

# A Process Engineering Analysis of India's Petrochemical Sector

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The petrochemical sector of India is growing rapidly, with an expected investment of ~USD 87 billion in the next 10 years. This paper showcases the development of a Linear Programming (LP) framework integrated with energy system modelling towards analysing optimal feedstock utilization, production planning, and carbon emissions reduction under varying market scenarios. By utilizing available Government of India data and literature studies on optimization, a data-driven approach is proposed that provides a framework to encourage planning for cost efficiency, reducing dependence on imported feedstocks, and eventually helps strengthen India's position in global petrochemical markets. The results of this analysis are expected to be of interest to technology developers, the process engineering community, and policymakers who are working towards reducing carbon footprints and enhancing sustainability to achieve India's net-zero goal by 2070.

## 1. Introduction

The petrochemical industry plays an important role in various sectors, including manufacturing, agriculture, healthcare, and construction. It provides necessary raw materials for producing plastics, synthetic fibres, fertilizers, pharmaceuticals, and various other products. India is one of the largest consumers of petrochemicals in Asia, with upcoming projects focusing on meeting future requirements. In 2022, global chemical sales (excluding pharmaceuticals) reached approximately \$220 billion, IBEF (2025). India ranks 6<sup>th</sup> globally and 4<sup>th</sup> in Asia in terms of chemical sales FICCI (2022). The Indian chemical industry was valued at \$220 billion in 2022, with projections indicating it to grow to \$300 billion by 2025. Additionally, the demand for petrochemicals in India is expected to triple by 2040, leading to planning for capacity expansions.

In India, Petrochemical production depends on various feedstocks, including ethane, propane, butane, Liquefied Petroleum Gas (LPG), natural gas, and naphtha. The choice of feedstock is influenced by factors such as availability, cost, and processing efficiency. Asia, mainly India and China, accounts for 60% of the world's naphtha consumption, making it the largest player in the global petrochemical sector IEA (2022). The use of natural gas in India is projected to grow at a compound annual growth rate (CAGR) of 12.2%, reaching 550 million m<sup>3</sup> per day by 2030 PPAC (2023). The increasing volatility in feedstock prices and availability emphasizes the need for strategic optimization models to manage resources effectively.

Linear Programming models for the petrochemical industry, which provide valuable insights into production planning, cost minimization, and supply chain optimization have been explored in several studies. Early research by Manne and Markowitz (1961) analysed production capabilities; however, their work did not account for demand fluctuations or economic constraints. Stadtherr and Rudd (1978) investigated the impact of changes in feedstock supply on industry structure, providing a foundation for long-term strategic planning. Based on these two seminal contributions Fathi-Afshar et al. (1981) introduced economic considerations such as capital investment, operating costs, and product pricing into Linear Programming frameworks, enhancing their applicability to real-world industrial scenarios. Further advancements include Fathi-Afshar and Yang (1985), who developed a model balancing production costs and environmental impact, addressing sustainability concerns. Recently, Derosa et al. (2019) created a comprehensive chemical industry network model for the

United States, which analysed disruptions caused by external factors such as hurricanes, demonstrating the resilience of different supply chain configurations.

In India, existing research has primarily focused on industry structure, technology transfer, and capacity expansion (Kapur, 1994). However, there is a gap in the application of optimization models to improve efficiency and support strategic planning which the current study seeks to bridge.

## 2. Development of an optimization model for feasible feedstock evaluation

Linear Programming (LP) is recognized as an important tool in process systems engineering for optimizing production, resource allocation, and cost efficiency within complex industrial systems. In the context of petrochemical operations, LP enables the mapping of feedstock availability to final product outputs under multiple constraints such as process capacities, demand requirements, and cost structures.

Previously, several studies have been done to develop mathematical models of the petrochemical industry to understand the petrochemical industry scenario. In their study, Manne analysed the potential product mix of alternatives that can be considered using the refining equipment and raw materials available in the United States Manne and Markowitz (1961). They developed a Linear Programming (LP) model for the analysis of production capabilities in the petrochemical industry and industrial complexes, in which they considered only capacity constraints. Subsequently, Stadtherr & Rudd (1978) studied shadow prices, which represent how much the objective value (such as total profit or cost) would change if the availability of a constrained resource (i.e., the right-hand side of a constraint) increased by one unit, assuming all other parameters remain constant and compared them with theoretical feedstock requirements. They also analysed the effect of perturbations such as feedstock supply in the industry. The insights from the literature have been utilized to develop the Linear Programming model for the Indian Petrochemical industry in this study. Data collection was carried out using reliable and official sources, including the Petroleum Planning and Analysis Cell (PPAC) for natural gas prices, the Federation of Indian Chambers of Commerce and Industry (FICCI) and the International Energy Agency (IEA) for demand projections. Additional data were obtained from peer-reviewed literature.

