VALORIZATION OF EXCESS LP STEAM FOR REDUCED CARBON FOOTPRINT OF UREA PLANTS

STAMICARBON

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SUMMARY

1 ABSTRACT

Traditional urea stripping plants produce an excess of low-pressure (LP) steam available at relatively low temperatures (below 150 °C), as usually not all the energy generated by the exothermic reaction of carbamate formation is reused inside the process. This steam is typically considered an unwanted product with a relatively low value due to the temperature limitation. The excess steam might even have to be vented, and this represents a waste of energy.

The aim of this paper is to explore avenues to achieve carbon footprint reduction and reutilization of what is traditionally considered 'waste steam'. Several methods are industrially available; this paper will outline two categories for potential reutilization of excess LP steam: reuse of LP steam as motive fluid of turbine drivers (Case a) – a common practice in a urea plant – and mechanical vapor recompression (MVR) of LP steam as a heat exchange medium (Case b).

Case a. Tecnimont has operated the CO_2 compressor turbine for a plant commissioned in the Middle East by utilizing surplus low-pressure steam at 4 barg, injecting it into the turbine as additional motive fluid for the driver. This solution resulted in a net shaft power saving of approximately 10 kWh(e) per ton of granular urea, corresponding to an energy reduction of about 0.04 Gcal per ton of urea.

Case b. MVR is a process where the generated 'waste' LP steam is compressed using an electrically driven compressor to convert it into high-pressure (HP) steam. This HP steam can then be used in other relevant sections of the urea plant. An interesting user of the compressed LP steam is the HP stripper. Within this category, a case study for a self-supplying steam system is also analysed.

In a bigger picture, such optimization can be applied in principle to both CO_2 and NH_3 stripping plants.

This innovation facilitates a reduction of the carbon footprint by replacing part of the energy consumption by traditional carbon-based steam boilers to renewable electricity sources by leveraging the exothermic energy from the urea synthesis process.

2 INTRODUCTION

In both conventional and stripping urea plants, heat must be supplied to the urea synthesis to decompose unconverted carbamate and evaporate excess ammonia and water. This heat is usually delivered as steam at pressures between 15 and 25 bara, termed as high-pressure (HP) steam in this paper. In stripping plants, this heat is recovered from an HP carbamate condenser – where unconverted ammonia and carbon dioxide are condensed to form ammonium carbamate – as low-pressure (LP) steam (typically around 4.5 bara at saturated conditions) and reused in LP heaters and other parts of the urea plant [1]. Due to the exothermic nature of the ammonium carbamate formation reaction, combined with the heat input from the HP steam, excess LP steam is produced. This excess steam translates to relatively low-temperature steam with temperatures below 150 °C. Due to the low temperatures, plants typically face challenges in utilizing this steam. To the writers' knowledge, in several cases (part of) excess steam ends up being condensed against cooling water or vented to the atmosphere. This represents a waste of energy and reduces the overall efficiency of the plant.

This paper explores methods to utilize the excess LP steam to enhance urea plant efficiency and reduce its carbon footprint.

3 UNDERSTANDING LP STEAM IN STAMICARBON UREA PLANTS

LP steam is produced in the synthesis section of a urea stripping plant. This steam results from removing the heat of condensation of unconverted ammonia and carbon dioxide to form ammonium carbamate. The LP steam pressure is crucial to controlling the pressure and temperatures in the synthesis section. LP steam produced in Stamicarbon urea plants is typically in the range of 4 to 6.5 bara. The corresponding temperatures and specific enthalpies from steam tables can be seen in Table 1. This represents the amount of energy available from condensing 1 kg of LP steam.

	Pressure	Temperature (saturation)	Specific ∆ enthalpy[1]
Lower value	4 bara	144 °C	2319 kJ/kg
Normal operation	4.5 bara	148 °C	2325 kJ/kg
Higher value	6.5 bara	162 °C	2341 kJ/kg

Table 1: Typical properties of LP steam in a Stamicarbon urea plant.

The produced LP steam is utilized in various parts of the urea plant. It is typically used in LP heaters, evaporators, the desorber in the process condensate treatment section, and to drive the ejectors of the vacuum condensers. Basically, the downstream section of the urea plant relies on LP steam for its energy needs. However, in traditional Stamicarbon CO_2 stripping plants, excess LP steam is produced. This steam, if simply vented to the atmosphere or condensed against cooling water, would represent an energy loss. For this reason, it is important to recover such energy sources to optimize the overall energy efficiency of the plant.

