



# Low-carbon pathway analysis of ammonium nitrate production: from coal to green hydrogen

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## ABSTRACT

In China, the production of Ammonium nitrate (AN) mainly depends on the Coal gasification to Ammonium Nitrate (CGAN) process, which consumes a lot of coal and contributes to large carbon emissions. This study critically examines the techno-economic attributes of the CGAN process, identifies the primary sources of carbon emissions, and proposes strategies for energy efficiency and emission reduction. Through an on-site investigation of an operational CGAN project, we conducted a comprehensive life cycle assessment focusing on energy, carbon emission, and water resource footprints, while also appraising the economic implications. Findings indicate that the coal to ammonia conversion exhibits the highest energy demand, whereas the nitric acid production stage incurs the most significant material usage. Energy expenditures constitute 50.98 % of the total production costs, with electricity and raw coal prices exerting considerable influence on the cost of ammonium nitrate. In addition, this study provides an in-depth analysis of the potential value of green-hydrogen coupling for the preparation of ammonium nitrate. While the current technology faces cost-related challenges, it shows significant promise for energy savings and emission reductions.

## 1. Introduction

Ammonium nitrate (AN), as an indispensable fertilizer in agricultural production, shows significant regional differences in its production patterns worldwide [1,2]. The global mainstream production route mainly uses natural gas as raw material. However, due to the relatively scarce natural gas resources in China, it has long relied on the coal gasification to ammonium nitrate (CGAN) to meet the huge domestic demand for nitrogen fertilizers [3]. However, the production of nitrogen fertilizers is extremely energy-consuming [4]. Especially, the coal gasification process generates a large amount of greenhouse gas (GHG) emissions [5,6]. This is clearly contrary to China's commitment to "carbon peak" and "carbon neutrality" [7]. Against this backdrop, exploring a low-carbon transformation path from coal-based to green hydrogen has become a key issue in balancing agricultural demands with ecological goals.

At present, the low-carbon transformation of ammonium nitrate production is confronted with dual constraints of economy and environmental protection [8,9]. Coal gasification technology, as a coal

conversion method that is highly efficient, environmentally friendly and flexible, has shown great potential in achieving environmental benefits and meeting carbon reduction requirements [10]. The inclusion of carbon capture and sequestration (CCS) is considered to be beneficial for environmental protection, as measured by pollutant emissions from hydrogen production from coal gasification [11]. Comparative analysis of coal and biomass methanol production demonstrated the feasibility of replacing coal with biomass in methanol production [12]. The use of biomass instead of coal for gasification reaction can save non-renewable resources and greatly reduce environmental pressure. However, the operating cost of using biomass instead of coal for gasification reaction is high [13]. Also, high energy consumption and large economic investments have a significant impact on the cost [14].

The economic and technical efficiency of 15 hydrogen production methods were compared [9]. From the current situation, hydrogen production from coal is still one of the lowest cost hydrogen production methods at this stage [15,16]. Hydrogen production from electrolysed water has the advantages of clean, non-polluting and high purity of hydrogen, but it also has the disadvantage of high cost [17]. According to studies, the cost of hydrogen production from electrolytic water

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Nomenclature			
AN	Ammonium nitrate	EIA	Energy Information Administration
ANU	Ammonium nitrate unit	FW	Fresh water
AS	Ammonia synthesis	FWU	Fresh water unit
ASU	Air separation unit	GHG	Greenhouse Gas
BU	Boiler unit	HAN	Hydrogen to ammonium nitrate
CCUS	Carbon Capture, Utilization and Storage	HTU	Hydrogen transport unit
CE	Carbon emissions	IRR	Internal Rate of Return
CGAN	Coal gasification to ammonium nitrate	LCA	Life cycle assessment
CGAU	Coal gasification to ammonia unit	LNG	Liquefied natural gas
CGS	Coal gasification slag	LPDS	Low-pressure deaeration station
CNY	Chinese yuan	NPV	Net Present Value
CTU	Chemical-water treatment unit	NU	Nitric acid unit
CW	Condensate water	PSFs	Public support facilities
CWRU	Central water reuse unit	SFA	Material flow analysis
CWU	Circulating water unit	STU	Sewage treatment unit
		WGS	Water-gas shift
		WTU	Water treatment unit

ranges between 1.34 and 2.27 USD/kg [15]. The high cost of electricity is the main reason that greatly limits the development of hydrogen production from electrolytic water. If electricity prices can be reduced by 50 %, the cost gap with fossil fuel hydrogen production can be significantly narrowed, thus improving its economic competitiveness [16].

Although coal plays an important role in economic development, China is making a concerted effort to mitigate the environmental impacts of coal by promoting renewable energy sources [18,19]. To achieve the Sustainable Development Goals, China needs to actively explore ways to produce nitrogen fertilisers, such as hydrogen, in order to reduce its dependence on coal and lower GHG emissions [6]. In this context, a comprehensive assessment model of low-carbon pathways was developed using coal-based ammonium nitrate as an example. The model should be able to analyse both material energy consumption and carbon emissions, as well as the reasons for the poor economic performance of the industry, so as to provide valuable policy recommendations for the industry and promote its future modernisation and progress.

