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Recent Efforts in Energy Conservation in Ammonia and Urea Plants

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Abstract

Ammonia and urea plants are highly energy intensive as both the feed and fuel are energy. There are exothermic and endothermic reactions during the production which offer opportunities for recovery of waste heat and its utilization in process itself. Over the years, technologies for production process of ammonia and urea have evolved with focus on reliability of operation and improving energy efficiency. There have been improvements in metallurgy, design of machines, and static equipments- and catalyst. Adoption of improved operational practices like optimization of process parameters and precise control of parameters with modern control instrumentation and advance process control software supplemented the energy conservation drive. In recent years, there has been focus on recovery and utilization of low grade heat. Change of feedstock from fuel oil or naphtha to natural gas has been another development which helped to improve the energy efficiency. Replacement of coal based captive power plants to gas turbine has given substantial benefits in steam and power generation. FAI has been monitoring the energy performance of ammonia and urea plants since 1987-88. There has been continuous reduction in energy consumption in ammonia and urea plants both due to addition of more efficient capacity and improvement in old plants. The weighted average energy consumption in ammonia and urea plants has been reduced by more than 34% over last 3 decades. Overall energy consumption of Indian plants is better than average of world plants. The paper describes some of the notable measures adopted in the recent past to improve the energy efficiency in ammonia and urea plants.

Key words: Ammonia plant, urea plant, energy conservation, efficiency, utilities, offsites

1. Introduction

Production of fertilizers is highly capital, energy and technology intensive. Therefore, operation at high efficiency levels is essential for viability of the business. Ammonia is an essential intermediate for production of both nitrogenous and complex fertilizers. The energy accounts for about 90% of variable cost of ammonia production. Ammonia accounts for 80% of energy consumption used in production of urea and other fertilizers. Energy conservation has always remained a focus area in fertilizer sector. Production, movement and sale price of urea are regulated by the government. Energy consumption norm is a major parameter in calculating the cost of production of urea units reimbursed under urea pricing and subsidy policy. Energy consumption norms under the policy for urea are revised downward periodically by the government to save on subsidy outgo.

Fertilizer industry in India started its journey on large commercial scale in 1950s. During the first few decades of development, variety of raw materials were used for production of ammonia viz. coke oven gas, coal, naphtha, furnace oil and natural gas. Over the years, fertilizer pricing policy led the switch of feedstock to natural gas. Natural gas is a cleaner fuel and gas based plants are more energy efficient. There was shortage of natural gas in mid-nineties. Some of the plants changed to mixed feed of naphtha and natural gas. Three new plants were commissioned on naphtha as feedstock. With the availability of imported re-gassified liquefied natural gas (RLNG) in 2005 and with mandate under urea pricing policy, all non-gas plants changed feedstock from naphtha and fuel oil to natural gas during 2005 to 2020. Presently, all urea fertilizer plants are operating on natural gas as feedstock (**Table 1**). There were no new ammonia-urea plants during 1999 to 2018. However, existing plants increased their capacity through de-bottlenecking again driven by pricing policy. During the de-bottlenecking exercise, plants also incorporated energy saving measures. There has been considerable efforts and investment in energy saving projects with or without debottlenecking of capacity. A new ammonia-urea plant was commissioned in 2019 after a gap of almost 20 years. Five more new ammonia-urea plants will be commissioned in next 1-4 years. The latest plants with state of the art technology are highly energy efficient and would help in reduction of overall energy consumption of ammonia and urea industry. The vintage and capacity-wise characteristics of ammonia plants are given in **Table 2.**

FAI has been monitoring energy consumption in ammonia and urea plants since late 1980s. A standardized methodology for collecting the energy consumption data for battery limit of ammonia and

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Table 1. Share of feedstock in ammonia plants

Feedstock	% Capacity based on various feedstocks	
	As in 1980	As in 2021
Natural Gas	13.8	100.0
Naphtha	54.9	0.0*
Fuel Oil	20.8	0.0
Coal	10.5	0.0
Total	100.0	100.0

* one plant is using mix of naphtha and natural gas due to non-availability of sufficient NG.