4 COMMON PRACTICES FOR REUTILIZATION OF EXCESS LP STEAM

This section outlines examples of common industrial practices for reutilization of excess LP steam in urea production facilities. The first example describes LP steam injection into turbines for CO_2 compressor driving. The second example covers the use of LP steam as a heating medium for energy consumers in the off-site systems, such as demin-water de-aerator or warehouse heating.

4.1 Reuse of LP steam as motive fluid for turbine drivers

Steam turbines are critical components in the energy and industrial sectors, converting thermal energy from steam into mechanical work. Traditionally within ammonia fertilizer complexes, HP steam is used to drive the turbines to maximize the thermodynamic efficiency of compressors driving systems. To further improve overall plant efficiency, the excess LP steam from the plant can be injected into the turbine and used as motive fluid for the driver.

One of the main challenges in the design of LP steam injection turbine is represented by the significant variation of exhaust volumes, since the energy content per unit of mass of motive steam is less when using lower-pressure steam at saturated conditions.

However, recent advancements in the application of modern 3D steam turbine design tools have made the valorization of excess LP steam possible. By selecting appropriate steam turbine exhaust size and optimizing the blade design, substantial energy benefits can be achieved [2].

[1] ∆ *Enthalpy is the difference between the enthalpy of saturated steam (at the indicated pressure) and the enthalpy of condensate at 100 °C.*

One of the primary benefits of injecting LP steam is improvement in thermal efficiency. Introducing steam at a lower pressure allows the driven compressors to make better use of the available thermal energy, reducing the overall heat rate of the auxiliary boiler, or making an equivalent amount of HP steam available for other purposes (e.g., for power turbo generation). This not only lowers operational costs but also reduces greenhouse gas emissions, contributing to a more sustainable energy production process.

Tecnimont (MAIRE Group) successfully commissioned a urea plant in the MEA area in late 2019 by implementing the injection of excess LP steam generated by the process into the CO_2 compressor turbine. The practical benefits are described below.

The process scheme of the CO_2 compressor driving system is shown in Figure 1. The CO_2 compressor is driven by an extraction-admission-condensing steam turbine. HHP steam from the ammonia plant at about 45 bara and 398 °C is fed to the inlet of the turbine. HP extraction steam used for the urea stripping process is made available at about 22 bara. The excess LP steam at around 3.9 bara enters the lower-pressure stage of the turbine to further drive the compressor, and the exhaust steam is condensed in the water-cooled condenser at about 0.11 bara.

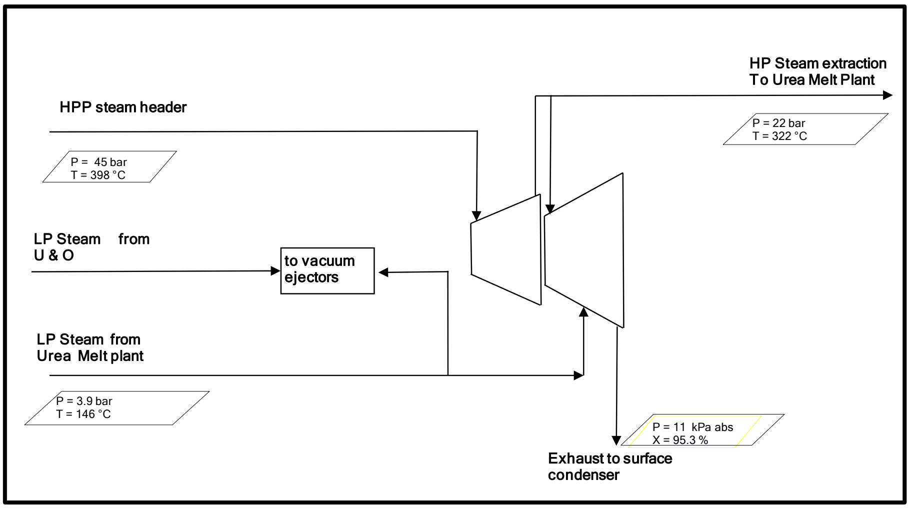

Figure 1: Typical scheme of the CO_2 compressor steam driving system.