## 2. Methods

In this study, most of the data were collected from the CGAN company based in China. The project has been in operation for many years, and its technology and statistical system are relatively mature, so the relevant data has reliability and validity. The physical parameters and economic data in the article come from on-site research, enterprise reports and on-site inquiries, such as the price of own coal, investment costs, energy consumption and other data. However, some of the data were not included in the statistics because they were not disclosed due to commercial confidentiality. Some of the data were also obtained through estimation, and expert opinions were consulted on those data that differed significantly from the current overall level.

### 2.1. Process description

In the CGAN process, coal is used as the raw material. Syngas is produced through a gasification process, which is then used to synthesize liquid ammonia, nitric acid and ammonium nitrate. In addition, by-products such as liquefied natural gas (LNG) can be produced. The process consists of a coal gasification to ammonia unit (CGAU), a nitric acid unit (NU), an ammonium nitrate unit (ANU), and supporting systems such as boilers unit (BU), air separation units (ASU), water treatment unit (WTU), storage warehouses (BW), and public support facilities (PSFs). Detailed information on data collection and processing is

provided in the supplemental information. The process design is illustrated in Fig. 1 and described in the Supplemental information Section S1.

## 3. Results and discussion

### 3.1. Sensitivity analysis

In order to assess the economic viability of the process, a sensitivity analysis of the investment costs was carried out. The investment costs include direct expenditures for the construction and installation of infrastructure such as buildings, equipment and pipelines. The design life of the infrastructure is 60 years, while the equipment and piping are expected to have a life of 15 years.

The key financial indicators for this study, including the net present value (NPV), internal rate of return (IRR), and payback period, are detailed in Table 1. The total investment is 4.82 billion CNY. The calculated payback period is 6.54 years, which means that the initial investment can be recovered in 7 years. Within a relatively reasonable timeframe, the project investment can realize the capital return, indicating that the process is feasible and attractive at the economic level.

Sensitivity coefficients for production costs play an important role in measuring the impact of fluctuations in raw material and energy prices on production costs. In this process, the slope of the sensitivity coefficient is positively correlated with the impact on project economics [20]. Fig. 2 provides an in-depth analysis of the impact of price fluctuations of electricity, raw coal, thermal coal and water on production costs. The sensitivity coefficients are all positive, which means that when the unit prices of these inputs increase, the costs increase accordingly. The sensitivity coefficients clearly show that the price of electricity and raw coal has the greatest impact on the economic viability of the project, which indicates that their price fluctuations have the greatest impact on the cost of production.

Improving the economic viability and sustainability of the project requires reducing the consumption of energy and raw materials through the use of innovative technologies and optimizing processes. In the next sections, each material's losses will be analyzed in detail to find ways to reduce the operating costs of the project.

### 3.2. Substance flow analysis

#### 3.2.1. Process material flow analysis

The flow of substances in the process from coal to ammonium nitrate has been analyzed, and the material flows in the CGAN process are clearly depicted in Fig. 3. The material conversion of the production

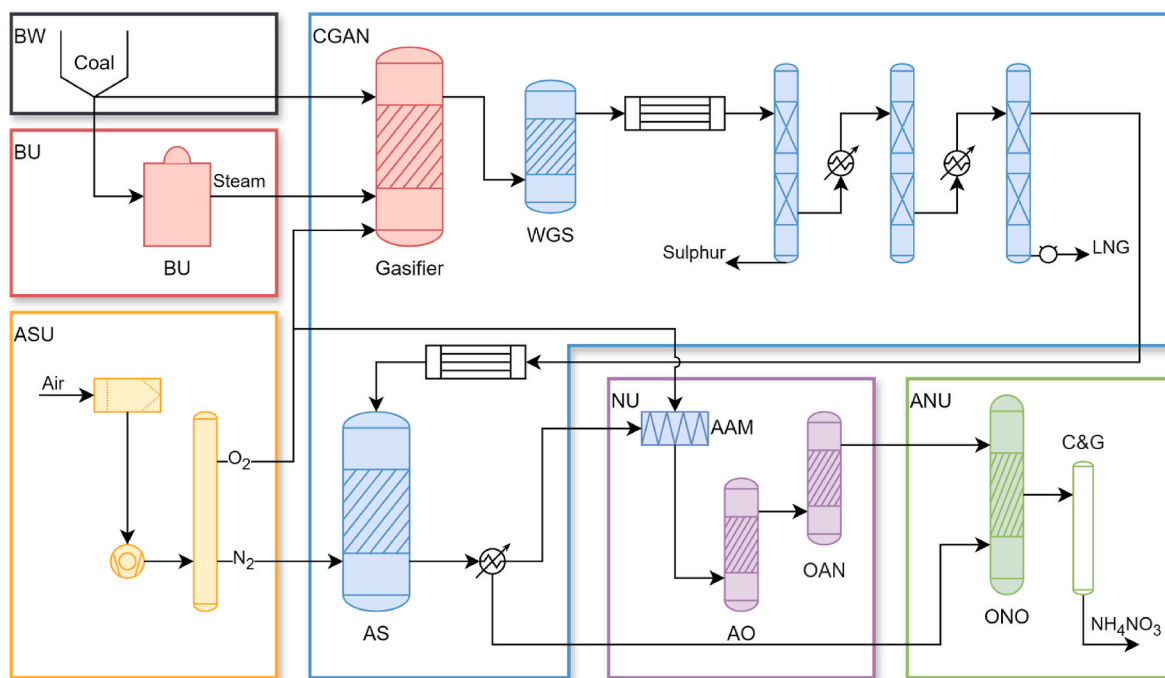


Fig. 1. The process diagram of the CGAN.