### 2.1 Model Assumptions

The LP model is based on the following assumptions:

- i. The chemical industry can be visualized and represented as a network of chemical processes.
- ii. Material flows define the processes that involve chemical and/or physical transformations. The material interactions among processes are linear, and thus the processing network is represented as a linear input/output matrix
- iii. There exists a specific supply/demand environment and process capacity limitations.
- iv. Transportation and environmental externalities are excluded.

### 2.2 Objective Function

The economic model of the industry is shown in Figure.1. includes processes that transform chemical intermediates and feedstocks, and within the specified process capacity limits  $B_j$ . The feedstock supply constraints at the national level are represented by  $S_i$ . The objective function aims to optimize production levels  $X_j$  such that total production costs, represented by  $C_j X_j$ , are minimized, keeping the revenue from exports, given by  $E_i Q_i$ . This approach ensures that market demand is met effectively while keeping overall production expenses as low as possible as per Eq 1 Al-Amer et al. (1998).

$$Profit = \sum_{i=1}^n E_i Q_i - \sum_{j=1}^n C_j X_j \quad (1)$$

**2.3. Constraints** The constraints considered in the model are as follows:

**2.3.1. Supply Limitations:** The availability of raw materials and feedstocks is expected to be limited by factors such as seasonal variations, market conditions, or geopolitical issues. Skouteris et al. (2021).

i) Process Capacity Limitations: This limitation ensures that production does not exceed the maximum capacity of the equipment. it also ensures that the production rate prevents operational inefficiencies or breakdowns

ii) Demand constraints: These are related to market demand, including seasonal variations, customer preferences, and contractual obligations.

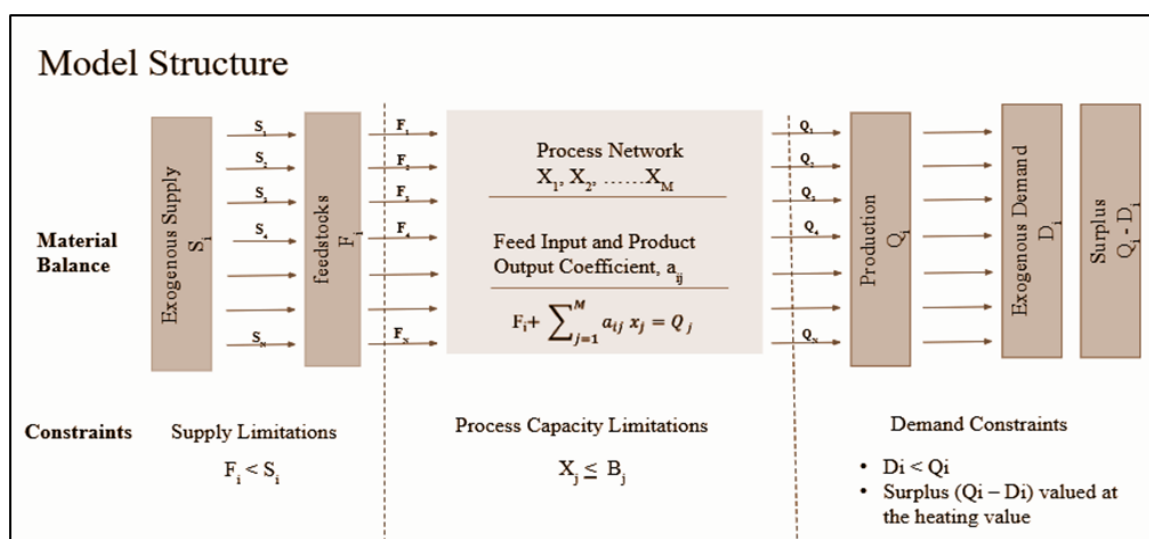


Figure 1: Linear Programming Model Structure for the Indian Petrochemical Industry, Al-Amer et al. (1998).

**2.3.2. Lower Bound:** Minimum Production Levels: Some petrochemical production processes have minimum operating levels due to technical or economic reasons.

**2.3.3. Upper Bound:** Three variables can be specified as the Upper Bound:

- Process Capacity ( $B_j$ ): The process capacity represents the maximum production level for each process.
- Feedstock Supply ( $S_i$ ) represents the maximum number of raw materials available for processes.
- Product Demand ( $D_i$ ): Product demand may be considered as a target that the LP model shouldn't exceed.

### 3. Methodology

Based on the collected data, a linear programming (LP) model was formulated in LINGO software to optimize the allocation of feedstocks to petrochemical products with the objective of profit maximization for the Indian Petrochemical Industry. A scenario analysis was then conducted by varying feedstock prices and Compound Annual Growth Rates (CAGR) to assess the economic implications under different market conditions. Given its importance to the Indian petrochemical industry and its high energy demand, ethylene was chosen as the focus of this analysis.