Figure 2 shows the profiles of admission steam and output power during a four-day demonstration run. The power obtained in each turbine stage has been calculated as the mass flow of steam admitted to that stage multiplied by the difference of enthalpy between inlet and outlet. Looking at the graph, it can be noted that the power delivered by the LP steam induction (green line, scale on the right) is directly proportional to the LP induction steam flow (purple line, scale on the left). Considering an average production of 1670 MTPD of urea during the trial, the power obtained by injecting LP steam into the turbine is 705 kW (averaged for 96 hours), resulting in a net saving of 10.1 kWh(e)/t of urea.

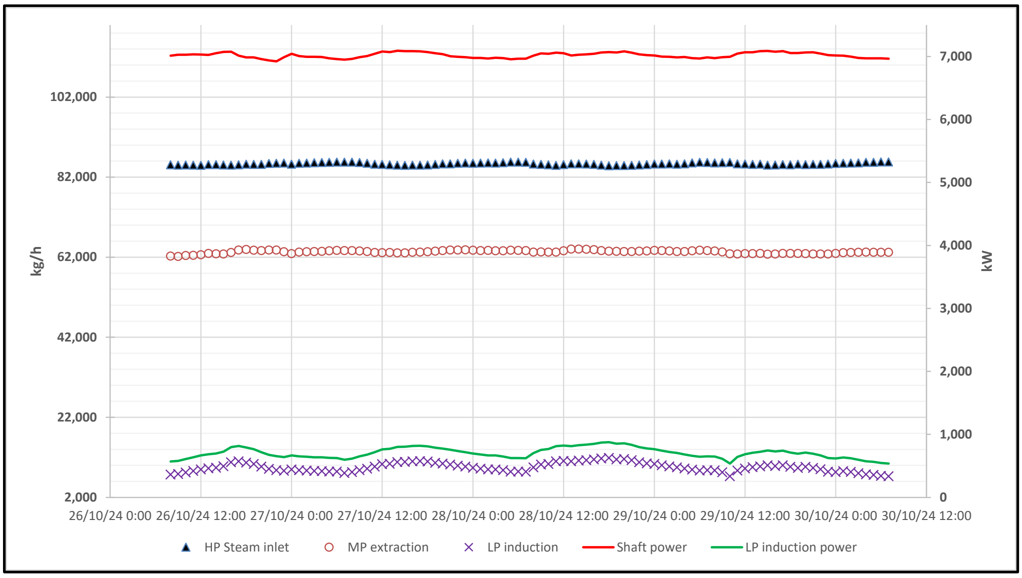

Figure 2: Profiles of admission steam and turbine output power during a 96-hour trial.

Based on the practical example of the case study analyzed here, the urea plant designed and put into operation by Tecnimont reported an increase in shaft power efficiency of about 10 kWh(e)/t of urea granules and a reduction of 0.04 Gcal/t of urea after adopting this technique. This represents a saving of 4.3% of the total fuel gas consumption for this plant, based on the reference urea plant consumption of 0.94 Gcal/t of urea granules (excluding the energy consumption for the ammonia production). The case study highlights the real-world advantages and potential for widespread adoption of injecting LP steam into steam turbines. This potential offers several energy advantages, including improved thermal efficiency, reduced fuel consumption, and enhanced operational flexibility, especially in situations where HHP steam available from the complex is limited.

4.2 Reuse of LP steam as heating medium for offsite users

Usually when urea plants are integrated with ammonia production facilities, there is need for stripping steam to evacuate dissolved oxygen from the boiler feed water used in the HP steam generator of the steam methane reformer or ammonia synthesis systems. Since the de-aerator operating pressure is slightly above atmospheric pressure, the level of steam exported by the urea plant is particularly fitting for this purpose.

Another application, especially suitable for plants located in geographic areas with a humid and relatively cold climate, is to provide a heating system into the closed environment of the urea warehouse. This prevents the relative humidity of the ambient air from crossing the curve of critical relative humidity of the product inventory, thus avoiding caking and preserving the ideal physical properties of the product, even for relatively long storage periods. The concept is outlined in the example shown in Figures 3a and 3b. In an unheated environment, with a relative humidity of 90% and an ambient temperature around 10°C (conditions commonly observed during winter in many continental European countries), the water vapor pressure in the air (blue curve) exceeds that of the saturated urea solution eventually forming on the surface of granules (red curve). This means that the product can absorb moisture continuously until the solid is completely dissolved on the outer surface of granules. This condition typically leads to sticking of urea particles and caking of the stockpile.

