertainty in the case of revamps, the uncertainty is expressed as a fraction of the expected savings in energy costs

$$\beta = \frac{1}{\tilde{\alpha}\overline{\Delta C_{\mathrm{E}}}} \tag{8}$$

with:

$\overline{\Delta C_{\mathrm{E}}} = \sum_j p_{\mathrm{E},j}\overline{\Delta q_{\mathrm{E},i,j}}$ average energy cost saving of revamp alternatives
$\tilde{\alpha}$ uncertainty parameter expressed as fraction of the energy cost savings

4.3. Modeling stock development

Investments in new plants are only occurring to the extent that existing production capacities have to be replaced or new production capacities need to be built up. On the other hand, revamps will only be carried out, if the base plant has still some remaining lifetime. Therefore, a modeling of the production capacity stock is required. An overview of this modeling is given in Fig. 2.

The stock development is dependent on investment decisions and on the development of production. The latter determines the required quantity of new production capacity according to the following stock equation:

$$N_k = \max\left\{\frac{O_k}{\kappa_k} - \left(K_k - \frac{\Delta t}{l_k}K_k\right); 0\right\} \tag{9}$$

with

N_k new production capacity for product k
O_k production output for product k

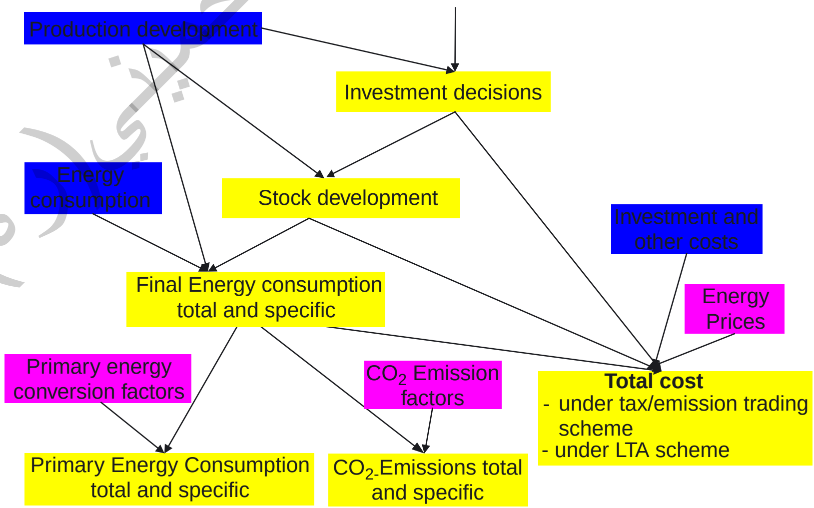

Fig. 2. Overview of modeling of stock development.

κ_k capacity utilisation factor in the production of product k
K_k existing production capacity (capital stock) for the production of product k
Δt investment period considered
l_k lifetime of production equipment

If the (planned) future output O_k exceeds the possible production from the existing stock K_k minus the part of the stock which is scrapped during the planning period $\Delta t/l_k K_k$, then new production capacity N_k is needed. Which technology within a number of technology alternatives is used to build up this production capacity, is modeled through the investment Eqs. (1) and (2). If no technology alternatives exist, then the stock equation simply describes the gradual replacement of the existing stock by the new, best available technology. From the stock development and technology data on energy consumption the final energy consumption for the stock is determined. Using data on primary energy equivalents, CO_2-emission factors and energy prices, then the corresponding primary energy consumption, CO_2-emissions and costs are derived. Again, input data are shown in blue and computation results in yellow. General, non-technology-specific data are indicated with a pink background.

4.4. Application of the modeling to the ammonia production

For new plants, the technology options listed in Table 5 have been included in the modeling (cf. [2,30,31]. The BAT design level for energy consumption is currently below 28 GJ/t, but for operation in practice one has to account for start-ups and non-optimal operation conditions. More conventional designs may consume some 1.5 GJ/t more, with some savings on operation costs due to the use of conventional iron catalysts instead of ruthenium based catalysts. The estimated capital costs for a new greenfield plant are approximately at 240 €/t NH_3 annual capacity [8]. Investment cost for partial oxidation plants are considerably higher. One factor is the need for a cryogenic air separation to produce

Table 5
Data for new investments

Plant type	Specific energy consumption (GJ/t)	Investment cost (€ per t/a)	Operation and maintenance cost[a] (€/t)	Uncertainty parameter (%)
Steam reforming Fuel: natural gas Standard new plant	29.5	240		5
Steam reforming Fuel: natural gas Best available technology	28.0			5
Steam reforming Fuel: naphta	31.5	270	0	5
Partial oxidation Fuel: heavy fuel oil	36.5	360	1	5
Partial oxidation Fuel: coal	47.5	600	4	5

[a] Difference compared to the standard gas fired steam reforming plant.

