

# Assessing Operational Resilience Within the Natural Gas Monetisation Network for Enhanced Production Risk Management: Qatar as a Case Study

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## ABSTRACT

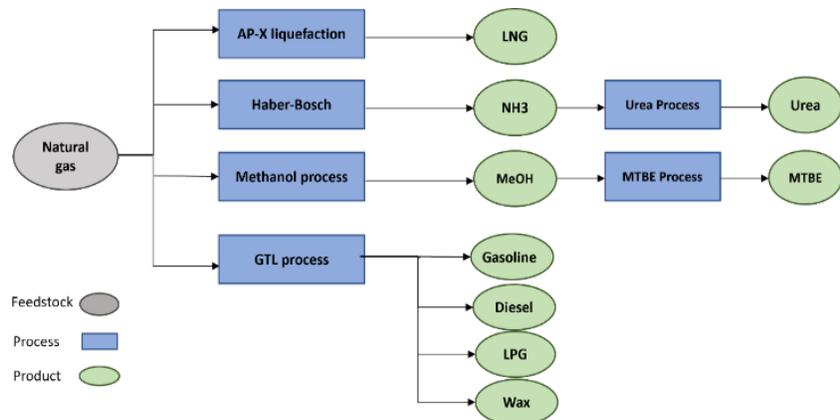
The turbulence in energy markets poses risks to energy suppliers, impacting profitability. Whilst risk mitigation is crucial for new projects, adapting existing infrastructure to evolving conditions incurs additional costs. For natural gas dependent economies, the natural gas industry faces exogenous uncertainties represented by demand and price fluctuations, and endogenous risks arising from inadequate proactive planning. This study evaluates the resilience of optimised Qatar's natural gas monetisation infrastructure under different cases by examining the network's ability to meet production targets amid process disruptions and market volatility. The analysed network includes 6 direct and indirect utilisation routes, represented by liquefaction, Haber-Bosch, methanol, gas-to-liquids, MTBE and urea processes to produce 9 products. First, process simulations and market assessments were used to obtain operational and market input data. Second, a mixed-integer linear programming model was used to optimise the natural gas allocation to processes under 9 case studies for a planning horizon of 10 year (2024-2033) with an objective of profitability maximisation. Third, the resilience% of processes and the overall network was estimated as per the model's suggested allocation strategy to evaluate the infrastructure utilisation efficiency. Process resilience below 100% indicates vulnerability to disruptions. Incorporating operational and market data increased network resilience from 74% to at least 82%, highlighting the value of flexibility in planning. Furthermore, allowing dynamic natural gas allocation improved profitability by at least 27% compared to a baseline scenario lacking operational and market considerations. The findings highlight the importance of adaptive strategies in ensuring long-term economic sustainability.

