Low Energy Consumption Ammonia Production: Baseline Energy Consumption, Options for Energy Optimization

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1 Introduction

The specific energy consumption of ammonia production was reduced over many decades. Figures of about 7 Gcal per ton of ammonia were reached in the early 1990s with some values even slightly below. However, in the following years this trend did not continue. Low energy consumption often was partly sacrificed for low investment cost.

With generally increasing natural gas prices today, and projects in high gas-cost countries, the focus seems to return to energy consumption again, thus raising the interest in even lower energy consumption figures.

This paper discusses the theoretical and practical lower limits of energy consumption. It highlights some typical loss mechanisms, including the suggestion of improvements where possible and a brief explanation of the physical backgrounds where reduction measures are not available. Furthermore, some recommendations are given for the comparison of consumption figures, because these are not uniquely defined numbers but depend on parameters like climatic conditions and on the plant specific selection of the boundary.

2 Motivation

Natural gas prices are increasing all over the world. Natural gas is not anymore a cheap by-product of oil production but it is a valuable raw material for which several paths to market exist. Ammonia and fertiliser production is only one of these and has to compete with other chemical production, export as LNG, power production and other.

Some fertiliser plants have already lost the ability to produce competitively due to rising energy cost. The value of energy savings increases with rising gas prices. Therefore investments in energy efficiency are justified and can be seen as an investment for the future. The amount of the possible savings is illustrated by the example that a saving of 0.1 Gcal per ton of ammonia is equivalent to a net present value of 8.65 million USD at a natural gas price of 3 USD per million BTU for a 2000 mtpd plant and for the economic background data as shown in Table 1.

Economic evaluation – example		
Energy saving	0.1	Gcal/t NH_3
Plant capacity	2000	t/d NH_3
Natural gas cost	3.00	USD/MMBTU
Net present value of saved energy	8.65	million USD
Economic background data:		
Onstream days	350	days per year
Interest rate	5	% per year
Time horizon	15	Years

Table 1: Example for the economic evaluation of a reduction in energy consumption. The net present value of the saving of 0.1 Gcal per ton of ammonia is 8.65 million USD under the given conditions, that means, if the investment to realise this saving is less than this sum, it is attractive.

In addition to the economic advantage of a low energy consumption, there is the fact that the CO_2 emissions would be reduced as well, and even credits might be given if a CO_2 emission trading scheme is established.

3 Historic Development

The specific energy consumption of new-built ammonia plants was reduced significantly in the 1970s. Since about 1990, there is no more clear trend in the data. Figure 2 shows some historical figures from plants commissioned from 1960 to 1980, where a dramatic reduction in energy consumption from 9.5 to 7.2 Gcal per ton of ammonia can be seen, which equals a reduction by about 25 percent. From 1990 on, some data from recently built plants are shown with figures between 6.8 and 7.4 Gcal per ton of ammonia.

It seems that the trend towards reduced energy consumption has been slowed down or even has come to an end. The question is whether this is due to low gas cost or due to physical reasons, meaning that no more reduction is possible. This shall be investigated in more detail in the following section.

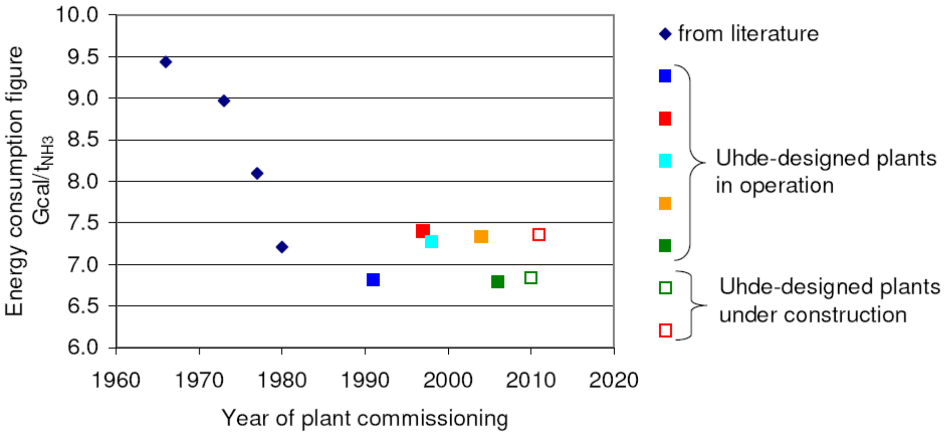

Figure 1: Specific energy consumption per ton of ammonia; historical figures from literature and data of some recent Uhde plants.