**Table 1**  
Economic analysis results.

Parameter	Value
NPV [ $10^4$ CNY] (@10 %)	50,810.74
Internal rate of return (IRR)	6.57 %
Payback period [years since evaluation date]	6.54
Total capital investment [ $10^8$ CNY]	48.20

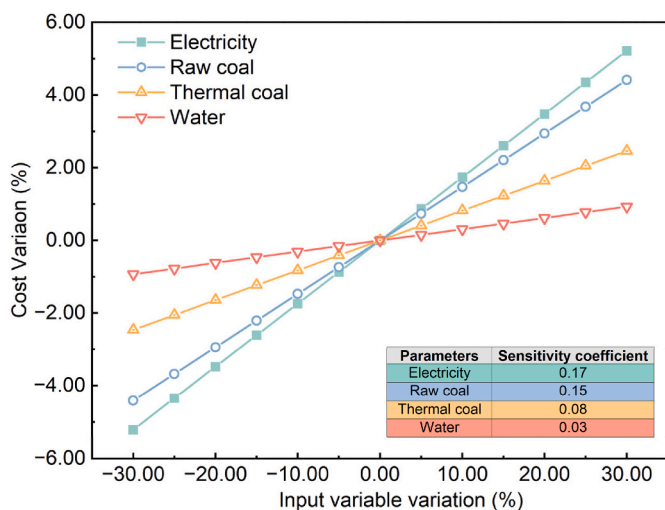


Fig. 2. Sensitivity analysis of important economic parameters.

process is mainly concentrated in the Ammonia Unit (AU). The coal gasification process for ammonia production consumes a large amount of materials. Its main inputs are coal, oxygen, and steam, which are used to produce a hydrogen-rich syngas. Subsequently, the syngas reacts with nitrogen in an ammonia-synthesis reaction to produce liquid ammonia. The ammonia is then transported to the NU and ANU for further reactions. The main output products are ammonium nitrate, liquid ammonia, and liquefied natural gas (LNG).

As the main raw material, the properties of coal should not be overlooked. The results of analyzing the properties of the raw coal are presented in Table 2. The coal has an ash content of 32.93 % and is characterized by high volatile matter, high ash, and high sulfur content. Consequently, the production process generates recoverable substances such as sulfur - containing compounds and hydrocarbon oils, along with carbon dioxide, gasification slag, and other waste materials.

The production data indicates that the primary target products have stable outputs. Ammonium nitrate production is 48.54 t/h, and liquid ammonia production accounts for 19.84 t/h of the total production capacity. In practice, the process is continuously improved and optimized to fully and efficiently recover the valuable byproducts generated during the production process. The most important byproduct is LNG (6.11 t/h), which is generated in the liquid nitrogen wash process. This is due to the large difference in boiling points of the constituent gases [21]. Sulfur is recovered in the methanol scrubbing stage. This effectively reduces the sulfurous gases in the off-gas, with a production rate of 0.87 t/h. The WTU plays a crucial role in material recovery [22]. It can effectively treat the wastewater generated during the production process and simultaneously recover valuable substances therein, including hydrocarbon oils, tars, and remaining ammonia-containing products, thus achieving resource recycling.

The loss yields of each component in the ammonium nitrate production process were also investigated. In this process, the cumulative loss yield of the CGAN process is 1.97 %, which is within the acceptable range. However, the loss yield in the NU is 6.14 %, which is significantly higher than that in other units. There are two main reasons for this high wastage. First, as shown by the reaction in Table S1 (14),  $\text{NO}_2$  cannot be fully absorbed by water [23]. Second, defective commissioning of the nitrogen dioxide absorber tower equipment and negligence in the overall process led to material losses. Therefore, it is necessary to improve the production procedure of the nitric acid plant to minimize production - related losses.

### 3.2.2. Water utilization analysis

As a core element in industrial production processes, the utilization efficiency of water resources directly impacts the sustainable development of systems [24]. This study reveals the water metabolism

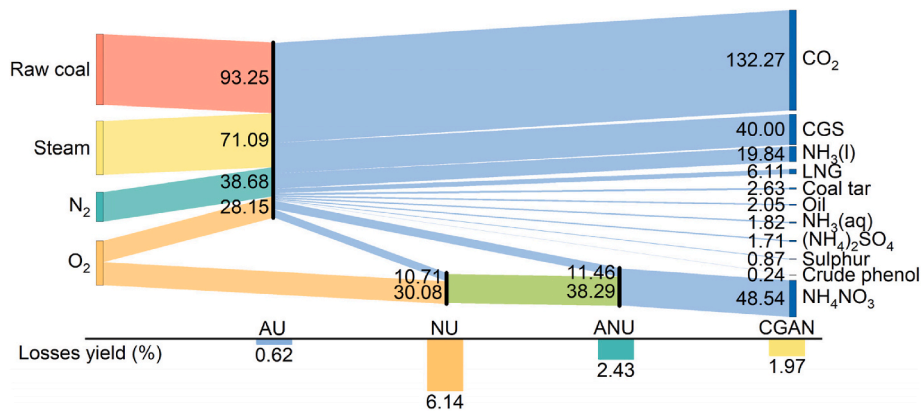


Fig. 3. Material flow and substance/product loss yields in the CGAN process.