However, when the ambient air of the environment is heated at least more than 5°C, the curve of the water vapor pressure in the air is below the water vapor pressure of a saturated urea solution. This means that desorption of moisture from the granules' surface takes place [3] and leads to a safe condition to prevent caking phenomena.

Usually, heating systems for such applications are realized with radiant panels heated by hot water. The thermal losses are compensated via an external heat exchanger, supplied with LP steam exported by the urea plant.

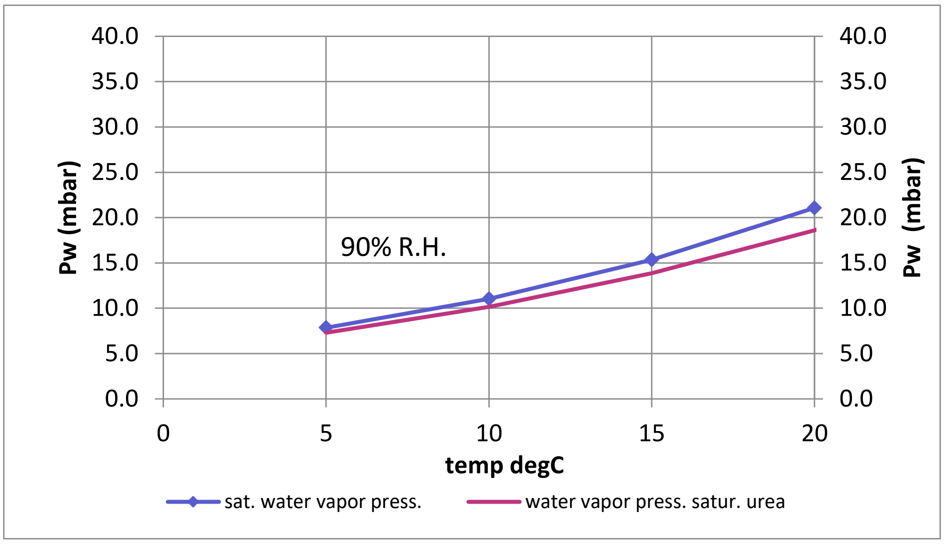

Figure 3a: The urea product absorbs moisture from the cold environment at 90% RH.

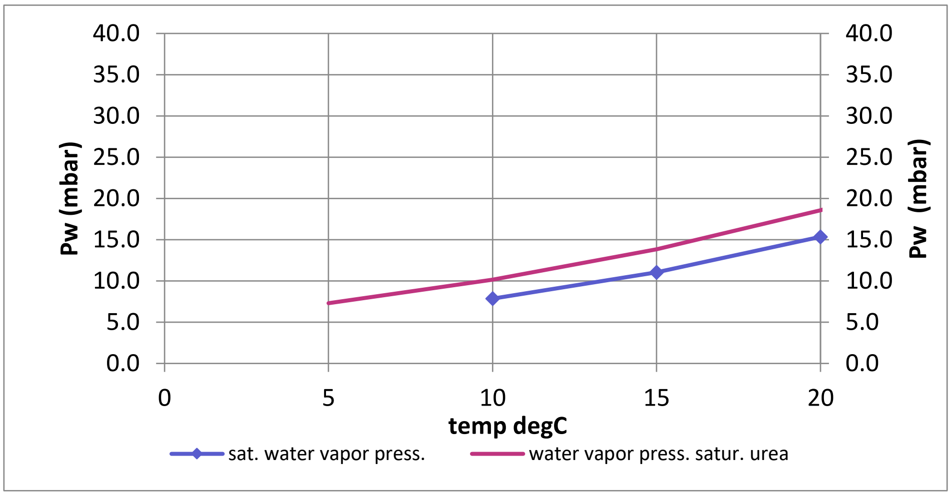

Figure 3b: Desorption of moisture from urea product to the heated environment.

To sum up, Tecnimont has designed several facilities by ensuring proper levels of integration between the steam networks of ammonia, urea and off-site systems, maximizing the reuse of excess LP steam generated in the urea plant.