4 Energy balance for ammonia production

4.1 Thermodynamic minimum

The minimum consumption for the production of ammonia from methane, air and steam, calculated from the stoichiometry of the overall chemical reaction, is 0.44 mole methane per mole of ammonia. Expressed by its lower heating value (LHV), this equals an energy input of 4.98 Gcal per ton of ammonia, which is the minimum feed. Out of these, 4.44 Gcal are recovered as chemical energy in the ammonia product. This is the thermodynamic minimum net energy input. The difference between these two is the minimum heat rejection from the ideal process. This is shown schematically in Figure 2. From the figures it is evident, that the thermodynamic minimum consumption can only be realised when the a credit is given for the energy value of the heat rejection.

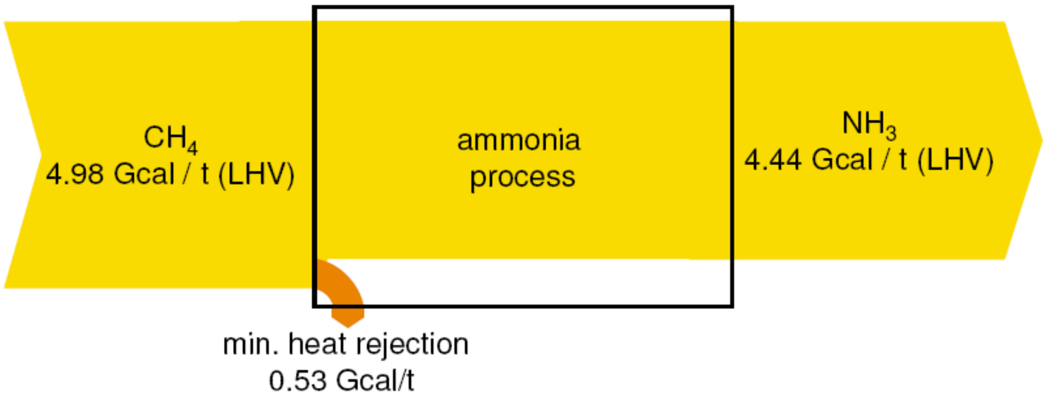

Figure 2: Minimum energy consumption of an ammonia process, based on the chemical energy content of methane as feedstock and of the product, expressed per ton of ammonia product. Feedstock quantity is the stoichiometric minimum requirement.

4.2 Real process

In the real process, the energy consumption is much higher for several reasons, for example:

- The process is taking place at elevated temperatures and pressures. Unfortunately, a significant portion of the heating requirements needs higher temperatures than offered by the hot process streams that are to be cooled down. Consequently, a perfect heat integration is impossible. This means, more energy must be added to the process, which can be only partly recovered from it for re-use while the rest is discharged to the ambient.
- A commonly used option to utilise the high-temperature waste heat is its conversion to mechanical energy by means of a steam cycle. The mechanical power serves the power demand of the pressure changes in the process. As for thermodynamic reasons heat can not be freely converted to mechanical power, further energy losses are inevitable.
- Mechanical work must be added to the process to overcome friction that can be observed e.g. as pressure drop or as limited efficiency of machinery.
- Further irreversibility can be found where heat is transferred with significant temperature difference. The temperature drop causes a loss in the thermodynamic quality of the transferred heat.
- The inlet and outlet streams do not come at standard conditions (e.g. subcooled ammonia product).
- Reactants are not fed in stoichiometrically but in excess (like process steam), and are not fully recovered.
- Natural gas does not come as pure methane.