Table 2  
Characteristics of the raw coal.

Parameter	M <sub>t</sub> , %	M <sub>ad</sub> , %	A <sub>ad</sub> , %	V <sub>ad</sub> , %	FC <sub>d</sub> , %	S <sub>t, d</sub> , %	Q <sub>net</sub> , kcal/kg
Raw coal	4.05	1.44	32.93	28.37	37.26	1.97	4445.65
Thermal Coal	4.50	1.62	42.39	24.65	31.34	1.20	3675.00

characteristics of the process system through establishing a water balance model in Fig. 4, showing a total system water consumption of 1068.30 t/h. The water network achieves three-level distribution: the main network accounts for 89.2 % of total supply, branch networks provide specific unit supply, with only 2.8 % entering PSFs.

The CW primarily serves two critical processes: firstly, collaborating with LPDS condensate for steam generation in BU; secondly, supplying NU and ANU for NO<sub>2</sub> absorption and AN crystallization respectively. Notably, 83.6 % of circulating water, partially treated chemical water, and STU effluent can be recycled through the CWRU.

The water consumption structure analysis indicates that steam system preparation constitutes the primary consumption (630.85 t/h, 43.01 %). Secondary consumption occurs in evaporation compensation systems (265.30 t/h, 24.84 %), including circulating cooling system make-up water (19.54 %), process power water (3.72 %), and utility water (1.58 %). The significant circulating cooling water consumption (208.70 t/h) mainly stems from the substantial cooling demand in AU, accompanied by considerable evaporation losses. Wastewater discharge forms the third major consumption pathway (337.28 t/h, 31.56 %). Although the system generates 588.68 t/h of wastewater, existing

treatment facilities can only process 21.57 % (127.00 t/h), revealing a significant supply-demand gap in treatment capacity.

This identifies key issues including low steam system efficiency, inadequate cooling water recycling, and suboptimal wastewater reuse rates. Recommended optimization measures include: (1) Implementing an “Ozone + BAF” process [25] to enhance coal chemical wastewater reuse rate beyond 75 %; (2) Conducting process water network optimization using pinch technology for staged reuse [26]; (3) Upgrading cooling tower systems to reduce evaporation losses [27].

### 3.2.3. Carbon emissions analysis

The carbon emissions from the CGAN process originate from three principal sources: the fuel combustion, the industrial process, and the heat and electricity purchased. Fig. 5 presents an analysis of carbon emissions and the total carbon emissions from the CGAN process amount to 408.03 tCO<sub>2</sub>/h. The carbon emission composition reveals that the industrial production process and coal combustion are the primary emission sources.

The industrial production process is the main source of emissions, accounting for 55.69 %. The emissions are mainly located in the synthesis gas preparation process of CGAN and the nitric acid production process of NU. In the process of CGAN, the raw coal is oxidized and the carbon element is converted into carbon dioxide. On the other hand, nitrogenous compounds are also released during the synthesis of nitric acid. The NO<sub>2</sub> cannot be fully absorbed by water. Moreover, poorly sealed equipment and pipes, along with open furnace doors, further contribute to increased carbon emissions.

Next, fuel combustion is another major source of emissions. In the CGAN process, the BU burns coal to obtain thermal energy resources to

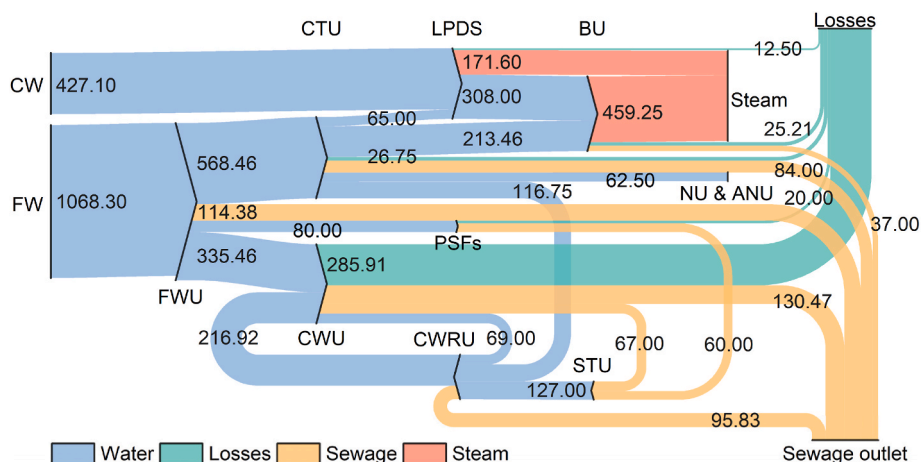


Fig. 4. The composition of water consumption.