5 MECHANICAL VAPOR RECOMPRESSION OF LP STEAM

Turbo-compressors are an emerging field of interest for high temperatures and large-capacity heat pumps for waste heat recovery [7]. Compressor vendors are increasingly becoming more adept with proven technologies particularly for steam compression. In this context, among the improved technologies related to the use of excess LP steam, mechanical vapor recompression (MVR) is a very interesting and promising application.

MVR involves the use of a compressor (usually electrically driven) to transform LP steam into HP steam. This process not only enhances the usability of excess LP steam but also reduces the need for additional HP steam generation, minimizing the consumption of carbon-based fuels. This application draws from parallels applied in other industrial processes. Examples can be seen in the paper industry [4], food industry [5], and even petrochemical complexes [6]. This paper describes how the MVR process can be particularly advantageous in a urea stripping plant.

The excess LP steam generated from the urea synthesis is compressed to HP steam for use in the urea stripper. In this way, the residual heat of the LP steam generated in the HP condenser at around 140-150 °C can be increased to a pressure (16-18 bara) suitable for transferring heat directly to the HP stripper. To make this process even more environmentally friendly, the compressor can be driven by renewable electricity. This is made attractive even further by the increased availability and cheaper supply of renewable electricity. The compressed steam, being used for example on the shell side of the HP stripper, can reduce the import of HP steam from battery limit. The proposed scheme is illustrated in Figure 4.

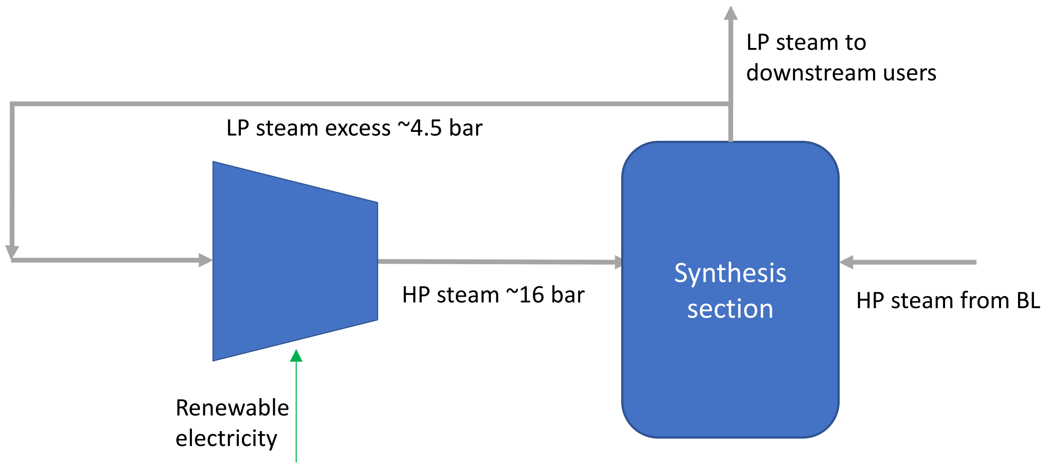

Figure 4: LP steam compression scheme.

Typically, HP steam in a urea stripping process is supplied by the steam network of an ammonia complex or by a steam boiler. The MVR concept is particularly interesting for steam deficient urea complexes, such as sites that do not have a complete ammonia train (comprising for instance only the ammonia loop, but not the syngas production), or cases where urea is an add-on unit and there is no availability of surplus steam. For example, sites with CO_2 capture/recovery technology and ammonia from a modular source or specific green ammonia technologies can benefit from this concept. By implementing MVR of LP steam, urea plants can de-bottleneck their processes and utilize all available excess steam. This approach not only improves energy efficiency but also reduces the dependency on HP steam imports.

5.1 Case study for a traditional Stamicarbon CO_2 stripping plant

A case study can be carried out in a traditional Stamicarbon CO_2 stripping plant. Figure 5 below shows a typical distribution of the LP steam users in the plant. About 24% of the LP steam produced in the synthesis section is excess (green in the figure). If no reuse of excess LP steam is foreseen, as discussed for instance in the applications of section 3, MVR is a valid alternative to maximize the overall energy efficiency of the urea plant.

For a 2000 MTPD urea plant, excess LP steam is in the order of magnitude of 20 ton/hour (240 kg/ton urea), and based on the enthalpy content of steam (see Table 1), this represents an amount of energy of about 12.5 MW.