Table 6
Data for revamp investments in natural gas fuelled steam reforming plants

Retrofit measure	Average improvement (GJ/t)	Range (GJ/t)	Uncertainty parameter (%)	Cost (€ per t/a)	Applicability		
					EU (%)	US (%)	India (%)
Reforming large improvements	4.0	±1.0	17	24	10	15	10
Reforming moderate improvements	1.4	±0.4	20	5	20	25	20
Improvement CO_2 removal	0.9	±0.5	33	15	30	30	30
Low pressure synth	0.5	±0.5	67	6	90	90	90
Hydrogen recovery	0.8	±0.5	50	2	0	10	10
Improved process control	0.72	±0.5	50	6	30	50	30
Process integration	3.0	±1.0	23	3	10	25	20

the required quantity of pure oxygen and nitrogen. For a 1800 t(STP)/d ammonia plant based on heavy oil residues the investment for the air separation unit producing 100 bar oxygen and 75 bar nitrogen is around US \$ 55×10^6 in Western Europe [2]. For lump-sum turn-key prices for ammonia plant the following figures are given as a rule of thumb: steam reforming of natural gas 100%, partial oxidation of heavy oil residues 150%, coal gasification based plant 250% [2]. For the valuation of the investment costs, a (real) interest rate of 12% is taken.

Table 6 shows the technologies considered for the revamping. It is evident that not all energy efficient technologies or energy efficiency improvement measures can be included in detail, especially due to missing data, particularly on investment costs. Moreover, the energy efficiency improvements linked to a technology improvement, say for example, advanced/improved steam reforming can vary considerably from one site to another. Therefore, not only average values have been compiled, but also the range of variation found in the literature (cf. Section 3.3).

Production growth has been close to zero in the last decade both in the US and in the EU and therefore also for the scenario runs no production growth is assumed in these countries. Production of nitrogenous fertilizers in India has on the contrary risen by 56% between 1990 and 2000 [32], corresponding to an average annual growth rate of 4.6%. Even if due to demand saturation and supply shortages for natural gas growth may be lower in the future, an average growth rate of 3% p.a. in the decade 2000–2010 is plausible.

Energy price data are summarised in Table 7. They are based on IEA statistics supplemented by additional information in the case of India [33,34]. For Naphtha, the price is based on average spot market price quotations for the period 7/2001–6/2002. Besides static price expectations also the hypothesis of high oil and gas prices is envisaged. Under this hypothesis, oil and gas prices raise to 1.5 times their current value between 2000 and 2010. Furthermore, two hypotheses on the valuation of CO_2 mitigation are considered. In the baseline case no price is attached to CO_2 emissions, whereas in an alternative hypothesis it is assumed that through a certificate trading scheme or other Kyoto instruments a price of 15 €/t CO_2 is established from 2005 onwards. The CO_2 hypotheses are combined with the energy price hypotheses, yielding a total of four different scenarios.

Table 7
Energy prices for industrial customers 2001

In €/MW h	EU	US	India
Natural gas	397	319	178
Naphtha	390	390	390
Heavy fuel oil	360	277	831
Hard coal	248	125	075
Electricity	1430	950	1970

5. Results

The development of total energy use and CO_2 emissions under the different scenarios is summarised in Table 8. Whereas in the EU and the US, substantial energy savings and CO_2 emission reductions are expected, the energy use and CO_2 emissions related to ammonia production are expected to grow in India due to the output growth. In specific terms, efficiency increases considerably in all three regions considered (cf. Table 9). The highest reduction is observed in India which has a rather high consumption level in 1995, but through revamp measures and the strong build up of additional capacities achieves consumption levels which are below those of the US in 2010. Production growth thereby induces an on average more recent capital stock which in turn leads to lower average specific consumption.

Under the high oil and gas price scenario, energy use and emissions are substantially modified. A particularly strong trend reversal is observed in the US, where emissions are found to increase by 15% under this scenario as compared to a decrease of 12% in the reference scenario. But also in India

Table 8
Scenario results for total energy use and CO_2 emissions

Year	Country	Scenario	Total energy use		Total CO_2 emissions	
			(PJ)	Change (%)	(Mt)	Change (%)
1995	EU		435		25.5	
	US		642		35.9	
	India		466		30.9	
2010	EU	Ref.	387	−11	22.4	−12
		High price	403	−7	25.1	−2
		15 €/t CO_2	386	−11	22.1	−13
		High price and 15 €/t CO_2	385	−11	22.1	−13
	US	Ref.	547	−15	31.6	−12
		High price	604	−6	41.2	15
		15 €/t CO_2	539	−16	30.4	−15
		High price and 15 €/t CO_2	541	−16	30.8	−14
	India	Ref.	539	15	34.3	11
		High price	562	20	38.2	23
		15 €/t CO_2	524	12	31.8	3
		High price and 15 €/t CO_2	526	13	32.2	4