Table 2. Vintage and capacity of ammonia plants

Vintage	No. of plants	Size (MTPD)	No. of plants
1. 1960s	3	<=600	7
2. 1970s	10	>600 & <= 1000	8
3. 1980s	12	>1000 & <= 1520	9
4. 1990s	12	>1520 to 2200	15
5. 2017	2		
Total	**39**		**39**

urea plants has been adopted. Status papers on energy conservation efforts of the industry have been published or presented in conferences from time to time. (Nand, 2019, Goswami and Nand 2015; Nand and Goswami 2011).

Later generation plants of 1980s and 1990s were put up based on relatively mature technologies. These plants have incorporated incremental developments over last 25-30 years. Older plants with vintage of 1960s and 1970s have continuously modernized to stay healthy to operate. A number of schemes have been adopted to improve energy efficiency by reducing energy requirement of both feed and fuel in the process, offsites and utilities over the years. Utilization of waste heat, upgrading equipment and machines with better efficient versions and optimizing process parameters have been part of energy saving drives in all plants.

The paper presents only the major technological and revamp/retrofit schemes implemented during last few years by many ammonia and urea plants.

2. Energy Conservation in Ammonia Plants

About 80% of energy requirement to produce urea and complex fertilizers is consumed in production of ammonia. Thus, ammonia plants have always remained in focus for energy conservation measures. The ammonia plants comprised of 7-8 distinct sections. Each of the sections has undergone modernization to exploit opportunity for energy savings. Some of the schemes required changes in more than one section to fully realize the benefits. The section-wise energy saving schemes are highlighted in the subsequent paragraphs.

2.1 Reforming Section

In the conventional steam reforming plants, there are two stages of reforming viz. primary and secondary. Part of the natural gas (methane) gets reformed in the primary reformer. The reformer is refractory lined furnace containing a number of catalyst filled tubes where endothermic reaction takes place. Heat is supplied through a large number of fossil fuel fired burners to raise temperature to 700-750 ^oC to activate the steam methane reaction in the catalyst filled tubes. The furnace flue gases pass through a convention chamber containing a number of heat recovery exchangers to utilize the waste heat. The waste heat is used for pre-heating the process air, the incoming steam and natural gas mixture, preheat boiler feed water, etc. The furnace flue stack temperature reflects the efficiency of waste heat recovery. Installation of additional heat exchangers and replacement of old exchangers with improved design for recovery of waste heat from furnace flue gases have been part of revamps/retrofits over the years. These modifications were implemented by plants depending on space available in convection section. After such modifications, the furnace flue gas temperature has been reduced to the level of 120 - 130 ^oC in most plants. It reflected that waste heat was recovered to the maximum extent.

Rest of the reforming which intentionally not completed in primary reformer is completed in the secondary reformer. In addition to steam present in the inlet of process gas, air is also introduced in the secondary reformer. Air constitutes 21% oxygen and combustion reaction along with steam reforming takes place which makes the overall reaction in the secondary reformer exothermic. The process gas temperature at the outlet of secondary reformer is about 1000 ^oC. This heat is utilized to generate high pressure steam in reformed gas boiler. Alternatively, this heat can be utilized to process more reformed gas in a reformer exchanger. Reaction heat is more effectively utilized for reforming gas than generating steam. The additional advantage is reduced size of primary reformer for same capacity. Alternatively, capacity of reformer section can be increased with addition of reformer exchanger. Additional steam can be generated in standalone boiler to meet the requirement at site. One of the plants in India has installed reformer heat exchanger during revamp and another greenfield plant with exchanger reformer is expected to be commissioned soon.

Steam-Carbon (S/C) ratio in the feed to primary reformer is one of the key parameters having bearing on energy efficiency. Excess steam is used to prevent the thermal cracking of the methane resulting in carbon formation and protect the catalyst from sintering. Most of the steam reforming ammonia plants maintain S/C ratio of 3.3 to 3.5 but excess steam requires energy and later steam condensate has to be treated. Therefore, lowering of S/C ratio to 3.0 or even lower have benefit of saving of steam and thus energy. However, this modification is guided by optimization in primary reformer and of steam requirement in the subsequent steps such as shift section. In recent revamps, four ammonia plant achieved S/C ratio of 3.0 - 3.1 with modifications in downstream sections.

Lower S/C ratio can also be achieved by shifting heat load from primary reformer to secondary reformer. Excess air in the secondary reformer is to be introduced for completion of reaction which lead to generating excess inerts. The inerts can be removed from syngas by installing a cryogenic purifier. Two ammonia plants have installed cryogenic purifier during revamp and maintain S/C ratio of 2.6. Another plant in order to change the feed from fuel oil to natural gas replaced its front with purifier technology and was able to achieve S/C ratio of 2.9.