When this amount of LP steam is compressed to the pressure level required by the HP stripper, a reduction of generation of an equivalent amount of HP steam is achieved. By calculating that 100 kWh/ton of steam is required to compress this excess LP steam to 16-18 bara (as required for the HP stripper), a compressor power of about 2 MW is estimated. Furthermore, 2.5 to 3 ton/hour of saturated steam can be generated at compressor interstages. The 20-23 ton/hour can then be deducted from the required HP steam import, achieving a reduction factor of 0.093 Gcal/t urea in fuel consumption after deducting the energy spent for the steam recompression. This represents a saving of almost 10% of the total fuel gas consumption for the urea plant (excluding energy consumption for the ammonia production). Effectively, this means that the excess exothermic energy released from the urea plant combined with electrical energy input for the compressor could replace a significant portion of the required HP steam import.

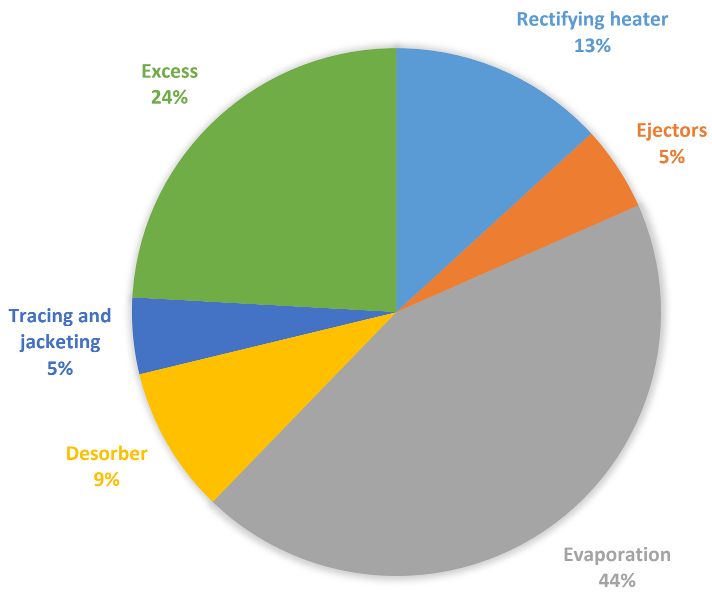

Figure 5: Typical distribution of LP steam users in Stamicarbon's traditional stripping plants.

5.2 The case study for a self-supplying steam system (zero HP steam import)

By maximizing excess LP steam produced in the urea process, a case can be made for a self-supplying steam system using MVR technology. A configuration in which enough lower-pressure steam is produced within the process and compressed to the pressure level required in the stripper is explored. As shown in this analysis, the implementation of this new application for certain plant configurations enables the complete elimination of HP steam import from the battery limit during normal operation.

The concept fits with the Stamicarbon Ultra-Low Energy (ULE) process, particularly for producing low concentration urea solution suitable for DEF or UAN production. An overview of the proposed configuration is illustrated in Figure 6.

