Improving resource efficiency in the Russian fertilizer industry through Best Available Techniques

Aleksandr Popov[1*], *Andrej* Malyavin[1], *Vera* Kostyleva[1], and *Irina* Tikhonova[1]

[1]Environmental Industrial Policy Center, 42, Olimpijskij prospect, Mytishchi, Moscow Region, 141006, Russia

Abstract. This paper discusses approaches to the efficient use of raw materials, fuel, and energy in chemical industry worldwide. It presents key indicators of material and energy consumption and assesses the potential for improving the resource efficiency of mineral fertilizer producers using ammonia synthesis as a case study. The findings highlight that the primary measures for enhancing resource efficiency in the fertilizer industry include government support for investment projects and initiatives aligned with the principles of Best Available Techniques (BAT), the development of sectoral standards with practical recommendations for applying BAT to improve resource and energy efficiency, the modernization of training programs, and the promotion of research and development focused on optimizing chemical engineering processes.

1 Introduction

1.1 Improving resource efficiency in the fertilizer industry: The role of Best Available Techniqes

Economic growth is fundamentally driven by advancements in science and technology. Advancements in science and technology are pivotal in pushing industry towards the transition from extensive to intensive resource utilization. Addressing technological challenges in national development increasingly relies on innovations in chemistry and chemical engineering, which are indispensable for safeguarding national security, defense capabilities, and food security – particularly amid rising geopolitical conflicts.

Industrial policy serves as a key instrument for increasing the competitiveness of the chemical sector by supporting the development of new installations and the modernization of the existing ones. However, the critical factors in industrial growth extend beyond the scale of chemical engineering processes or the number of production units, installations, and lines. Instead, the focus must be on improving process quality, environmental sustainability, and resource efficiency. Improving resource efficiency, particularly in large-scale, resource- and energy-intensive enterprises with major environmental impacts,

---

* Corresponding author: a.popov@eipc.center

requires the technological modernization of production processes. A key aspect of this modernization is an emphasis on the efficient use of natural resources, providing for the gradual evolution of production processes towards the implementation of BAT.

The fertilizer industry is intrinsically linked to agriculture, whose demands serve as the primary driver of its growth. The industry's products remain in consistently high demand within the global agribusiness sector. However, the production of mineral fertilizers is highly resource-intensive, requiring substantial amounts of minerals, energy, fuel, and water. One of the most pressing challenges in this industry is ensuring the efficient and rational utilization of raw materials and energy.

The fertilizer sector is currently facing several interrelated issues:

- Environmental impact through air pollution, wastewater discharge, and the accumulation of large-scale industrial by-products.
- High carbon intensity resulting from the fact that ammonia and nitric acid production processes are major sources of greenhouse gas emissions, including carbon dioxide and nitrous oxide.
- High energy intensity.

Addressing these challenges is essential given the industry's importance in ensuring food security, supporting exports, and complying with both national and international regulatory frameworks. A key solution lies in the modernization of production processes aimed at improving resource efficiency, reducing pollutant emissions, and reintegrating secondary resources into production or broader economic circulation.

1.2 Reflection of resource efficiency issues in the Russian regulatory framework

In Russia, the framework for sustainable development projects – including their objectives, key priorities, and evaluation criteria – is outlined in Government Order No. 1912-r (July 14, 2021). A core requirement for green project certification is demonstrating contributions towards the environmental sustainability. This encompasses energy conservation, enhanced resource efficiency, and the implementation of Best Available Techniques. Further details on eligibility and criteria for such initiatives are specified in Government Resolution No. 1587 (September 21, 2021), which provides actionable guidelines to align projects with national sustainability goals.

A critical regulatory and policy instrument for both industrial and environmental governance is the concept of BAT, which has gained widespread global recognition. In Russia, the framework for transitioning to BAT is outlined in Federal Law "On Environmental Protection" (altered to accommodate the BAT concept in 2014), along with various regulations and BAT standards.

Russia's legal, economic, and organizational frameworks for advancing energy conservation and enhancing energy efficiency are defined by the Federal Law "On Energy Conservation and Increasing Energy Efficiency". This legislation establishes mechanisms to promote sustainable resource use, drive innovation, and enforce compliance with efficiency standards across industries and sectors.

There are several regulations targeted specifically at industrial enterprises. Order No. 1299-r, dated June 20, 2017, approved a list of key equipment to be used for BAT implementation, which allows businesses to apply a special depreciation coefficient to the standard depreciation rate. The primary objective of using such equipment is to ensure the rational use of raw materials, energy, and materials while minimizing environmental impact. For the fertilizer industry, this list includes 130 items. Additionally, tax incentives are available for the use of high-energy-efficiency equipment and technologies as specified in Decree No. 600, dated June 17, 2015.