2.2 *Purification Section*

2.2.1 Carbon monoxide generated during reforming is converted to carbon dioxide and hydrogen in two stage shift reaction for thermodynamic considerations. The reaction should go to completion. Any unconverted carbon monoxide will have to be converted to methane which consumes hydrogen. Therefore, in recent times LT shift guard prior to LT shift reactor has been installed by a number of ammonia plants in the country. This is to maximize the conversion of carbon monoxide. A plant has changed the internal configuration of LT shift converter from radial to radial axial to reduce pressure drop across converter.

A number of plants have carried out modifications in carbon dioxide recovery section as it has significant energy saving potential. The endeavour is to reduce energy consumption in regeneration stage. The single stage regeneration has been changed to two-stage regeneration systems by a number of plants. Plants have also changed to better solvents. In recent revamps, a few plants have changed the solvent from hot potassium carbonate to amine based OASE White. Due to high solution flow rates, most of the equipment such as pump, columns, filters, etc were replaced. More efficient multistage pumps for lean and semi-lean solution and hydraulic turbines were installed in this section. DM/BFW heat exchangers were also installed to reduce process gas temperature going to re-boilers. With these modifications, regeneration energy of CO_2 removal section was reduced from level of 830 kCal NM^{-3} to 500-550 kCal Nm^{-3} of CO_2 and hydrogen loss in product CO_2 was also reduced from 0.8 mol% to 0.15 mol% (Singh et al., 2018; www.iffco.in).

Excess steam used in primary reformer is condensed. The condensate contains ammonia and methanol. Carbon dioxide also gets dissolved in the process condensate in raw gas separator. The older generation plants were using LP steam for condensate stripping for removal of dissolved ammonia, carbon dioxide and methanol. The process condensate is further treated in polishing unit for removal of trace amount of ammonia and carbon dioxide. The treated condensate is cooled from about 100 ^oC to 40 ^oC in water cooler. The LP steam after stripping is vented through stack and heat from treated condensate is lost in cooling. The plants of later generation have medium pressure condensate stripping. Part of MP steam from stripper is fed to primary reformer rather venting. There is also more heat recovery from outlet condensate with installation of feed effluent heat exchanger. This scheme has been implemented by a number of old plants during recent revamps.

2.3 *Synthesis Section*

Many plants improved the energy efficiency in ammonia synthesis section by installing additional reactor which reduces pressure drop and increases conversion per pass in the synthesis loop. A few plants have also changed the internal of two bed catalyst system to three bed catalyst system. The reduction in synthesis loop pressure from above 200 bar to level of 140 bar has been achieved. Except a few old plants, most plants maintain synthesis loop pressure in the range of 140-180 kg cm^{-2}.

The installation of additional converter (like S-50) resulted in increased conversion and hence increased temperature. A new MP boiler is installed for heat recovery which provided better operational flexibility by maintaining lower inlet temperature and improving ammonia conversion.

Purification of synthesis gas involves removal of moisture and oxides of carbon for which make-up gas is mixed with effluent gas exit of ammonia converter before entering ammonia separator. Ammonia wash unit has been installed in a few plants after the second stage discharge of synthesis compressor. Modification in synthesis loop resulted in reduced syn gas circulation power in recycle stage and lower temperature of make-up syn gas with a typical energy saving of 0.03 Gcal MT^{-1} ammonia (Singh et al., 2018).

3. Energy Conservation in Urea Plants

Energy conservation efforts in urea plants have been focused on reducing specific ammonia consumption and by reducing steam and power consumption. A number of schemes were implemented to utilize the waste/excess steam available which was being thrown to cooling towers.

3.1 Synthesis Section

Synthesis of urea takes place in urea reactor where ammonia and carbon dioxide react at high temperature and pressure. The reaction takes place in two steps. The first step involves formation of intermediate ammonium carbamate and second step is dissociation of ammonium carbamate to urea and water. The reaction is reversible and limited by equilibrium considerations. The un-dissociated carbamate is converted to its constituents i.e. ammonia and carbon dioxide in subsequent steps utilizing steam (HP/MP/LP). Higher conversion in reactor will lead to lower steam consumption in the subsequent steps and hence saving in energy.