Figure 3 shows a simplified example of the main energy streams of a real ammonia plant. The steam system is shown as a separate block. It consists of the equipment for steam generation (including feedwater preheating, and steam superheating) from process waste heat, and the turbines which turn this steam into work (motive power) which is sent back to the process for driving the compressors. Furthermore, it acts as supplier of process steam. An additional fired boiler is not part of this block.

The largest portion of the waste heat from the process is going into the steam system (2.98 Gcal/t) while only a smaller one goes into the cooling water or escapes as flue gas.

The ammonia plant in the example is a net exporter of steam. That means, from the process waste heat, more steam is produced than is consumed by the process and its turbines. Often, this export is welcome because there is a urea plant or another steam consumer next to the ammonia plant. Therefore, it is fair to value the export steam by the amount of gas which would be needed by an auxiliary boiler for its production. In the example in Figure 3, this is done, and therefore, a credit of 0.37 Gcal per ton of ammonia is given.

Besides natural gas, the plant in Figure 3 imports some electric power for driving some pumps. For a fair comparison of processes with different natural gas and electricity consumptions, it is necessary to bring them onto a common basis in order to make them comparable.

Instead of importing, the electricity could also be produced from the export steam in a turbine-driven generator. Therefore, it can be valued by the amount of gas which is needed to produce steam which in turn then produces this amount of electricity. In the example in Figure 3, this is 0.04 Gcal per ton of ammonia. Here a conversion factor of 2866 kcal per kWh is used, which corresponds to an overall efficiency of 30 percent in the power generation. A standard figure can be used for the conversion factor or it can be derived from the project-specific conditions. It is obvious that some conversion has to be made, because also the cost of electricity and gas reflects the fact that for the production of 1 kWh electricity about 3 kWh natural gas are needed.

The resulting overall consumption figure from summing up natural gas and electricity imports and credit for steam export is 6.91 Gcal per ton of ammonia for the reference plant shown in Figure 3 (see Table 2).

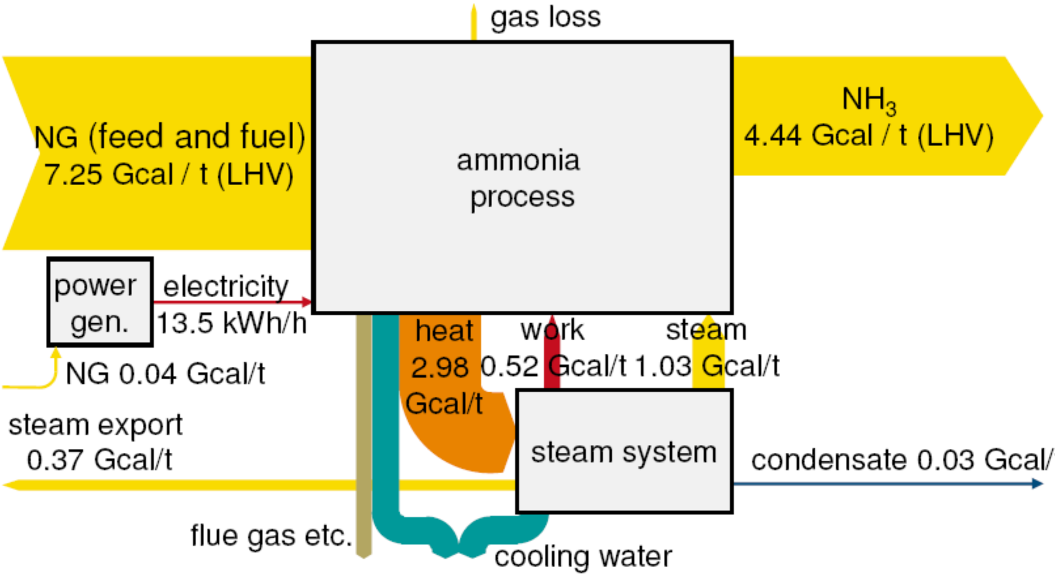

Figure 3: Energy flow diagram of an actual ammonia plant (simplified). Net energy consumption as per Table 2. Figures are in Gcal per ton of ammonia product.