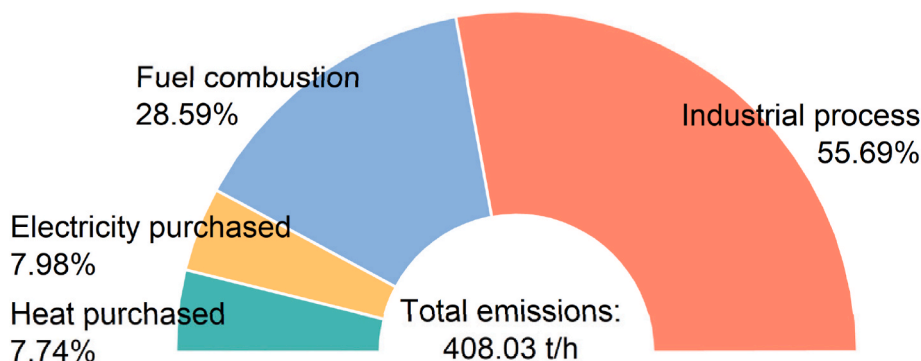


Fig. 5. The composition of carbon emissions.

drive the reaction. This process generates a large amount of carbon emissions, accounting for 28.59 % of the total carbon emissions. Moreover, purchased electricity and heat from the power generation process are also included in the calculation of carbon emissions, which account for about 16 % of the total emissions.

With the current process, improving the efficiency of the coal combustion and gas conversion processes is critical to achieving emission reductions. There is no carbon recovery pathway, so carbon emission reduction targets cannot be achieved directly. Carbon Capture, Utilization and Storage (CCUS) technology [11], although effective in reducing carbon emissions, currently lacks economic competitiveness and has certain limitations.

### 3.3. Energy consumption analysis

Energy consumption analysis has important application value in the fields of economic evaluation, energy saving, environmental protection and process optimization [28]. In this study, an energy consumption model of the coal-to-ammonium nitrate process was constructed based on the hourly scale (Fig. 6), and the quantitative characterization of energy flow was realized by calculating the phase changes of input and output substances and thermodynamic parameters of each process. The cumulative energy balance data shown in Table 3 reveals the energy distribution characteristics of the process system.

Process analysis shows that BU and CGAU constitute the core energy consumption of the system. In the total input energy of 3059.65 GJ/h, fuel coal provides 1179.73 GJ/h of heat for steam cycle through combustion, while raw coal (1746.25 GJ/h) has dual functions: its high

Table 3

The cumulative result of energy input and output (GJ/h).

Energy source		Energy value GJ/h	Proportion (%)
Inputs	Coal	1179.73	38.56
	Electricity	132.48	4.33
	Diesel	1.19	0.04
	Raw coal	1746.25	57.07
	Total	3059.65	100.00
Outputs	Byproduct	1092.98	83.13
	NH <sub>4</sub> NO <sub>3</sub>	221.8	16.87
	Total	1314.78	100.00

calorific value characteristics not only meet the heat demand of gasification reaction, but also provide sufficient hydrogen source for ammonia synthesis process. Electricity consumption (4.33 %) is mainly concentrated in equipment driving and utility maintenance, and diesel as an auxiliary energy only accounts for 0.04 %.

The analysis of energy transfer path shows that the energy carrier of the system presents two dominant characteristics: material flow and steam flow. Material transfer has been discussed in Section 3.2, which deals with steam flow. The steam system is divided into two tributaries from the high-pressure steam produced by BU: the gasification reaction steam (223.11 t/h) is used as the core gasification medium of CGAU, and the heat exchange steam (687.89 t/h, accounting for 70 %) maintains the heat balance of the gasifier through a circulating heat exchange network. It is worth noting that the heat transfer efficiency of the steam pipe network directly affects the overall energy efficiency performance.

Through the whole process energy efficiency evaluation, it is found

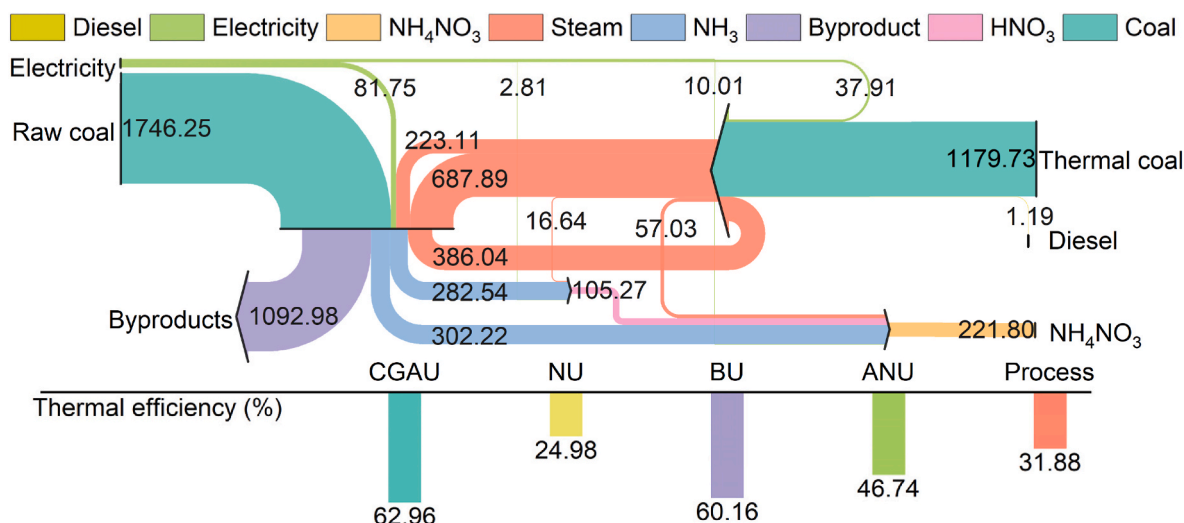


Fig. 6. Energy flow and thermal efficiency in the CGAN Process.