For improving conversion efficiency in reactors, modifications have been carried out to increase the surface area in the reactors by installing additional reactor trays. The newer design trays improve contact between ammonia and carbon dioxide and due to better MOC, weight on reactor liner can be reduced. A urea plant of 1970s vintage replaced 11 trays with high energy efficient trays and gained 1% in conversion (Singh et al., 2018). In recent revamps, some plants have installed vortex mixture and converter booster devices at the bottom of the reactor. This allows better intermixing of ammonia and carbon dioxide and increased conversion. A carbon dioxide conversion of 72% has been achieved in some plants.

In a carbon dioxide stripping urea plant operating with HP stripper, off gases are fed to HP carbamate condenser from top along with ammonia. In a unique revamp, this configuration was changed to HP split flow loop where HP carbamate condenser is changed to full condenser design and the HP stripper off gases are split into two parts. Only a small part of gas from HP stripper is fed to urea reactor. The major part passes first through the bottom of HP carbamate condenser and then after separation of carbamate solution directly to inert scrubber. As a result, the volume of inert gases passing through the reactor is reduced, thus improving the CO_2 conversion (Singh et al., 2018 and www.casale.ch).

Frequent breakdown also leads to energy losses during shutdown and start-up. To improve the reliability of urea reactor, plants have been replacing liners and old reactors with new reactors. A plant could save about 0.014 Gcal MT^{-1} urea energy after replacing old reactor with new reactor due to increased conversion and reduced steam requirement (Subramanian, 2021).

3.2 Decomposition and Concentration Sections

Decomposition of carbamate takes place conventionally in three stages, high, medium and low pressure sections. LP steam is generated by condensation of urea stripper off-gas in HP carbamate condenser. This LP steam is used in downstream sections to meet the process requirement. To utilise the surplus LP steam, many plants have installed MP pre-decomposer as revamp measures. The MP pre-decomposer provides an initial decomposition of carbamate flowing from the stripper bottom before entering the MP decomposer. This reduces the medium pressure steam requirement in MP decomposer and reduce extraction steam load of CO_2 compressor.

A pre-concentrator section has also been added by some plants. The pre-concentrator utilizes heat of condensation of carbamate vapours from the MP decomposer top separator portion which otherwise was going to cooling water. The waste heat generated from steam condensate tank, steam condenser and flash steam is dumped in cooling water. This heat can be utilized to generate LP steam in flash vessel. A plant utilized this LP steam in booster ejector to maintain 2^{nd} stage vacuum in concentration.

Installation of ammonia pre-heater upstream of existing HP ejector to utilize LP decomposer off gases also implemented in recent revamps.

3.3 Energy Savings in Machines and Equipment

3.3.1 Rotating Machines

Ammonia and urea plants employ large compressors and pumps driven by steam turbines. Reduction in steam consumption in these machines has resulted in considerable energy savings. The process air, synthesis gas and carbon dioxide are such large compressors and plants have carried out retrofits to improve the efficiency of these compressors. Low pressure surplus steam is utilized in vapour absorption refrigeration (VAR) system to generate cold which is used to cool the inlet gas to compressors by almost 10 °C. This measure helped to improve efficiency of compressor. For same plant load, it will result in saving of high pressure steam. A plant achieved an energy saving of about 0.03 Gcal MT^{-1} urea by installing VAR system in the ammonia synthesis gas suction chilling. Another plant realised energy saving of 0.01 Gcal MT^{-1} ammonia after installation of VAR in process air compressor. A plant achieved energy saving of 0.09 Gcal MT^{-1} urea after installation of VAR in carbon dioxide compressor. The replacement of old ammonia synthesis gas turbine with high efficient steam turbine resulted in energy saving of 0.073 Gcal MT^{-1} urea (Subramanian, 2021). As energy saving measure, VAR system has also been installed/planned in gas turbine generators.

In a revamp in 2020, a plant upgraded the synthesis gas compressor and turbine. The turbine modification included replacement of rotors, diaphragm assembly and nozzle segments with higher efficiency. The rotors of HP and LP compressor were replaced with energy efficient rotors, number of stages in both HP and LP compressor were reduced, high precision flow path construction and other modifications in diaphragm and impellers resulted in desired savings in steam. This plant was able to reduce energy consumption by about 0.165 Gcal MT^{-1} urea.