2 Materials and methods

The study was carried out on the basis of open sources of information, including Russian and international scientific publications, regulatory legal acts, reference books in order to systematize data on the resource efficiency of chemical and technological processes of the mineral fertilizer industry. The research is based on the methods of content analysis and desk study.

3 Results

3.1 Approaches to the rational use of raw materials and energy in chemical engineering processes

Manufacturing processes in the fertilizer industry are highly energy-intensive, with nitrogen fertilizers being the most energy-demanding. Among these processes, ammonia synthesis accounts for 80–90% of the total energy required to produce the final nitrogen-based fertilizer. At the same time, the production of ammonia, nitric acid, sulfuric acid, and ammonium nitrate generates secondary energy, such as steam and electricity. In the mid-1950s, the design energy consumption for ammonia production was approximately 62 GJ per ton. However, today, due to continuous advancements in process flow diagrams, the adoption of energy-efficient measures, and the implementation of advanced technical solutions, this figure has been significantly reduced to 27.6–31.8 GJ per ton of NH_3 [1-2]. The theoretical minimum energy consumption for ammonia synthesis is estimated at 20 GJ per ton of NH_3.

At the turn of the 20th and 21st centuries, energy consumption in Russian nitrogen fertilizer sector exceeded international benchmarks by 30–35% [3]. Since then, most nitrogen, phosphorus, potassium, and NPK fertilizer industries in Russia have undergone restoration and modernization. Newly commissioned plants are now required to adhere to BAT principles and meet sectoral BAT-associated emission limit values, as mandated by the Federal Law “On Environmental Protection”.

Chemical processes inherently involve the consumption of raw materials, fuel, and energy, alongside environmental impacts from gaseous, liquid, and solid emissions. When designing or optimizing a process flow diagram, the key objectives are to produce high-quality products in required volumes through economically viable methods, minimize resource use, and ensure safe environmental and occupational health conditions. The economic efficiency and environmental impacts of a chemical process are largely determined by resource use strategies, which focus on maximizing raw material conversion, minimizing losses, and recovering secondary resources. These combined efforts fall under the broader framework of resource conservation, with a critical component being energy efficiency.

Chemical processes rely on driving forces that determine equipment productivity. These forces vary by process type: hydromechanical processes depend on pressure gradients; mass transfer processes are driven by concentration gradients; heat transfer processes are governed by temperature gradients. A fundamental principle of resource conservation in chemical engineering is optimizing the driving force, which is achieved by increasing the concentrations of interacting reactants, increasing pressure levels, removing reaction products from the reaction unit, and adjusting temperature and pressure. The primary consumption of fuel and energy in chemical engineering is associated with heating and cooling process flows, including raw materials, intermediates, and final products. Strategies for optimizing fuel and energy use may include the following activities: adjusting temperature parameters and heat flow diagrams to minimize energy loss; integrating advanced combustion technologies to maximize fuel efficiency and energy output; reducing energy consumption in material grinding, transportation, and auxiliary processes; recycling waste heat and secondary energy streams (e.g., steam, stack gases); combining multiple production stages into unified, energy-efficient systems; developing closed-loop energy recovery networks to harness residual energy; scaling up production unit capacities to achieve economies of scale; implementing automated process control systems for real-time energy optimization. Resource-saving solutions include also the following: closed-loop recycling and advanced treatment techniques; developing efficient equipment layouts and pipeline configurations to reduce losses; use of high-performance catalysts; adopting Industry 4.0 tools (IoT, AI, predictive analytics) for smart, data-driven resource management.

3.1.1 The fuel and energy mix in the chemical industry

All chemical processes involve heat transfer, which is essential for heating raw materials and process flows, maintaining reaction temperatures in reactors and apparatuses, and regulating heat carriers. In addition to these process-related energy demands, chemical plants require thermal energy for heating production facilities and supplying hot water.

Steam of varying pressure and temperature is widely used in both process plants and off-site facilities. High-pressure steam (2.5–4.0 MPa, 250–435 °C) is utilized in compressor turbines and for heating high-temperature process flows. Medium-pressure steam (1.0–1.3 MPa, 200–300 °C) is used for heating pipelines and storage tanks as well as in steam curtain systems. Low-pressure steam (0.2–0.7 MPa, 120–220 °C) is employed for low-temperature flow heating and fire suppression systems. Most industrial facilities incorporate systems for steam condensate collection, purification, and return to the boiler feedwater system. Additionally, heating water is used as a heat carrier at temperatures of 110–130 °C in supply lines and 70 °C in return lines, serving applications such as heating impulse lines, control cabinets, and instrumentation devices.