Stream	Consumption or credit
feed and fuel	7.25 Gcal/t
Electricity	0.04 Gcal/t
steam export	–0.37 Gcal/t
Total	6.91 Gcal/t

Table 2: Calculation of net energy consumption of the ammonia plant from Figure 3. Electricity converted to natural gas equivalent by factor 2866 kcal/kJ.

5 Reduction of energy consumption

There are two approaches to reduce the energy consumption:

- Reduction of the heat release from the process: This will reduce the energy input needed to balance the losses.
- Increase of efficiency of the steam system: This will generate more value (steam or mechanical power) from the usable process waste heat.

As laid out above, the thermodynamic minimum energy consumption of the process is around 4.44 Gcal per ton of ammonia. In the process from Figure 3, 64 percent of its net energy consumption end up in the product. The numbers are taken from an actually built plant, which already consumes less than an average plant today, but for sure gives room for improvement. The question is how close one can get to this minimum figure with an optimised but realistic process and with equipment cost not exceeding all budgets.

Even optimised processes will have the following two major energy consumers:

- The reforming process will operate at high temperature with excess steam. Target is the maximum recovery of the heat input.
- The whole process will operate at elevated pressure, especially the ammonia synthesis, in order to drive the reaction and to facilitate product separation. This means, mechanical work has to be added to the process.

The process pressure dictates the shaft power demand of the synthesis gas compressor. If this is reduced by a lower synthesis pressure, more power is needed by the refrigeration system to separate the product by condensation from the synthesis loop. That means, the power requirement can not be reduced indefinitely.

To get an assessment of minimum realistic energy consumption, practical limits of both of the approaches mentioned above are explored.

- The major heat releases to the ambient are those to water coolers and losses by flue gas. Losses to water coolers cannot be avoided completely because in a practical process there is some waste heat present at an unfavourably low level. Also certain flue gas losses have to be accepted because one would like to stay well above 100 °C with the stack temperature.
- For the steam system an improvement to an overall efficiency of 40 percent is assumed. On efficiency changes in the steam system refer to Sections 6.3 and 6.4.

As a result, a figure around 6.5 Gcal per ton of ammonia seems to be a realistic practical baseline for the energy consumption. One should avoid to call it a minimum because it is not a fix value but it is influenced by ambient conditions, and by the definition of what is included in the figure and what not (refer to Section 7).

The figure is clearly not representing the economic optimum. The economic optimum would have to consider not only the operating cost but also the investment. To achieve this consumption figure, a significantly higher investment would be needed than typically made for an ammonia plant today.

Some examples for reducing the energy consumption are discussed in the following section. They are valid both for retrofits in existing plants as well as for new designs.

6 Examples for energy saving

6.1 Minimised heat release to the ambient

One approach to reduce the energy consumption is to minimise the heat release to the environment and to use the waste heat elsewhere in the process, instead. This reduces the energy import for heating purposes. The two major contributors to the heat release to the ambient are the reformer flue gas and the process waste heat to the cooling water.

Minimising the heat release means to utilise the available heat elsewhere in the process for preheating of streams. Thus, one has not only to identify the streams with heat loss to the environment, but one has at the same time to find another stream which can pick up this heat. If the waste heat is available at a high temperature level, it can be used for stream generation, which then can be used elsewhere for motive power. But the lower the temperature of the waste heat gets, the more challenging it becomes to find a suitable stream to which the waste heat can be transferred.

The heat available in the reformer flue gas can for example be used for:

- Preheating of combustion air
- Higher preheating of feed / steam and process air
- Integration of a pre-reformer and re-heating in the flue gas duct

However, the practical implementation is sometimes difficult because limits arise, for example by higher NO_x formation at higher combustion air temperature, and by constraints of material of construction in the case of preheating of the process streams.