### 4. Model Results

In this study, the profitability of the Indian petrochemical industry by considering different feedstock prices (natural gas) and various Compound Annual Growth Rates (CAGR) was estimated utilizing publicly available data and feedstock and product economic data from the Indian Chemical Council (2024). One of the goals of the study was to analyse how fluctuations in natural gas prices affect overall industry profits and how market growth (CAGR) can mitigate these effects. Optimization model scenarios were investigated for a range of natural gas prices (from US\$2 to US\$15 per MMBtu) and CAGR values (5%, 7%, and 10%) to identify the best profitable scenarios.

The results in Table 1 indicate that potential profits are higher at lower natural gas prices (<\$5/MMBtu), with a maximum projected profit of \$20.19 billion at \$2/MMBtu and 5% CAGR. As gas prices increase, profitability decreases due to increased production costs. However, when the market grows at a higher growth rate (CAGR above 7%), it helps reduce these losses by enabling increased production and exports.

Table 1: Overall Indian Petrochemical Industry Projected Profit at Different Compound Annual Growth Rate (CAGR) and Natural Gas Price Levels

Feedstock Price (NG Price in US\$/MMBTU)	Profit at 5% CAGR (USD Billion)	Profit at 7% CAGR (USD Billion)	Profit at 10% CAGR (USD Billion)
2.0	20.19	27.3	40.6
2.7	15.9	22.0	33.7
3.0	13.0	18.5	29.3
5.0	7.16	10.6	17.8
7.0	4.33	6.50	10.9
10	2.26	3.40	5.90

The model estimates that the Indian petrochemical industry can achieve a maximum projected profit of \$20.19 billion when the natural gas price is \$2/MMBtu and the CAGR is 5%.

However, as natural gas prices increase, projections for profits decline due to increasing production costs. A higher CAGR (above 7%) helps reduce this effect by increasing production and exports, while at gas prices above \$10/MMBtu, projected profits drop at higher rates of market growth exhibited by high CAGR values. The analysis shows that projected profits are highest when natural gas prices are below \$5/MMBtu, indicating the industry's strong dependence on the cost of natural gas. Figure 2 shows the product selection trends under varying natural gas prices and market growth rates (CAGR), based on the optimization model outputs. To help India stay competitive in the global petrochemical market, it's important to keep feedstock prices stable and affordable. However, if the industry grows quickly (higher CAGR) and gas prices remain low, the chances of steady growth and better profits improve.

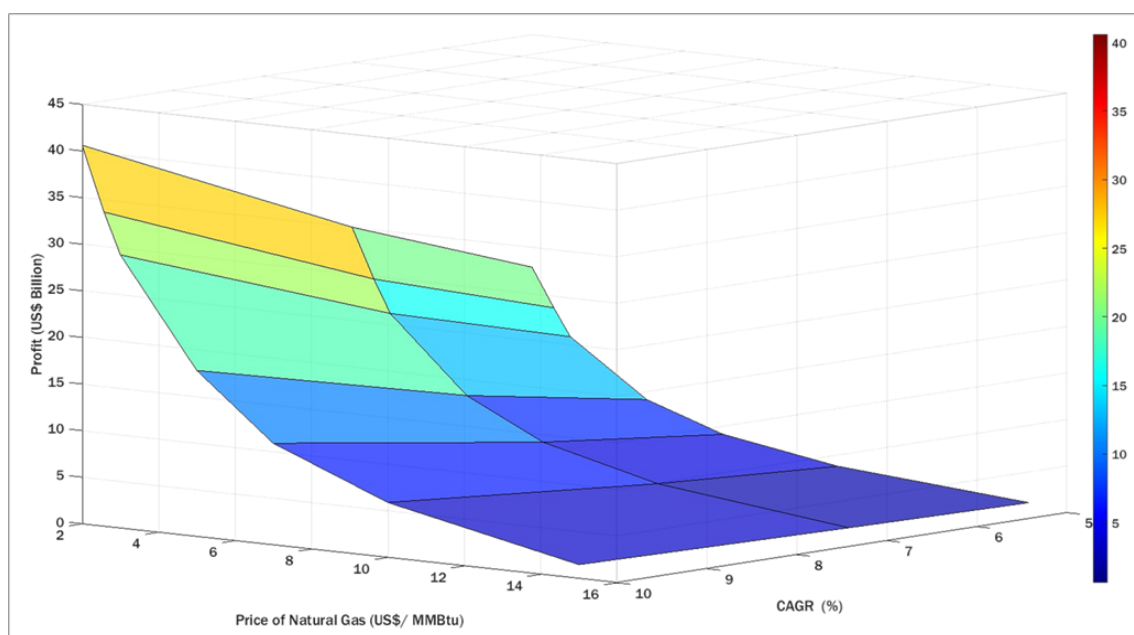


Figure 2: 3D surface plot showing profitability trend with varying CAGR and Natural Gas price. Areas of higher profit are concentrated in the low-price-high-growth zone.