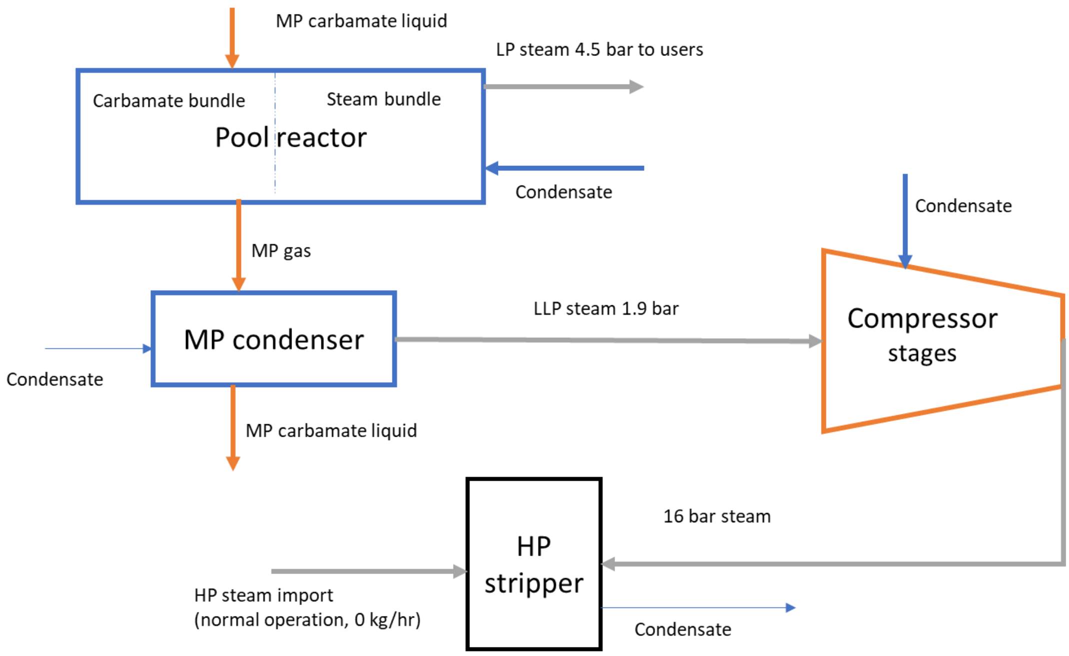

Figure 6: A conceptual urea plant with zero HP steam import during normal operation.

Key features of this configuration are as follows:

1. *Low concentration urea solution product*

   In this case study, DEF is produced, but UAN could also be a product. This effectively reduces the amount of LP steam utilized in the downstream process, as there is no evaporation and process condensate treatment section, thus lowering the LP steam requirement of the plant.

2. *Adoption of a ULE pool reactor with double bundle*

   One bundle is used to produce 4.5 bara LP steam, while the second bundle is for MP decomposition of carbamate from the urea/carbamate solution from the HP stripper, generating the main amount of several MP carbamate vapors (in the ULE plant concept several streams of MP vapor are generated).

3. *Heat utilization from MP vapors*

   In a conventional ULE plant, the heat from the generated MP vapors is used to concentrate the urea solution in the first stage evaporator up to 95 wt% by utilizing the heat of condensation of the MP vapors. In the self-supplying steam configuration for DEF/UAN production, it is not required to concentrate the urea solution. Therefore, the heat from the MP vapors is used to generate another level of steam at about 1.9 bara, termed as LLP steam. This LLP steam is produced via heat exchange of the MP vapors against steam condensate. The pressure of the generated LLP steam depends on the available pressure of the MP vapors.

4. *Compression of LLP steam*

   The generated LLP steam is compressed to HP steam sufficient for operation of the stripper.

5. *Optimizing LP steam*

   The amount of LP steam available is optimized by adjusting the different involved heat exchanging areas and applying the suitable stripping efficiency in the HP stripper. Furthermore, an additional amount of saturated LP and HP steam can be generated at the compressor interstage cooling section by the injection of the required steam condensate to de-superheat compressed steam.

6. *Lower stripping efficiency*

   Operating at lower stripping efficiency with a ULE synthesis allows for a lower pressure requirement for the steam applied to the stripper (around 16 bara in this case). This also leads to less biuret formation.

7. *Design optimization of MP section*

   The quality and quantity of the LLP steam produced is also influenced by the operating pressure of the MP section. A higher MP pressure allows for a higher LLP steam pressure with a trade-off of lower amount of LLP steam generated.

For a plant capacity of 1500 MTPD urea solution for DEF, it is determined that the amount of LLP steam generated, compressed and sent to the HP stripper shell side is 32 ton/hr;sufficient for the stripper operation in normal conditions. The estimated power of the multi-stage steam compressor with an assumed polytropic efficiency of 80% is around 4.2 MW, which is equivalent to a specific electric power consumption of 70 $kWh_{(e)}$/ton urea.

A sensitivity analysis, illustrated in Figure 7, was conducted to assess the feasibility of this concept as a grassroot initiative, with key variables identified in the process.