that CGAU and BU obtain more than 60 % thermal efficiency by the coal-based direct heat release characteristics. ANU efficiency is about 46 %; The NU only achieves about 25 % efficiency due to its reliance on secondary heat transfer. The key to improve energy efficiency lies in the optimization of steam system, which is suggested to be improved by the following measures: Using new heat transfer materials to optimize heat transfer area; Construction of steam classification utilization system; Shorten the heat transmission distance by optimizing the network topology. Especially for NU unit, it is suggested to explore the synergistic scheme of waste heat recovery and process strengthening to achieve a step improvement in the energy efficiency of the whole system.

### 3.4. Economic analysis

The production cost of CGAU project comprises two major components: operating costs and comprehensive costs. Operating costs primarily include raw material expenses (coal, catalysts, chemical additives) and energy costs (electricity, water, steam). Comprehensive costs encompass non-operational expenditures such as equipment depreciation, labor and maintenance cost, and other costs such as finance. As shown in Fig. 7, the annual production cost reaches 859.40 million CNY with a unit production cost of 1770.51 CNY/t.

The project's operational costs demonstrate a pronounced energy-intensive profile, with energy expenditures accounting for 38.08 % of total operating costs, a characteristic manifestation of coal chemical enterprises. Detailed analysis reveals three core components: Electricity costs are driven by two factors: the high-load operation of large-scale production equipment and the regional market-oriented pricing mechanism (138.89 CNY/GJ = 0.5 CNY/kWh). Coal procurement employs a pithead pricing strategy, effectively eliminating long-distance transportation costs, intermediary markups, and quality degradation. Steam supply utilizes dedicated pipeline connections with adjacent power plants, achieving real-time delivery, zero transportation costs, and maintaining stable pressure. Notably, potential cost optimization of 12 %–15 % can be realized through waste heat recovery systems [29], tiered electricity pricing mechanisms, and smart grid management deployment.

Secondly, equipment depreciation accounts for 27.85 % of the total cost. The reason is that the project equipment is complicated and the

initial investment is large. The long operation time and frequent use of equipment lead to the shortening of the service life of the equipment, and the depreciation life is also shortened. At the same time, the frequent use of equipment and long operation time also increase the cost of repair and maintenance, which further aggravates the proportion of equipment depreciation in the total cost.

Raw materials and chemicals account for 23.02 %, where precious metal catalysts, despite constituting less than 5 % of total consumption, contribute 62.3 % of this cost category. Implementing catalyst regeneration technology is projected to reduce this cost.

### 3.5. Green hydrogen substitution process

In the pursuit of carbon neutrality, the traditional coal chemical industry faces a serious challenge to reduce carbon emissions. To explore this, we use green hydrogen instead of coal gasification for hydrogen production. This approach employs alkaline electrolyzer technology for hydrogen production, which is subsequently utilized in the AN process, as an alternative to coal-based hydrogen generation. The data for this analysis were sourced from Liu's study [30], with the sections on NU and ANU remaining unaltered.

The process flow of hydrogen to ammonium nitrate (HAN) is shown in Fig. 8, and the material flow diagram for HAN is shown in Fig. 9 (a). The HAN process reduces the coal gasification and BU, resulting in a cleaner and more efficient material handling process. This not only reduces equipment complexity and footprint, but also reduces energy consumption and pollutant emissions. For example, in the coal gasification process, large amounts of pollutants such as carbon dioxide and sulfides are generated, which are avoided in the HAN process.

Meanwhile, Fig. 9 (b) shows the losses. The cumulative material losses yields of the whole process is 7.83 %, which is 5.86 % higher than that of the CGAN process. This may be due to the fact that some parts of the production process are not optimized enough, the quality of raw materials is not stable or the performance of the production equipment is not satisfactory, which leads to an increase in material loss.

Fig. 9 (c) presents the thermal efficiency, which clearly shows that the total thermal efficiency of the process reaches 40.98 %. The significant improvement of about 9.00 % compared to the CGAN process fully demonstrates the advantages of the HAN process in terms of energy