Energy loss to cooling water can for example be minimised by maximising the HP steam production from waste heat in the ammonia synthesis. This can be done by installing two converters with an HP steam waste heat boiler after each of them and by minimising the temperature difference in the gas / gas heat exchanger.

Waste heat to cooling systems can also be reduced by selection of higher efficient machinery. In all compressors, the temperature of the process fluid increases. This heating is typically not desired, and therefore it is rejected to the cooling water in the interstage coolers. In a more efficient compressor, less energy is converted into heat, and the shaft power demand is less. See section 6.4 for an example. The same is true for the turbines that are used within the steam cycle. Here, higher efficiency leads to reduced specific heat rejection from the cycle which is equivalent to higher cycle efficiency.

6.2 Extended physical desorption in CO_2 removal unit

The CO_2 removal unit requires a certain amount of heat for the regeneration of the solvent. Typically, the regeneration of the solvent is done by combining the effects of physical desorption (flashing) and stripping with steam. For example, in a CO_2 removal unit using aqueous MDEA as solvent (Figure 4), the regeneration of the CO_2 loaded solution is often done as follows: First, the solution from the absorber is flashed into the high-pressure flash vessel, then into the low-pressure flash vessel, the latter typically operating at approximately 1.5 bar abs. By these two flashing steps, solved CO_2 is released from the liquid. The resulting so-called semi-lean solution is sufficiently lean in CO_2 to be used for the bulk CO_2 absorption. For the top stages of the absorber, however, a stream of solution with even lower CO_2 content is needed. It is obtained by feeding a part stream of the semi-lean solution to a stripper where the remaining CO_2 is expelled by stripping with steam. The resulting lean solution is fed to the absorber top where it is able to reduce the CO_2 content of the process gas to a few hundred ppm. The stripping step is the energy-intense step of the solvent regeneration.

By introducing a third flashing step downstream of the low-pressure flash vessel as shown in Figure 4, even more CO_2 is expelled out of the liquid by pressure reduction. This extends the physical desorption of CO_2 from the solvent.

The operating conditions of the existing low-pressure flash are maintained unchanged. Its pressure is more or less fixed by the need to cool and vent the CO_2 stream or to feed it to the suction side of the CO_2 compressor if it is fed to a urea plant. From the low-pressure flash, the solution is let down to the newly introduced so called low-low pressure flash vessel. As it is operating near atmospheric pressure, or even below it, it is often also called atmospheric flash vessel, or vacuum flash vessel.

The two beneficial effects are as follows:

- The solution flow rate and the CO_2 concentration of the stripper feed get lowered, therefore its reboiler needs less heat to achieve the same outlet concentration.
- By the lower CO_2 content of the semilean solution, less liquid has to be circulated to the absorber in order to pick up the same amount of CO_2.

Figure 4 shows the typical reductions in heat and flow rates.

As an adverse effect, mechanical work is needed to overcome the pressure difference which is introduced by the additional let-down step. By an additional blower, the CO_2 vapour from the low-low pressure flash must be compressed to the pressure of the existing low-pressure flash in order to be exported from the system as before.

In a newly built plant, the lower circulation rate allows for smaller pumps and vessels. In a revamp situation, it can generate room for capacity increase.