**Keywords:** Natural gas monetisation, Operational flexibility, Resilience, and Flexibility

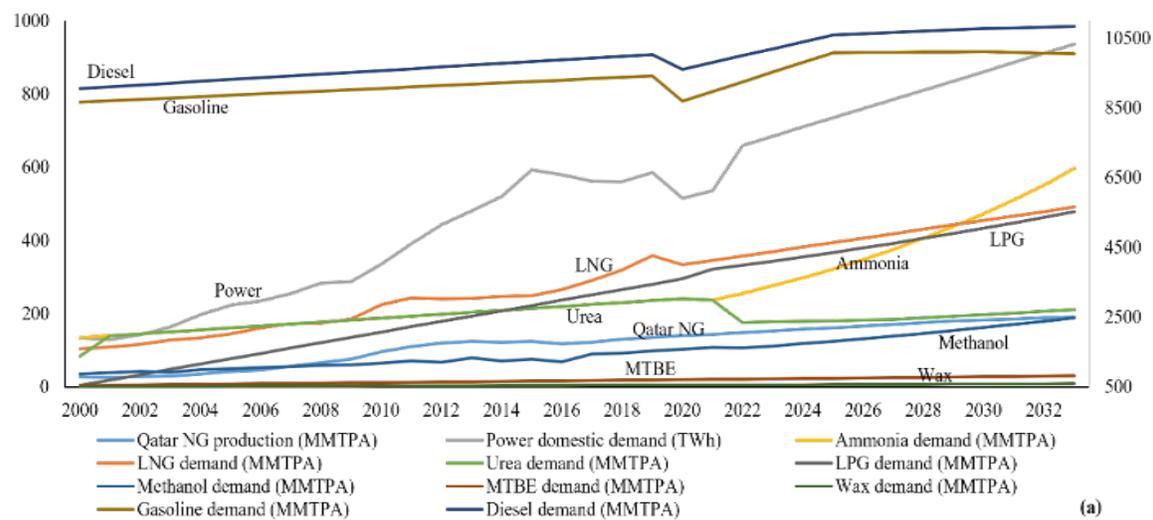
## INTRODUCTION

The rapid global growth in populations and economies has led to an increase in energy consumption for industrialisation, transportation, urbanisation, food production, and drinking water production. Increased interest for utilising different energy resources has dominated countries for energy generation, including fossil-based fuels and renewable energy resources. However, following the adoption of the Paris Agreement on climate change in 2016, a significant transition toward cleaner energy resources has been observed to mitigate greenhouse gas emissions. Natural gas has been recognised

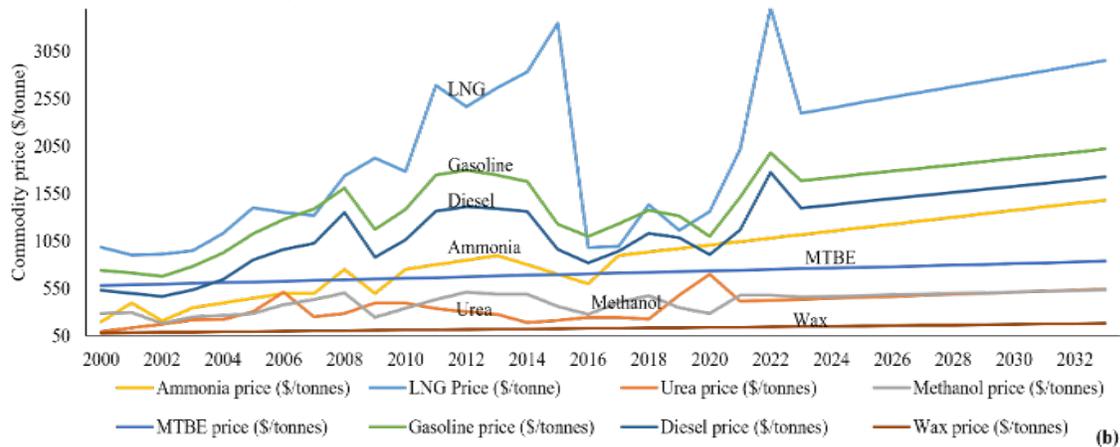
as a cleaner energy resource in national energy and environmental roadmaps until the full transition to renewables. Overall, different chemical and physical natural gas monetisation options have been deployed to produce value-added products wherein each produced commodity has different applications, markets, and pricings. Hence, end-markets play a critical role in shaping the overall economic sustainability and growth of gas-based economies. For the state of Qatar, the country has deployed direct and indirect monetisation routes for monetising its fundamental resource. This includes direct processes, including gas-to-power liquefaction, gas-to-liquids (GTL), Haber-Bosch technology, and the methanol



**Figure 1.** Investigated Qatar-based natural gas monetisation network, managed by QatarEnergy.



\*The right y-axis represents gasoline and diesel prices in MMTPA.  
 \*\*The left y-axis represents Qatar NG production, domestic power demand, LNG demand, ammonia demand, urea demand, methanol demand, MTBE demand, LPG demand, and wax demand trendlines.



**Figure 2.** Input market data for optimising annual natural gas allocation: (a) demand data and (b) price data.

process, and in-direct routes, such as methanol to methyl tert-butyl ether (MTBE) and ammonia to urea.