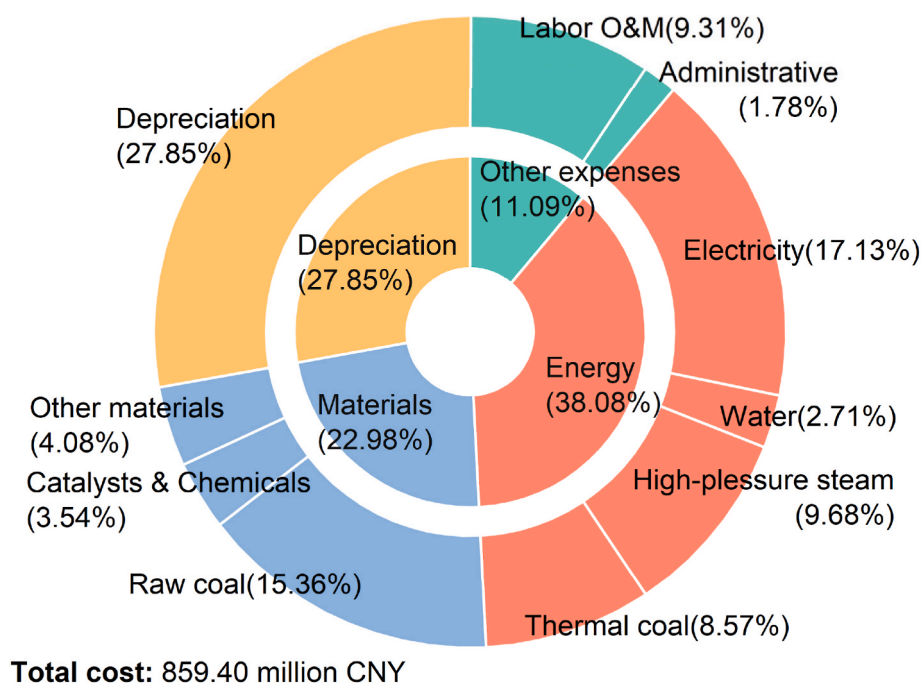


Fig. 7. Production cost composition analysis.

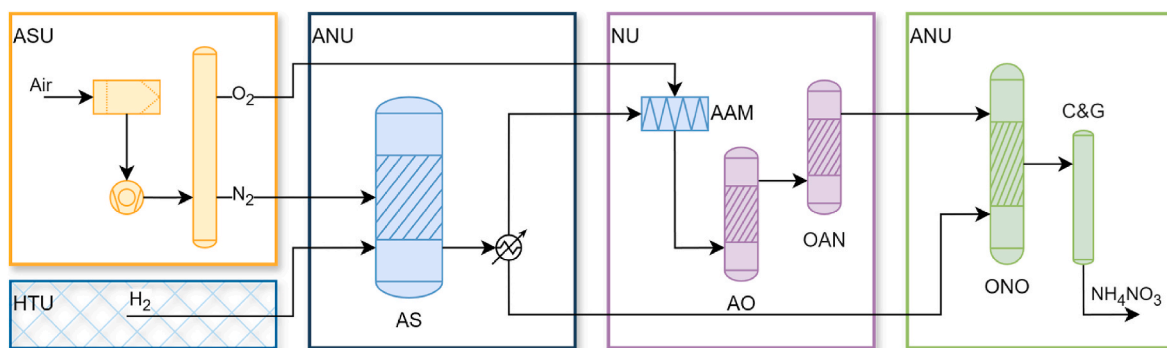


Fig. 8. The process diagram of HAN.

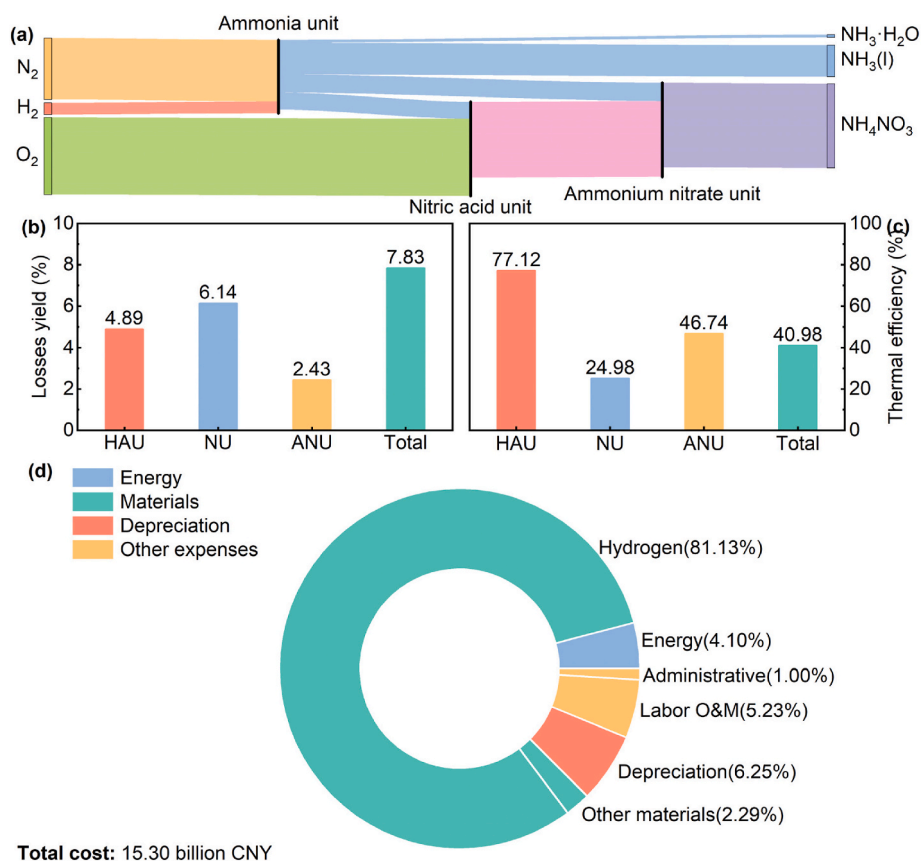


Fig. 9. Scheme of the HAN process. (a) Sankey diagram; (b) Losses yield of substance; (c) Thermal efficiency diagram; (d) Production cost composition analysis.

utilization. This is due to the fact that the process directly utilizes hydrogen to produce energy, avoiding the energy loss in the conversion and utilization of coal. In order to further improve thermal efficiency, more advanced energy-saving technologies and equipment, such as waste heat recovery systems and high-efficiency heat exchangers, can be considered. Also, energy consumption and waste can be reduced by optimizing the production process.