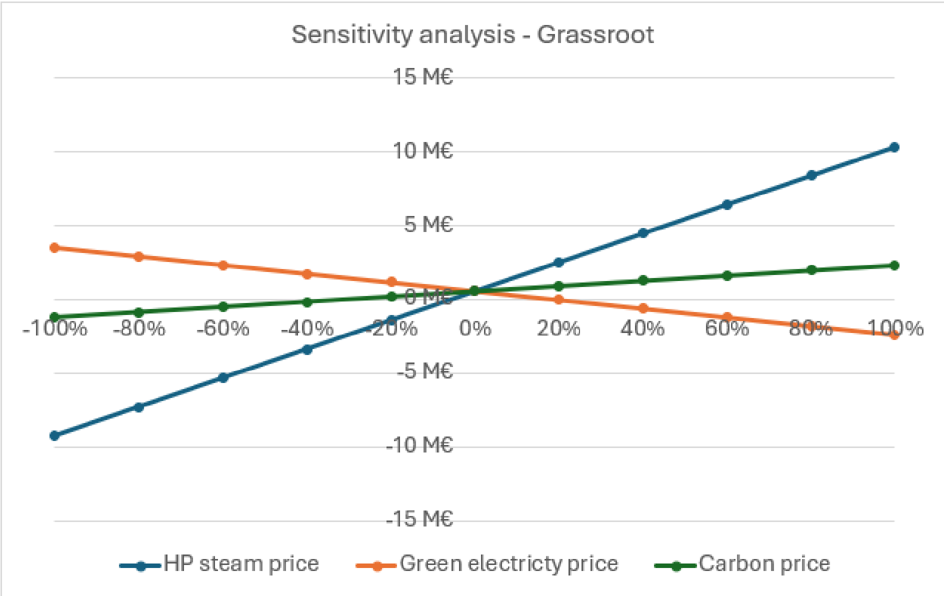

Figure 7: Sensitivity analysis of MVR application to grassroot urea plant with zero HP steam import.

The horizontal axis represents percentage changes in each variable (from -100% to +100%), while the vertical axis shows the resulting Net Present Value (NPV) in million euros (M€). The NPV represents the expected profitability of the project. The HP steam price, green electricity price, and carbon price are found to have significant impact on the NPV of the project. As observed in Figure 7, the HP steam price is the most influential factor. As HP steam price increases, NPV rises sharply. This confirms that higher HP steam prices make the application of MVR economically attractive due to the overall reduction of HP steam import to the urea process. Application of this concept in regions with a high HP steam price, such as China and Europe, would be economically favorable. An increase in the carbon price also has a positive impact on the NPV. Since it is expected that carbon prices will increase in the future, applying MVR to reduce the carbon footprint of a urea plant leads to more favorable economic benefits. A factor with a negative impact on the NPV is the green electricity price. Higher electricity costs worsen the process economics. Therefore, implementing this concept in regions where the price for renewable electricity is low, such as North Africa or the Middle East, offers greater advantages.

6 CONCLUSION

In conclusion, the efficient utilization of excess LP steam in urea plants presents a significant opportunity to enhance overall plant energy efficiency and reduce the carbon footprint of urea plants. By implementing innovative methods such as reusing the steam as motive fluid for turbine drivers, utilizing it as a heating medium for offsite users and employing MVR, plants can effectively harness the energy from excess LP steam.

The reuse of LP steam as a motive fluid for turbine drivers has demonstrated substantial energy savings and improved thermal efficiency, as evidenced by Tecnimont's successful implementation in a new urea plant. Additionally, using LP steam for heating applications, such as demin-water de-aerators and warehouse heating, helps maintain optimal storage conditions and prevents product degradation.

MVR offers a promising solution for transforming LP steam into HP steam, thereby enhancing its usability and reducing the need for additional HP steam generation or consumption of carbon-based fuels. This approach is particularly beneficial for steam-deficient urea complexes and reduces dependency on HP steam imports. This facilitates a reduction in the reliance on carbon-based steam boilers and enables the transition to renewable electricity sources, indicating a potential for a broader application of steam MVR in the fertilizer industry.

In this paper, a configuration in which enough lower-pressure steam is produced within the urea process and compressed to the pressure level required in the stripper has been explored. With this new application of MVR technology, it has been demonstrated that, for some plant concepts, it is possible to eliminate the HP steam import completely from the battery limit during normal operation.

The application of MVR technology to eliminate HP steam import is found to be profitable when combined with the right economic conditions, such as high HP steam price, higher carbon prices, and lower renewable electricity costs.

By adopting these methods, urea plants can contribute to a more sustainable and environmentally friendly operation. The integration of these practices not only optimizes energy use but also aligns with the industry's goals of reducing greenhouse gas emissions and enhancing operational flexibility.

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