In another revamp of synthesis gas compressor by a plant, LP and HP case old rotors with vane less diffuser were replaced with low solidity diffuser. The original casing, bearings and seals remained same. Anti-surge control valves and LP side couplings were also replaced. These modifications resulted in increase in overall efficiency of compressor from 67% to 74% (Singh et al., 2018).

Trimming size of large pumps to meet the low load requirement, installation of variable frequency drives (VFDs) and changing drive of some small capacity steam driven pumps to motor drive have improved efficiency. A plant of old generation has replaced the low efficiency steam turbines of ID/FD fans with higher efficiency turbines resulting in energy saving of 0.05 Gcal MT^{-1} urea (Subramanian, 2021).

It has been established that smaller pumps and turbines are more efficient if driven by power than steam. Many plants changed drives of smaller pumps from steam turbine to motor drive. One of the plants with surplus power available from captive power plant recently changed its carbon dioxide compressor drive to motor in two of its streams. The expected energy saving is around 0.05 Gcal MT^{-1} urea in each stream. Change of steam driven ammonia refrigeration compressor with motor drive was carried out by another plant with energy saving of 0.05 Gcal MT^{-1} urea.

Another scheme that has been successfully adopted in a few plants is to use gas turbine to drive process air compressor and exhaust gas is used to generate steam in boiler.

3.3.2 Static Equipment

Ammonia and urea plants utilize a number of heat exchangers for recovery of heat from process gas, steam and hot streams. Replacement of older heat exchangers with better design heat exchangers has resulted in energy saving. For example, in primary reformer convection section better design (plate type) heat exchanger with larger surface resulted in higher heat recovery and its utilisation. Similarly, old generation plants have replaced the CO_2 direct contact cooler with better efficiency heat exchanger resulting in energy saving of 0.003 to 0.01 Gcal MT^{-1} urea. Replacement of ammonia product cooler to utilize cooling duty in the product ammonia resulted in reduction in suction temperature of refrigeration compressor and thus energy saving 0.007 Gcal MT^{-1} urea. Improving reliability of exchangers and boilers can help in reduction in leakages and unwanted shutdown leading to energy losses.

3.4 Energy Conservation Schemes in Utilities

Change of fuel from coal/fuel oil to natural gas for steam and power generation has resulted in substantial saving in overall energy of the complex. The installation of gas turbine (GT) with heat recovery steam generation (HRSG) has improved efficiency in power generation. Three plants with coal based power generation and facilities, plants have changed to GT-HRSG. The commissioning has been delayed due to pandemic. This is expected to result in energy saving of around 0.2 Gcal MT^{-1} urea in each unit.

Retrofit of conventional wooden cooling tower with pultruded FRP structural components in two cells resulted in power saving of about 54 kW h^{-1} due to reduced water circulation rate. The latest plants have now gone for concreate based cooling towers for more reliable and efficient operation (Inamdar et al., 2018).

There is large amount of water requirement for process and cooling. Plants are making continuous effort to reduce raw water consumption and generation of effluents. These include reuse/recycle of water within the plant. The raw water consumption for ammonia and urea plants has reduced from 12.0 M^3 MT^{-1} urea in 1990-91 to 6.1 M^3 MT^{-1} in 2019-20. The waste water discharge has been reduced by more than 80% during the same period. Conservation of water has also contributed to saving in energy in treatment of raw water and effluents.

4. Performance of Ammonia and Urea Plants

4.1 Ammonia Plants

The result of various energy saving schemes implemented over the years is reflected in reduction in energy consumption of both ammonia and urea plants over last 3 decades. The weighted average energy consumption for ammonia plants has been reduced from 12.48 Gcal MT^{-1} ammonia in 1987-88 to 8.19 Gcal MT^{-1} ammonia in 2020-21, a reduction of 34.3%. **Figure 1** shows the trend of energy consumption in ammonia plant.

Comparison of energy consumption of Indian ammonia plants shows that the average energy consumption of Indian ammonia plants is lower than average of the world plants.