Table 9
Scenario results for specific energy use and CO_2 emissions

Year	Country	Scenario	Specific energy use		Specific CO_2 emissions	
			(GJ/t)	Change (%)	(t/t)	Change (%)
1995	EU		35.6		2.09	
	US		40.7		2.27	
	India		46.3		3.07	
2010	EU	Ref.	31.7	−11	1.84	−12
		High price	33.0	−7	2.06	−2
		15 €/t CO_2	31.6	−11	1.81	−13
		High price and 15 €/t CO_2	31.5	−11	1.81	−13
	US	Ref.	34.7	−15	2.00	−12
		High price	38.2	−6	2.61	15
		15 €/t CO_2	34.2	−16	1.93	−15
		High price and 15 €/t CO_2	34.3	−16	1.95	−14
	India	Ref.	34.4	−26	2.19	−29
		High price	35.8	−23	2.43	−21
		15 €/t CO_2	33.4	−28	2.03	−34
		High price and 15 €/t CO_2	33.5	−28	2.05	−33

emissions increase by 12% points compared to the reference scenario and in the EU reduction is slowed down by 10% points. This is mostly due to the installation of a significant proportion of coal-fired plants from 2005 on, when prices turn to the disadvantage of oil and gas. As an example, the market shares for the various plant types in India are shown in Table 10 for the different scenarios.

On contrary, the introduction of a CO_2 penalty strengthens the trend towards low-carbon, highly energy efficient technologies. This is apparent in Table 10 for the new plants and in Table 11 the effects on revamp investments is shown. It is apparent that the CO_2 price scenario leads especially to increases

Table 10
Scenario results for market shares of different production technologies in India in 2010

	Reference (%)	High price (%)	15 €/t CO_2 (%)	15 €/t CO_2 and high price (%)
Plants built 1995 and later				
Steam reforming, natural gas fuelled	27	23	28	27
Steam reforming, natural gas fuelled, BAT	33	29	36	37
Steam reforming, naphtha fuelled	0	0	0	0
partial oxidation, heavy fuel oil fuelled	0	0	0	0
Partial oxidation, coal fuelled	7	15	3	3
Plants built before 1995	33	33	33	33

Table 11
Scenario results for market shares of different revamp technologies in India in 2010 (expressed as share of the applicable market segment)

	Reference (%)	High price (%)	15 €/t CO_2 (%)	15 €/t CO_2 and high price (%)
Reforming, large improvements	98	98	99	99
Reforming, moderate improvements	97	98	98	98
Improvement CO_2 removal	43	44	54	56
Low pressure synth	58	58	63	64
Hydrogen recovery	84	85	87	88
Improved process control	71	72	77	77
Process integration	94	95	96	96

in the market shares of those technologies like improved CO_2 removal, which have so far only gained moderate market shares. The combination of CO_2 prices and high gas prices leads to somewhat higher penetration rates, but the gain over the pure CO_2 price scenario is not that strong, particularly since the high prices only have full effect in 2010, whereas the CO_2 price is applied from 2005 on.

Additional scenario runs have been carried out with a CO_2 penalty of 50 €/t, but these yield almost no additional CO_2 reductions.

6. Discussion and final remarks

The analyses have shown that ammonia production, despite being a mature technology, still offers substantial potentials for energy efficiency improvements, especially in existing plants. Thereby, a long time perspective has to be taken given the long lifetime of the installations. Even by the year 2010, one cannot expect that the current BAT level is achieved by the average of all plants.

Furthermore, it has become apparent that uncertainty considerably affects the future prospects of energy efficiency improvements. Heterogeneity of the performance and operation conditions of individual plants is a first type of uncertainty, which will reduce the impact of any price and policy measure. This type of uncertainty is well handled by the developed novel modeling approach which notably avoids the shortfall of ‘penny-switching’ observed in linear programming models like MARKAL.

A second type of uncertainty is, however, still persisting. The share of plants to which a particular revamp option is applicable is often only poorly known. Even as far as current consumption levels are concerned, information is still subject to errors and uncertainty. This uncertainty affects the achievable level of energy efficiency improvements, but it less affects the comparison of alternative policy instruments or price scenarios.

Finally a third type of uncertainty remains. This concerns future price and policy developments themselves. The situation in the past years has shown that international energy prices are strongly volatile and difficult to predict and also international climate policy is far from heading to a clear direction. Since policy will develop its effects in the ammonia business (and elsewhere) mostly in the long run, a clear strategic decision is required if effects are expected until the year 2010.

Acknowledgements

We are grateful to Mr Jozeph Messen, Manager Process Engineering Urea of Stamicarbon b.v. and Dr Detlev Claes, Head of Fertilizer Division of Krupp Uhde GmbH for their kind and sincere cooperation during this research work. We gratefully acknowledge the Alexander von Humboldt Foundation for awarding the Fellowship to one of the authors—Dr Rafiqul Islam to carry out this research project, the outcome of which is reflected in this paper.

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