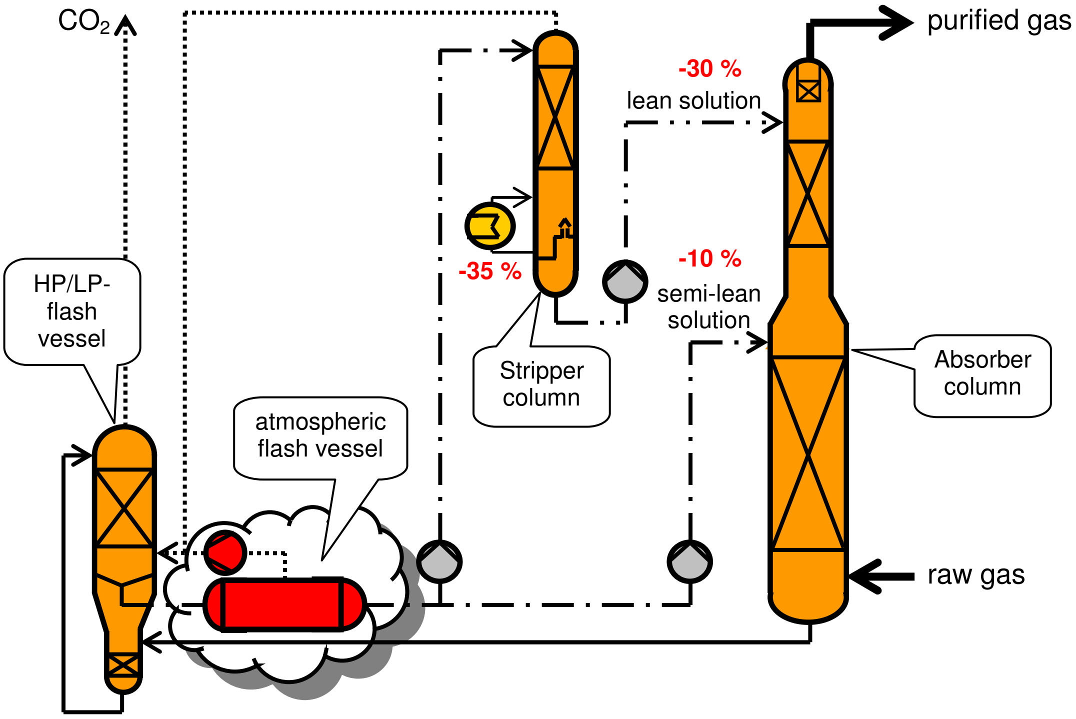

Figure 4: Atmospheric flash vessel downstream of the high pressure and low pressure (HP / LP) flash vessel in the solvent regeneration section of an MDEA CO_2 removal unit.

6.3 Increased efficiency of energy conversion

Any steam reforming process must be operated at elevated temperature. Typically, the reforming temperature is at about 700 to 800 °C. This means, heat must be added to the system for bringing the feed streams to reaction temperature. As the overall reforming reaction is endothermic, more heat must be fed to the system than can be recovered by cooling the effluent streams.

Waste heat is available in the process gas from the reforming section and in the flue gas from the reformer and / or from fired heaters (if any) which are installed for heating. Waste heat which is not directly used by the process is utilised for steam generation and superheating. From the steam system, energy is returned to the process as compressor shaft power.

The thermal efficiency of the steam system is defined as the ratio of mechanical work output from the steam turbines divided by the net heat input to produce it. In a plant with a modern high-pressure steam system (around 125 bar steam drum pressure and 535 °C superheater outlet temperature), the efficiency is close to 30 percent. Compared to modern power plants, this is a relatively low figure.

The overall efficiency is, among others, a function of the efficiency of the steam turbines (see Section 6.4). For thermodynamic reasons, it is limited by the operating temperatures of the steam system. Even the maximum theoretical efficiency of a steam cycle with the above parameters, without any mechanical loss, is 60 percent only (Carnot efficiency).

In modern power plants, significantly higher pressures and temperatures are used, and even supercritical conditions are common.

In contrast to a power plant, in an ammonia plant there are some constraints which prevent the designer to arbitrarily increase steam pressure and temperature.

Indeed the temperature levels of the process and the reformer flue gas would allow for higher steam parameters. But at higher steam-side temperatures in the boiler and superheater, also the metal temperature would increase. A temperature limit arises from the fact that the process side of the heat exchangers is affected by the corrosion effect of metal dusting at elevated surface temperatures. This effect originates from the CO content in the process gas, and does not occur in power plants.