With the increased uncertainties imposed on the market due to supply shocks, geopolitical tensions, and

pandemics, the influence of uncertainties on existing and planned oil and gas supply became crucial for producers, consumers, and policymakers. Such assessments are especially important given the fluctuation's consequences

in terms of economic disruptions, energy security, and environmental sustainability. In the literature, researchers addressed the effectiveness of quantitative decision-making tools to evaluate the cost-effective utilisation of natural gas under market uncertainties [1,2]. Li et al., [3] utilised mathematical formulation as a decision-making tool and developed two scenario-based two-stage stochastic programming models for investigating optimal natural gas infrastructure development under market uncertainties. Additionally, Attia et. al. [4] developed a multi-objective stochastic mathematical programming model for tactical planning in the downstream sector of the oil and natural gas supply chain, addressing uncertainties in petroleum product prices and demand. On the other hand, managing an existing supply chain under uncertainties represents more challenges due to systems restrictions related to deployed infrastructure. Earlier studies investigated the optimal natural gas allocation to a multi-level network comprising different natural gas monetised products under demand and price uncertainties using quantitative decision-making tools represented by agent-based modelling and mathematical programming [5,6]. Fundamentally, the tools have been deployed for allocation under economic or environmental objectives, considering market data and operational data. The results of the studies provided crucial insights in terms of the economic added value of switching production capacities of different processes within the network based on market performance. Yet, the resilience (i.e., the ability of the network to withstand disruptions) of such a decision was not evaluated as a decision metric. This study addresses the gap in natural gas network optimisation under uncertainty by evaluating the resilience of allocation decisions proposed by decision-making tools. It focuses on optimising annual natural gas distribution within Qatar's multi-level network, considering uncertainties in demand and pricing, as well as operational constraints for flexible operations. This approach enables an understanding of the added value of operational flexibility from economic, environmental, and resilience perspectives in the context of natural gas network planning and management.

## METHODOLOGY AND DATA

This work utilises a data-driven mathematical programming model as a quantitative decision-making approach for the optimisation of natural gas allocation to processes within the Qatari natural gas monetisation network, managed by QatarEnergy. The approach aims to justify the importance of such models in addressing market volatility and enhancing economic attractiveness by adjusting the annual production capacities dynamically, based on demand, prices, and operational constraints. Figure 1 illustrates the Qatar-based natural gas

monetisation network, comprising four direct natural gas utilisation processes (i.e., AP-X liquefaction, Haber-Bosch, Methanol process, and GTL process) and two indirect processes (i.e., Urea process and MTBE process) for the production of nine products (i.e., LNG, ammonia, methanol, gasoline, diesel, LPG, wax, urea and MTBE).

## Input Data

The proposed mathematical model integrates projected annual demand and commodity prices with technical data from Qatar's natural gas processes to optimise resource allocation. Demand and price historical and forecasted data for the period between 2000 and 2033 were derived from online sources, with data gaps addressed using interpolation and cross-verification techniques [7-9]. Additionally, the study herein focuses on 10-years planning horizon (2024-2033) to balance practicality and flexibility, minimising long-term forecasts risks. Figure 2 illustrates the price and demand time series associated with different products. In terms of operational data, technically validated operational bounds for the production processes were considered (Table 1).

## Mathematical Model Formulation

With an aim to optimise annual natural gas allocation to the multi-level production network, the model proposed herein is a mixed-integer linear programming model (MILP), formulated and solved using the concept of superstructure. The objective function of the model aims to maximise the overall network's profitability (revenue-cost) by optimising the annual allocation of available natural gas ( $M_t$ ), to a process ( $J_k$ ) in the process structure  $k$ . Fundamentally, each product within the network is associated with a revenue that influences the first part of the objective function. While the second part of the objective function is influenced by the fixed process's cost ( $F_i$ ), the varied operating cost ( $C_{it}$ ), and the natural gas share allocated to a process ( $m_{it}^{in}$ ). The model can be summarised as follows:

### Objective function, Maximise:

$$\sum_{j \in J_i} \sum_{t \in \tau} R_{jt} m_{jt}^{out} - [\sum_{i \in I} F_i + \sum_{i \in J_k} \sum_{t \in \tau} C_{it} m_{it}^{in}] \quad (1)$$

### Constraints:

The following conservation constraint ensures continuity in flow dynamics for all process structures:

$$m_{kt}^o = \sum_{i \in J_k} m_{it}^{in} \quad \forall k \in \mathcal{K} \ \& \ t \in \tau \quad (2)$$

For fixed operational conditions (temperature and pressure), the yield ( $X_{ij}$ ) for converting natural gas ( $i$ ) to a product ( $j$ ) remains the same at time  $t$ :

$$m_{jt}^{out} = X_{ij} m_{it}^{in} \quad \forall i \in J_k, j \in J_i \ \& \ t \in \tau \quad (3)$$

Each process in the network operates within variable boundaries, known as upper and lower limits. The

following constraints ensures that natural gas allocated to a process falls within the upper and lower limits (4)-(5). Additionally, constraint (6) is a non-negativity constraint, while equation (7) ensures that the total natural gas feed allocated to processes is less than or equal to the total allocated feed to the process structure  $k$  at time  $t$ :

$$m_{it}^{in} \leq U_i y_i \quad \forall i \in \mathcal{J}_k, j \in \mathcal{J}_i \text{ \& } t \in \tau \quad (4)$$

$$m_{it}^{in} \geq L_i y_i \quad \forall i \in \mathcal{J}_k, j \in \mathcal{J}_i \text{ \& } t \in \tau \quad (5)$$

$$m_{it}^{in} \geq 0 \quad \forall i \in \mathcal{J}_k, j \in \mathcal{J}_i \text{ \& } t \in \tau \quad (6)$$

$$m_{it}^{in} \leq U_i y_i \quad \forall i \in \mathcal{J}_k, j \in \mathcal{J}_i \text{ \& } t \in \tau \quad (7)$$

Finally, as the problem focuses on optimising the network based on international market demand, equation (8) ensures that the produced product flow from a process  $j$  at time  $t$  is less than the global demand:

$$m_{jt}^{out} \leq D_{jt} \quad \forall j \in \mathcal{J}_i \text{ \& } t \in \tau \quad (8)$$

The model and the constraints have been explained intensively in Yusuf et. al. [5]. The formulation presented herein was solved using Gurobi optimisation software (Gurobi 11.0) and implemented using python programming language within the Jupyter Notebook environment.

## Case Studies

The MILP presented herein was considered for optimising natural gas allocation in 3 main cases with 7 sub-scenarios (total of 9). Fundamentally, the cases differ based on the consideration of upper and lower limits, forecasted market data, and the decision of whether to allow the model to divert surplus natural gas to other processes. For the description, the cases can be described as the following:

- **Case 1:** considers a business-as-usual scenario wherein the model allocates natural gas to processes.
- **Case 2:** considers natural gas allocation to processes based on forecasted demand and operational limits
- **Case 3.1:** considers planned LNG shutdown for the period of 1 month every two years
- **Case 3.2:** considers planned ammonia shutdown for the period of 1 month every two years
- **Case 3.3:** considers planned GTL shutdown for the period of 1 month every two years
- **Case 3.4A:** considers *planned shutdown* of LNG, ammonia, and GTL for the period of 1 month every two years with no surplus natural gas allocation to other processes
- **Case 3.4B:** considers *planned shutdown* of LNG,

ammonia, and GTL processes for the period of 1 month every two years with no surplus natural gas reallocation to other processes

- **Case 3.5A:** Considers *planned shutdown* of LNG, ammonia, and GTL processes for the period of 1 month every two years and *unplanned shutdowns* with no surplus natural gas allocation to other processes
- **Case 3.5B:** Considers *planned shutdown* of LNG, ammonia, and GTL processes for the period of 1 month every two years and *unplanned shutdowns*.