Energy used by chemical plants is typically generated at thermal power plants, boiler houses, and secondary energy units. The primary fuel sources include natural gas and fuel gas produced on-site. Most plants also maintain a fuel oil reserve as a backup energy source. Given that primary energy sources – such as fossil fuels – undergo multiple transformation stages (drilling, beneficiation, processing, transportation, and distribution) before reaching industrial enterprises, energy conservation at the final consumption stage plays a critical role in reducing the specific energy intensity of a country’s GDP.

3.1.2 Thermodynamic approaches to energy efficiency in chemical engineering

The development and optimization of chemical processes require a feasibility study that considers safety regulations and environmental protection standards. A fundamental aspect of this evaluation is thermodynamic analysis, which examines the transformations of matter and energy within a given system. Various thermodynamic methods – such as enthalpy, entropy, and exergy analyses – help define the technical feasibility of process improvements and identify potential energy-saving opportunities. The rationality and effectiveness of these improvements are then confirmed through a technical and economic assessment.

One of the most effective methods for reducing energy consumption in chemical engineering is pinch analysis, which utilizes thermal curves to optimize heat integration within a system. By implementing pinch analysis, industries can minimize fuel and energy consumption while reducing pollutant emissions [4]. The method involves analyzing a process flow diagram to identify heat sources (hot streams) and heat consumers (cold streams). The enthalpy balance is calculated, and graphs of heat flow vs. temperature are plotted. The pinch is the point of the narrowest temperature difference between composite heat curves, representing the smallest possible temperature gap in an inter-stream heat transfer system.

The enthalpy axis overlap of these curves determines the maximum recoverable heat – the amount of heat that can be transferred from hot to cold streams. In regions where the cold composite curve extends beyond the hot composite curve, heat recovery is not feasible, necessitating the use of external heating utilities (e.g., steam). Similarly, in areas where the hot composite curve extends beyond the cold composite curve, heat must be removed via external cooling utilities (e.g., cooling water).

The magnitude of the pinch point directly affects heat exchanger design and operational costs. If the pinch value approaches zero, the driving force of heat transfer at that point becomes negligible, requiring an infinitely large heat transfer surface area to facilitate heat transfer. Conversely, as the pinch value increases, the required heat transfer surface area decreases, but the demand for external utilities rises. The goal of pinch analysis is to determine the optimal pinch point, balancing capital expenditures (CAPEX) and operational expenditures (OPEX) in the design or modernization of a chemical engineering system.

3.1.3 Secondary energy sources and utilization

Modern chemical companies possess significant reserves of secondary energy, which can be harnessed to meet the thermal energy demands of individual production facilities. These sources include:

- Heat from flue (exhaust) gases emitted by process furnaces and units.
- Hot streams whose thermal energy remains unused in manufacturing processes.
- Secondary steam.
- Heat contained in return steam condensate.
- Exhaust steam.

The optimal utilization of high-temperature stack gases (above 400 °C) is achieved through waste heat boilers, which generate saturated or superheated steam. In the chemical industry, various types of waste heat boilers are used, including fire-tube, convection, and radiation-convection designs. When dealing with corrosive environments, specialized waste heat boilers and recovery units are employed to ensure durability and efficiency. Additionally, exhaust gas heat can be recovered and repurposed for air heating or fuel preheating.

3.1.4 Utilization of low-grade secondary energy

Low-grade heat can account for up to 50% of the total secondary energy in chemical facilities. Sources of low-grade heat include contaminated wastewater, exhaust air, waste steam, low-temperature (below 300 °C) flue gases, and other cooled process flows.

The integration of low-grade heat into the fuel and energy mix of the chemical industry is a critical challenge. Various technological solutions have been developed to improve heat recovery efficiency, including multi-stage flash distillation units, heat-pipe units, contact devices with specialized nozzles, recuperative heat exchangers, regenerative heat exchangers, and heat pumps.

Among these, heat pumps are particularly effective in improving low-grade heat utilization. A heat pump upgrades low-temperature heat (e.g., from cooling tower discharge, geothermal water, or other residual heat sources) to a higher temperature suitable for practical applications, such as industrial heating or residential hot water systems. This energy-efficient transfer relies on an external power input, which varies by system type: compression heat pumps – use a mechanical drive (e.g., electric compressor) to pressurize refrigerant, raising its temperature; absorption heat pumps – require an external heat source (e.g., natural gas, steam, or waste heat) to drive the refrigerant cycle. In the chemical, petrochemical, and oil refining industries, heat pump systems are widely used for recovering heat from distillation fractions, liquid discharge flows, and moist stack air resulting from drying processes [5–7].