Table 4 lists the carbon emission data of the green-hydrogen

Table 4  
Green hydrogen alternative carbon emissions.

Parameters	Fuel combustion	Industrial process	Electricity purchased	Heat purchased	Total
CE (tCO <sub>2</sub> /h)	0.00	94.95	7.45	31.57	133.97

coupling scheme, which is 133.97 tCO<sub>2</sub>/h. Compared with the coal gasification method, the carbon dioxide emission of this scheme is reduced by 274.06 tCO<sub>2</sub>/h, which is about 2/3. The carbon emissions highlight the importance of adopting hydrogen as an alternative to mitigate global warming. However, it should be noted that the financial costs of this option are currently high. This is mainly due to the high production cost of hydrogen, as well as the large investment in related equipment and technology.

Fig. 9 (d) details the production cost, which amount to 15.54 billion CNY. And the unit production cost is 3270.93 CNY/t. At this stage, the total production cost of the HAN process is higher than that of the CGAN, mainly due to the high unit production cost of hydrogen, which is about 25.65 CNY/kg [30]. However, as the energy efficiency of hydrogen production gradually improves or the cost of electricity decreases, the economics of the hydrogen production process may become better.

Table 5 details the unit production costs for different electricity

**Table 5**  
Effect of electricity price change on green hydrogen cost.

Electricity costs (CNY/kWh)	Unit production costs (CNY/t)
0.19	1741.91
0.20	1791.23
0.50	3270.93

prices. When the price of electricity is reduced to 0.19 CNY/kWh, the operating cost of the hydrogen production process drops to 1741.91 CNY/t, which is already lower than that of the coal gasification process. This suggests that the hydrogen production process has the potential to replace traditional methods as the relevant technology continues to improve in the future.

#### 4. Conclusions

In conclusion, this presents a detailed assessment of the traditional coal chemical route represented by ammonium nitrate production, with an in-depth look at material and energy consumption and the economic impact of each process unit, as well as an analysis of the potential of the green-hydrogen coupling scheme. Key findings include.

1. The initial investment of the project is large, and it is expected to recover the cost within 7 years, which indicates that the process is economically viable and attractive. As the key variables, the fluctuation of electricity price and coal cost will have a significant impact on the economic feasibility of the project.
2. The capacity of the CGAN process for  $\text{NH}_4\text{NO}_3$  is 48.54 t/h. During the production process, valuable resources are fully recycled through continuous optimization. The overall material energy loss of the whole process is small, mainly concentrated in the nitric acid unit. The process needs to be optimized and the energy management of the nitric acid unit strengthened to reduce the losses. Water resources are consumed in recycled water and wastewater, and it is necessary to introduce more advanced wastewater treatment processes and improve the recycling rate of recycled water in the coal chemical industry. For the current process, there is no pathway for  $\text{CO}_2$  recovery, and CCUS technology needs to be coupled. The thermal efficiency of the coal gasification process for ammonium nitrate is 42.97 %, and the internal energy transfer is mainly based on material transfer and steam. For this process, the utilization of steam in the process needs to be improved.
3. The annual production cost of the CGAN project is calculated at 859.40 million CNY/year, with a unit cost of 1770.51 CNY/t. In this project, energy is the main operating cost. Although coal is the main energy source, the electricity consumption is too high, accounting for 17.13 %. On the one hand, green power can be considered, on the other hand, the equipment should be optimized to reduce the loss. Raw material and chemical consumption accounted for about 23 %, and the catalyst is a precious metal, resulting in high cost. In the future, we should focus on energy saving and emission reduction, improve energy utilization, optimize equipment management and reduce raw material costs in order to achieve the goal of cost reduction.
4. Compared with the traditional CGAN process, the HAN process demonstrates a nearly 9 % improvement in thermal efficiency and a two-thirds reduction in carbon emissions, with considerable potential for carbon reduction. At present, electricity price is a key factor affecting the promotion of HAN technology. When the electricity price drops to 0.19 CNY/kWh, the cost of the HAN process becomes more competitive. Therefore, promoting the priority application in regions with relatively low electricity prices has become the core path for the large-scale promotion of the HAN process.

This study provides valuable insights for optimizing the coal

chemical industry and paves the way for future research on green hydrogen and green power coupling traditional industries for sustainable development directions.

#### CRedit authorship contribution statement

**Chongyi Yang:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Xingxing Cheng:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Jiansheng Zhang:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Fengming Bai:** Resources, Investigation.

#### Data availability

Data will be made available on request.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijhydene.2025.151400>.

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