All cases considered demand and price forecasts, in addition to upper and lower limits, except for case 1. The outputs of the allocation were analysed in terms of profitability, resilience%, and production capacity.

## RESULTS AND DISCUSSION

The MILP model was implemented to optimise the allocation to the natural gas network comprising 4 direct and 2 in-direct routes on annual basis for the time horizon of 10 years (2024-2033). The model optimises with the objective of maximising the total profit of the products sales based on market performance by allowing the model to change the production capacity within the upper and lower operational limits. The allocation decision was then evaluated by estimating the resilience of each process and the overall resilience of the network. This, in turn, allows the decision-maker to employ resilience index as a decision-making metric to evaluate the added-value of flexible operations in natural gas network planning. The sub-sections below discuss the results represented by profitability, allocation strategy, and resilience.

### Profitability Assessment

With the objective to maximise profitability based on market performance and flexible allocation, Table 2 summarises the achieved profitability under different cases. Case 1 represents a baseline scenario under a business-as-usual scenario wherein natural gas is allocated to processes regardless of the global market performance and upper operational limits for processes, resulting in the lowest profitability estimate.

The results indicate that introducing market data as input data in the decision-making process have enhanced the allocation strategy by at least 21% by achieving the profitability maximisation targets in cases 2-3.5B. However, the values differed in the cases as per the considered assumptions. For example, in the cases (case 3.4A and 3.5A) where surplus natural gas was restricted for reallocation to other processes, lower profitability values have been achieved. This, in turn, justifies the economic added value of flexible operations in natural gas network planning for enhanced profitability under

dynamic market conditions.

**Table 2:** Maximum profitability estimation for all cases for optimal flexible natural gas allocation to processes.

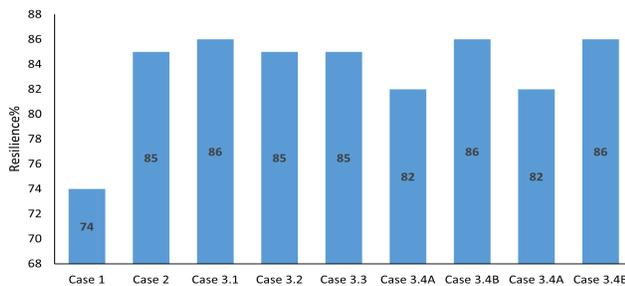
Case	Profit ( $\times 10^{12}$ \$)	Case	Profit ( $\times 10^{12}$ \$)
Case 1	2.10	Case 3.4A	2.66
Case 2	2.91	Case 3.4B	2.87
Case 3.1	2.87	Case 3.5A	2.66
Case 3.2	2.87	Case 3.5B	2.87
Case 3.3	2.91		

## Resilience Assessment

While profitability values could justify the added value of flexible operations in efficiently responding to exogenous uncertainties, resilience index (resilience%) could be another metric to evaluate the added value of flexibility. Fundamentally, resilience reflects the efficiency in utilising existing infrastructure, wherein higher efficiency percentages indicate higher efficiency in utilising the deployed infrastructure. Figure 3 below demonstrates a bar chart summarising the average resilience% estimated for each case study.

For the baseline scenario where flexible boundaries of processes were not considered in the assessment, a resilience index of 74% was achieved for the model's suggested allocation strategy. Additionally, the absence of market data as an input data to the model restricted the model's efficiency in considering the performance of end markets in the decision-making process.