3.1.5 Automation and Industry 4.0

A crucial aspect of resource conservation in the chemical industry is the implementation of hierarchically distributed automated process control systems, including advanced process control (APC) systems, manufacturing execution systems (MES), enterprise resource planning (ERP) systems, and online analytical processing (OLAP) systems. The integration of information and communication technologies with industrial processes improves the efficiency of individual processes, facilities, and entire industries. This transformation marks a new phase of industrial development, known as Industry 4.0 [8].

Today’s industrial facilities generate vast amounts of data through multiple measurement channels, and with the expansion of Industry 4.0 technologies, this data volume is expected to grow exponentially. The implementation of Industry 4.0 components—such as the Industrial Internet of Things (IIoT), digital twins, big data analytics, and predictive maintenance systems – creates new opportunities for optimizing resource efficiency in chemical processes.

3.1.6 Energy management

Energy management is a strategic framework for optimizing energy consumption and costs, with the dual objectives of enhancing efficiency and mitigating environmental harm. When defining energy efficiency targets and operational roadmaps, enterprises prioritize key indicators, including: resource reduction (cutting fuel and energy use in absolute terms, per-unit metrics, and their proportion within production costs) and environmental stewardship (minimizing environmental impacts by lowering greenhouse gas emissions, reducing carbon footprints, and adhering to sustainability standards).

Energy management standards provide methodologies for improving energy efficiency. Key steps include the following: developing a comprehensive energy policy; allocating resources and establishing a dedicated energy management team; generating detailed energy consumption reports; defining baseline energy levels and performance indicators; setting energy efficiency targets; devising implementation plans.

A fundamental tool in energy management is the energy audit. It involves measuring and analyzing a company’s fuel and energy consumption, evaluating current energy use, identifying potential areas for improvement, and preparing a detailed report with findings and recommendations.

3.2 Ammonia synthesis in Russia: Resource consumption

The ammonia synthesis process currently in use consists of several key stages:

- Natural gas compression.
- Desulphurisation.
- Primary and secondary steam methane reforming.
- Shift conversion.

- Carbon dioxide removal.
- Methanation.
- Syngas compression.
- Ammonia synthesis and separation.

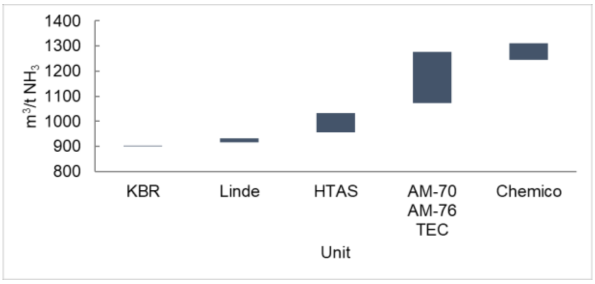

Fig. 1. Natural gas consumption in ammonia production.

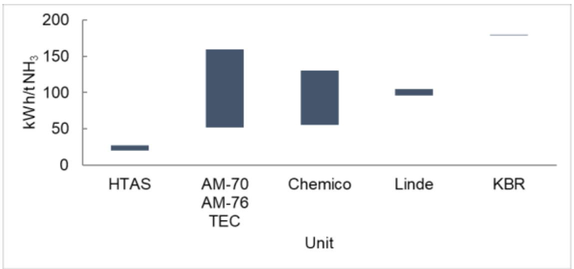

Fig. 2. Electricity consumption in ammonia production.

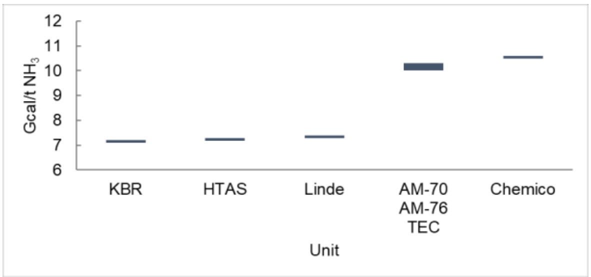

Fig. 3. Total energy consumption in ammonia production.

Figures 1–3 illustrate resource consumption ranges for ammonia synthesis at Russian facilities, including those commissioned and modernized in different years. The charts present resource consumption values as columns, depicting minimum to maximum levels.