For the sake of internal benchmarking, ammonia plants have been divided into four quartiles

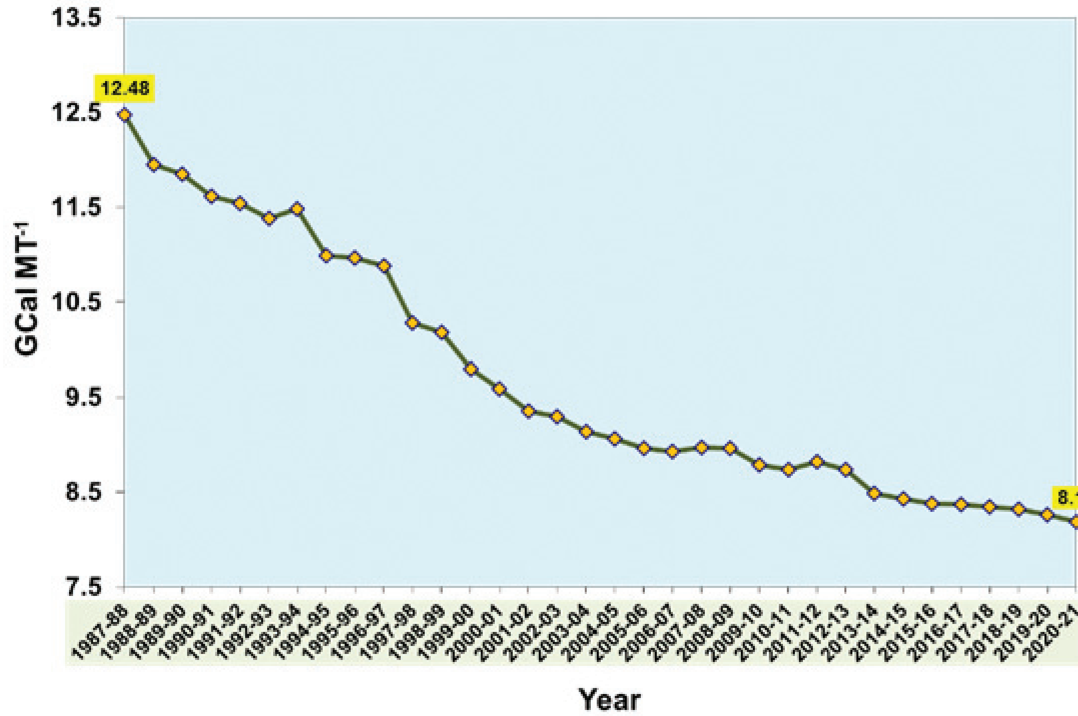

Figure 1. Trend in energy consumption in ammonia plants

depending on their energy consumption (**Figures 2**). The quartile excludes two outlier plants. It can be seen that the best 25% are having energy consumption of 7.45 GCal MT^{-1} ammonia while the last 25% energy consumption is 9.55 GCal MT^{-1} ammonia. The latest plant commissioned in 2019 achieved 7.15 GCal MT^{-1} ammonia. The best old plant which has undergone a major revamp achieved an energy consumption of 7.24 GCal MT^{-1} ammonia.

4.2 Urea Plants

As observed in ammonia plants, the corresponding reduction in energy consumption is also reflected in urea plants. The weighted average energy consumption of urea plants is reduced from 8.87 Gcal MT^{-1} urea to 5.78 Gcal MT^{-1} urea for the same period again a reduction of 34.8%. **Figure 3** shows the trend of energy consumption in urea plants.

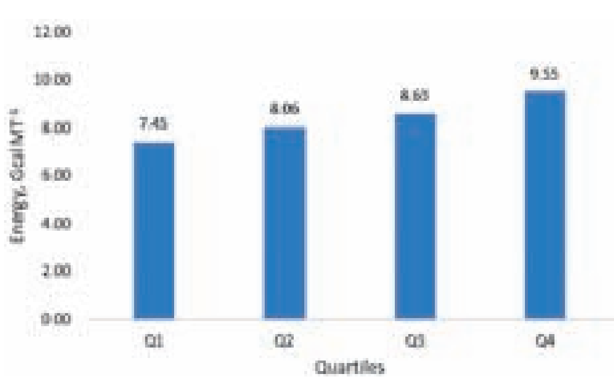

Figure 2. Energy consumption quartiles for ammonia plants

In case of urea, the best 25% plants showed weighted average energy consumption of 5.21 GCal MT^{-1} urea **(Figure 4)**. The latest generation plant energy consumption was 5.0 GCal MT^{-1} urea while another plant of mid 1990s also achieved the same energy consumption level in 2020-21. The plants which are in the last quartile in both ammonia and urea plants include plants which utilize coal for generation of steam and power and old plants including those converted to gas from naphtha.