When the optimisation of the steam system is discussed, the environment of the plant must also be considered. Different strategies are recommended, depending on whether there is the possibility for steam export or not.

Possibility for export is given for most ammonia plants as they are situated in a complex together with a urea plant. The urea plant is a net consumer of steam and electricity, so all surplus steam can be sent to the urea plant and / or for electricity production.

In this case, to satisfy the whole demand, often the ammonia plant steam system is enlarged by additional steam production, either by increased reformer firing or by a separate gas-fired auxiliary boiler. In both cases, this does not lead to an improvement of the system. Energy-wise, it is a better choice to use a separate energy conversion system, such as a combined cycle power generation, that is not limited by the constraints of the process-attached steam cycle. Thus the overall efficiency of the energy system can be improved.

If the steam system efficiency is for example increased to 40 percent, this would reduce the consumption figure of the ammonia plant by 0.25 Gcal per ton. In addition to that, about the same saving would be realised in the rest of the complex (urea and utilities).

This does not change the quality of the ammonia process but it provides the possibility to get a credit for energy export and it lowers the energy consumption of the whole complex and lowers the production cost of the final product, e.g. urea.

The situation is different if there is no possibility of steam export. Then there is no way of improving the energy balance by a credit for export. In this case, the heat transfer from the process to the steam system must be reduced in such a way that steam export gets zero (0.37 Gcal/t in the example in Figure 3).

This requires more changes in the process, as it calls for a reduction of the heat output by the process. This is done by using process waste heat as much as possible for preheating of other process stream and only as much as needed for steam generation.

An important element in this concept is the fired steam reformer. Its flue gas can be used to obtain higher preheat temperatures (reformer inlet temperatures) of the media. This reduces the firing demand in the reformer and the heat exported from the flue gas to the steam system. Limits are given by the material of construction of the reformer inlet piping.

The heat transfer to the steam system can be further reduced if not only the heat of the flue gas, but also the heat of the process gas is kept inside the system and is used to preheat the reformer inlet streams. This leads to concepts of heat exchange reforming and autothermal reforming where the only energy input to the reforming is heat release by the oxidation of a part of the process gas.

In an extreme case, there is not enough waste heat available for gas preheating and for generating the steam needed. In this case, a fired heater is added again. This is then no more an energy improvement, as by its flue gas a new loss is created which in principle is of the same nature as the reformer flue gas which one wanted to minimise.

6.4 Use of energy-efficient machinery

The shaft power of the compressors of a typical 2000 mtpd ammonia plant sums up to more than 50 MW. Steam turbines are used as drivers. The compressor and turbine efficiencies have an impact on the overall energy consumption of the plant.

Table 3 compares the guaranteed steam consumption figures for the syngas and refrigeration compressor turbines from the proposals of two well reputed vendors for a recent project.

Machine	Parameter	Vendor 1 (base case)	Vendor 2
Synthesis gas compressor turbine	HP steam inlet	250.4 t/h	250.4 t/h
	MP steam extraction	181.7 t/h	190.1 t/h
	Δ MP steam avail.		+8.4 t/h
	Δ consumption figure		–0.08 Gcal/t NH_3
Refrigeration compressor turbine	MP steam inlet	34.9 t/h	31.8 t/h
	Δ MP steam avail.		+3.1 t/h
	Δ consumption figure		–0.03 Gcal/t NH_3

Table 3: Difference in consumption figure by different efficiencies of compressors and turbines. MP steam valued at 3300 kJ/kg.

The syngas compressor driver is an HP steam turbine with an MP steam extraction, and the refrigeration compressor turbine is an MP steam turbine. The different turbine efficiencies lead to different MP steam quantities which are available for export. At vendor 2, the efficiencies of both compressors and turbines are higher, leading to a consumption figure which is by 0.11 Gcal/t lower.

With the economic boundary conditions from Table 1, the net present value of this saving is 9.5 million USD.

6.5 Reduced pressure drop

In the ammonia process, compressors bring the reactants to a pressure which is favourable for the reaction and for product separation. The selection of the pressure has an impact on the shaft power demand.