#### 4.1 Comparison of Different CAGR Scenarios

The model identifies ammonia, ethylene, and propylene as the most profitable products across different scenarios as shown in Figure 3. These results highlight the importance of focusing on high-value petrochemicals to maximize returns.

i) High Growth Scenario (CAGR Above 7%): The modelling results indicate that at a CAGR of 7% or higher. Ethylene (6.679 million tonnes), Propylene (6.086 million tonnes), have the highest production volumes, which indicates strong demand from industrial and agricultural sectors. Fuel gas utilization and raffinate indicate limited

growth, indicating that their market demand remains weak even for high-growth conditions. The increase in revenue suggests that higher growth rates enable market expansion, potentially increasing exports.

ii) Moderate Growth Scenario (CAGR Around 5%): In this scenario, total production is ~28% lower than in the high-growth scenario. Ethylene production remains strong at 4.547 million tonnes along with propylene (4.325 million tonnes) as in the high growth scenario, however, there is a noticeable decrease in fuel gas and raffinate output. This indicates that moderate growth supports high-demand petrochemicals as ethylene and propylene and does not improve the outlook for lower-demand products, such as raffinate, similar to the high growth scenario.

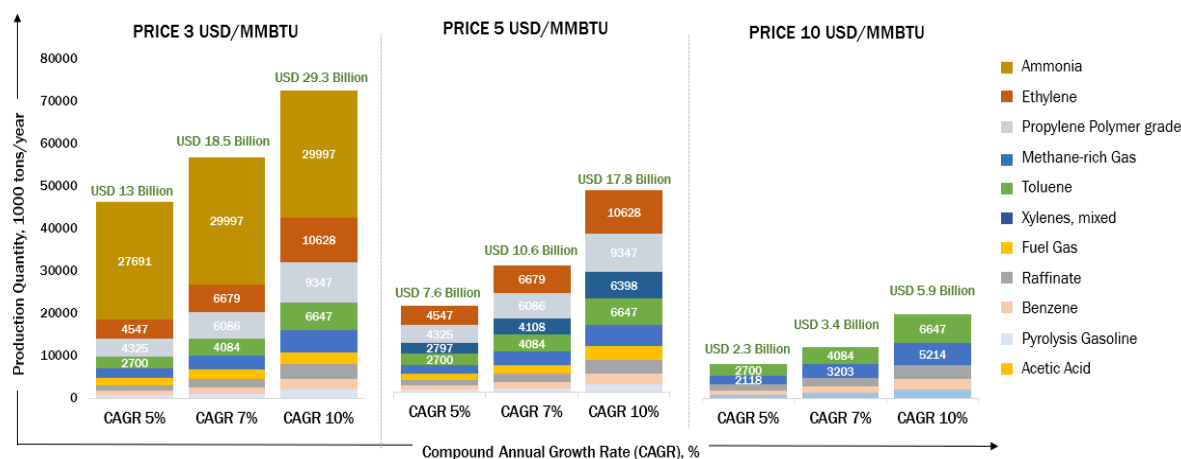


Figure 3: Linear Programming Model results of product selection trends across scenarios. High-value products like ethylene and ammonia dominate under low gas prices and high growth rates

## 5. Conclusions

This study evaluates how India's petrochemical sector can balance profitability and sustainability in the phase of evolving global energy market dynamics and challenges posed by climate change. Using Linear Programming framework combined with renewable energy utilization scenario modelling, the impact of fluctuating natural gas prices and varying compounded annual growth rates (CAGR) may impact industry was analysed. The results show that the industry's profit potential is highly sensitive to feedstock costs. The highest projected profitability \$20.19 billion was achieved under a low natural gas price scenario of \$2/MMBtu combined with a 5% CAGR. However, as gas prices rise, profitability drops significantly due to increased production costs.

In summary, this research provides the first step for policymakers, investors, and industry leaders. It is expected that with the help of this framework strategic decision making in areas such as feedstock sourcing, market expansion, and renewable energy adoption which serve as the essential levers for envisioning a competitive and climate-resilient future for India's petrochemical industry shall be enabled.

## Disclaimer

In this article, the views and opinions of the authors expressed herein do not necessarily state or reflect those of the Government of India or any agency thereof. The financial estimates used for analysis may be classified as Class 5 at the Concept Screening Level. These estimates are essentially employed for planning of research and development activities to identify the highest impact areas.

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