The ammonia consumption per tonne urea (MT per MT) is also a measure of efficiency. It has been reduced from the level of 0.589 in 1990-91 to 0.574 in 2020-21. The weighted average steam and power requirement in urea plants has reduced from the order of 1.50 Gcal MT^{-1} in 1990-91 to 1.08 Gcal MT^{-1} urea in 2020-21. The best figure achieved by a plant in 2020-21 was 0.77 Gcal MT^{-1} urea.

5. Conclusion

Indian ammonia and urea plants have undergone several rounds of major revamps/retrofits constantly to improve the energy efficiency. There have been modifications in each section in ammonia and urea plants to save energy. The earlier developments were focused on utilizing high grade waste heat. Of late, the focus shifted to utilize low grade heat. The

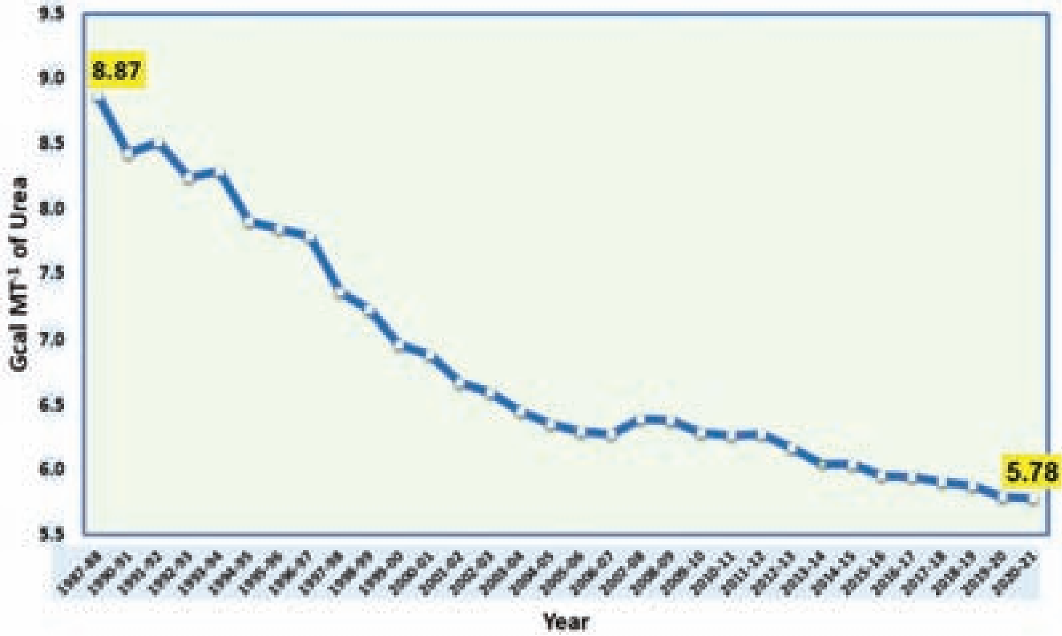

Figure 3. Trend in energy consumption in urea plants

integration of waste heat from one plant to other plant also helped in improving the energy efficiency in integrated ammonia and urea complex. Plants of older vintages have taken advantage of latest developments in equipment and replaced old compressors and turbines with more efficient one to reduce steam and power consumption. The all-round efforts made for energy conservation in ammonia and urea plants improved energy efficiency by more than 30% over last three decades. The limiting factor for further reduction has been replacement cost of capital equipment with long payback period of more than 10 years.

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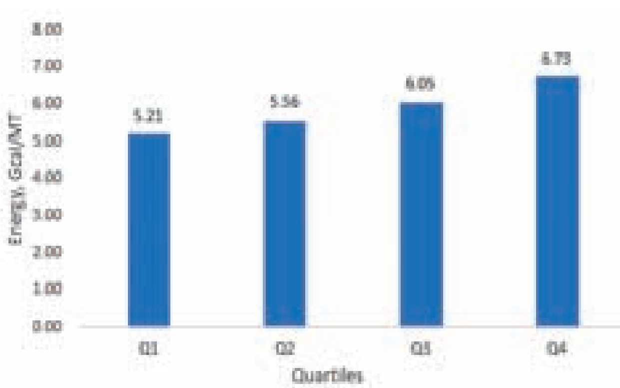

Figure 4. Energy consumption quartiles for urea plants

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