In addition, the compressors have to recover the pressure which is lost within the process by friction or dissipation. Typically, pressure loss from reformer outlet to suction side of the natural gas compressor is 6 to 9 bar, and pressure drop of the ammonia synthesis loop is at around 10 bar.

If the pressure drop in the ammonia plant front end is reduced by 1 bar, for example by reactors and heat exchangers with lower pressure drop, this would reduce the overall consumption figure only by 0.007 Gcal/t. The net present value of the gas saved by the lower shaft power of the syngas compressor is 600000 USD (economic boundary conditions as given in Table 1). This means, if this pressure drop reduction can be achieved by an investment less than this sum, it is worth to do it.

7 Comparison of consumption figures

The energy consumption of a plant is an important parameter to assess its economic value because it is the major contributor to its production cost, even at low energy prices. However, just comparing the numbers might be misleading if one is dealing with plants at different locations in the world or with different concept studies for plants for the same location.

For example, in a lower temperature climate, a lower energy consumption can be achieved with less technical effort. If one is comparing consumption figures, one has to make sure that the boundary for the energy balance is selected identically for all. A low consumption figure might not be the result of a good process but of a favourable selection of the boundary or battery limits.

Refer to Table 4 for a checklist and some examples what to observe in the comparison.

Key word	Comment
Climatic conditions	Are climatic conditions comparable? At lower ambient and cooling water temperatures the energy consumption naturally gets lower.
Natural gas supply conditions	The natural gas feed usually needs to be compressed before being fed to the process. The compression power needed is depending on the supply pressure. Thus, a lower consumption figure can also be the result of higher supply pressure.
Ammonia export conditions	What is the split of ammonia export streams between warm export (at ambient temperature, e.g. to a urea plant) and at refrigeration level (e.g. to storage tank)?
Selection of boundary	Verify that the chosen boundaries are identical and meaningful. Besides process units, check whether or not the following is included: process condensate stripper, BFW pumps, refrigeration power for process, natural gas compressor power (note 1).
Electricity	Is electricity consumption included and converted into natural gas equivalent (see Section 4.2) (note 1)?
Natural gas	For which natural gas composition is the consumption figure calculated?
Import streams	Is energy consumption of air separation unit and of fired heaters included if necessary for the process?
Credits for exports	Steam export can be credited by the heating value of the amount of natural gas which would have to be spent if the steam was instead produced in a separate boiler. Check the assumed boiler efficiency. Sometimes export of warm condensate is credited, sometimes not.
Catalyst conditions	Are the consumption figures valid for fresh catalyst or end of life?
Utilities	Is energy consumption of utilities like cooling water, demineralisation unit, instrument air etc. included? (Normally this is not done.)

Note 1: For the figures in this text, the mentioned consumers are all included.

Table 4: Checklist for calculation and comparison of consumption figures.

8 Summary

Today's ammonia plants are with energy consumptions near 7 Gcal per ton of ammonia already close to the thermodynamic minimum energy input of 4.44 Gcal per ton. Therefore, it is getting more and more difficult to find further reductions. In addition to that, at low gas cost, the higher investment for further energy saving is not always justified.

Improvements can be made in the process and in the energy recovery and conversion system. Examples for improvements in both of them are given in the text above. Also the reasons for limits for some changes – like corrosion effects at higher temperatures – are discussed. With such improvements, it seems that a reduction to about 6.5 Gcal per ton is possible without dramatic changes in the process. This figure must not be seen as an absolute limit. It is a baseline for the energy consumption which can be crossed only with high efforts.

During the process selection for a new plant, a low consumption figure always looks attractive, but it must be considered at this time already, that it can be achieved only with a high investment (capex), and that the lowest possible consumption figure or operational expenditure (opex) for this reason is not coinciding with the overall economic optimum. For a proper selection, both numbers must be looked at. Consequently, depending on the cost of energy, the optimum consumption figure can be different for different projects and locations.