4 Discussion

4.1 Strategies for improving the resource efficiency of ammonia synthesis units

Ammonia synthesis units generate excess high-grade heat during several key stages, including primary and secondary reforming, shift conversion, and ammonia synthesis. A significant portion of this heat is recovered to produce high-pressure steam, which is then used to drive compressors. As a result, modern ammonia synthesis facilities typically do not require external energy sources for mechanical operations and, in some cases, can even export energy in the form of steam or electricity.

The resource efficiency of ammonia production can be further improved through the following measures:

- Installing a natural gas saturation unit.
- Installing a tubular reactor in the reforming section.
- Adding an extra ammonia synthesis tower.
- Installing a waste heat boiler after the synthesis tower.
- Utilizing autothermal reforming.
- Reducing inert gas content in the circulating gas and improving ammonia extraction—such as extracting ammonia with water under pressure after condensation.
- Applying pre-catalysis in the ammonia synthesis stage.
- Cryogenic extraction of hydrogen from tank and purge gases.
- Lowering the pressure during synthesis to reduce energy consumption in syngas compression.
- Replacing the traditional steam power cycle with a more efficient combined-cycle power system.

A topical issue for the Russian fertilizer industry is the need to improve resource efficiency in the context of ensuring technological sovereignty and self-sufficiency in production. An analysis of various interpretations of technological sovereignty in modern literature [9–11] suggests that it can be defined as a nation’s ability to independently advance its scientific, technological, and industrial capabilities. This includes conducting fundamental and applied research, developing and implementing critical technologies and equipment, and engaging in international cooperation while avoiding unilateral dependence on other countries.

In order to achieve technological sovereignty in fertilizer production, it is necessary to eliminate dependence on imported technologies and components in related industries, including machine tool building, chemical engineering, power engineering, precision engineering, and manufacturing of fine chemical industry products. Reaching this objective will require collaborative efforts from research institutions, industrial enterprises, and government bodies to reduce dependence on imports, ensure long-term industrial sustainability, and make the Russian fertilizer industry more competitive.

5 Conclusion

The resource efficiency of the fertilizer is influenced by several key drivers, including the degree of raw material utilization, integrating by-products and secondary products into production, expanding the product range, the degree of automation and digitalization, the use of highly active and selective catalysts in catalytic processes, and the implementation of energy-efficient process equipment.

Globally recognized approaches to the rational use of raw materials, fuel, and energy in chemical processes include identifying potential sources using various thermodynamic analysis methods, utilizing low-grade secondary energy, using low-waste and waste-free technologies, applying the principles of industrial symbiosis and green chemistry, introducing process automation, implementing Industry 4.0 technologies, and using energy management strategies.

Support for projects and initiatives aimed at improving resource efficiency in the fertilizer industry can be facilitated through several measures [12], such as:

- A system of government support for investment projects and initiatives focused on resource and energy efficiency and conservation.
- Developing standardized documents to provide practical recommendations for the application of BAT to improve resource and energy efficiency in ammonia, fertilizer, and inorganic acid production.
- Updating academic programs to include topics on the application of BAT in specialized sectors.
- Supporting research and development efforts.

References

1. Energy Efficiency and CO_2 Emissions in Ammonia Production, IFA, https://www.inference.org.uk/sustainable/images/2009_tech_energy_efficiency.pdf
2. Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals – Ammonia, Acids and Fertilizers (2007), https://eippcb.jrc.ec.europa.eu/reference/large-volume-inorganic-chemicals-ammonia-acids-and-fertilisers
3. I. Bashmakov, Energy Efficiency **2**, 369–386 (2009)
4. I. Kemp, Pinch Analysis and Process Integration. A User Guide on Process Integration for the Efficient Use of Energy (Butterworth-Heinemann, 2007), https://www.sciencedirect.com/book/9780750682602/pinch-analysis-and-process-integration
5. A. Kiss, S. Landaeta, C. Ferreira, Chem. Eng. Trans. **29**, 379–402 (2012)
6. A. Jana, Energ. Convers. Manage, **77**, 287–297 (2014)
7. F. Schlosser et al, Renew. and Sust. Energ. Rev. **133**, 110212 (2020)
8. L. Dalenogare, G. Benitez, N. Ayala, A. Frank, Int. J. of Prod. Econ. **204**, 383–394 (2018)
9. J. Edler, K. Blind, H. Kroll, T. Schubert, Res. Policy, **52**, 104765 (2023)
10. A. da Ponte, G. Leon, I. Alvarez, Telecom. Pol. **47**, 102459 (2023)
11. F. Crespi, S. Caravella, M. Menghini, C Salvatori. **56**, 348–354 (2021)
12. D. Skobelev, Proc. 19th Intern. Multidiscipl. Sci. GeoConference. **5.1**, 291-298 (2019)