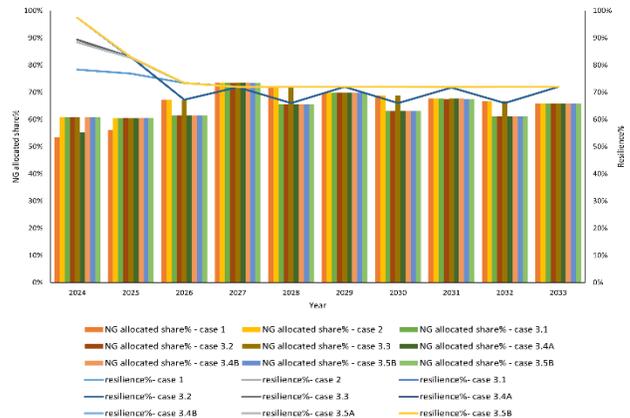
On the contrary, case studies considering flexible boundaries and market input data resulted in higher resilience%, with values between 85-86%, due to the model's suggested allocation strategies. Yet, in the cases (i.e., case 3.4A and 3.5A) where the model was not allowed to divert surplus natural gas feed to processes resulted in a reduced resilience value by 4% compared to the same cases that considered surplus natural gas diversion (i.e., case 3.4B and 3.5B). This justifies the importance of reallocating surplus natural gas during times of disturbance to other processes to enhance the overall network infrastructure utilisation.



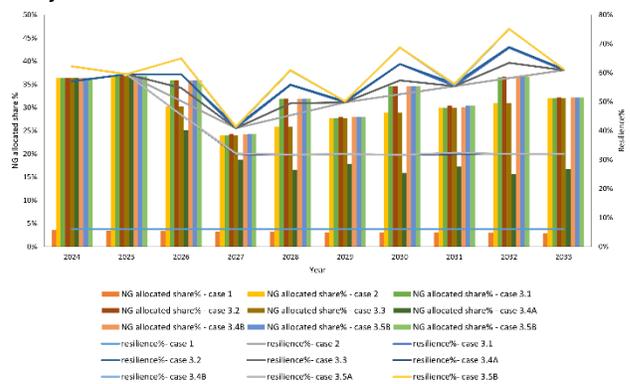
**Figure 3.** Average Resilience% estimated for each case study as per the allocation strategy for maximum achieved profitability.

## Processes assessments

To analyse the allocation strategies suggested by the model for maximising profitability under each case, it crucial to highlight that natural gas is the primary resource to the four direct processes (i.e., liquefaction, Haber-Bosch, methanol, and GTL processes). Hence, this section focuses on the natural gas allocation strategies to the primary processes under each scenario. Figures 4-7 demonstrates the natural gas allocation share% and the achieved resilience% associated with each primary process in the network under the investigated case studies.



**Figure 4.** Annual natural gas allocated share% and resilience% to the liquefaction process under each case study.



**Figure 5.** Annual natural gas allocated share% and resilience% to the GTL process under each case study.

Given that LNG is the most primary product in the Qatari natural gas portfolio, liquefaction capacities are the largest in the network, with an expected LNG production capacity to reach 142 MTPA, 85% from the current production capacity, by 2030. Hence, due to the infrastructure availability, the model prioritised allocating natural gas to the liquefaction route to meet the lower operational limits throughout the cases, as shown in Figure 4. This in turn justifies the high natural gas allocated share (more than 50%), in addition to the high resilience%. Yet, throughout the planning horizon, the resilience

associated with the cases dropped as influenced by the operational shutdowns.

On the other hand, natural gas allocated to the GTL process was the second highest after liquefaction. This is due to the infrastructure capabilities and the high market demand and prices associated with liquid fuels. Hence, the model favoured allocating natural gas to the GTL process for all process except for case 1 wherein no market data were used as an input to influence the decision-making process. This justifies the efficiency of utilising market data as an input data for informed decision-making.

As shown in Figure 6, the model allocated more than 20% of natural gas to the Haber-Bosch process to produce ammonia in case 1 when no market data and no upper operational limits were considered. This, in turn, resulted in overestimating the achieved resilience% wherein a value of 100% was achieved throughout the planning horizon for case 1. Yet, as more data were introduced to the model under the different case studies, the natural gas allocated share under cases (case 2- case 3.5B) remain almost the same by achieving natural gas allocation as per the maximum available capacity, which contributed into high resilience% values.

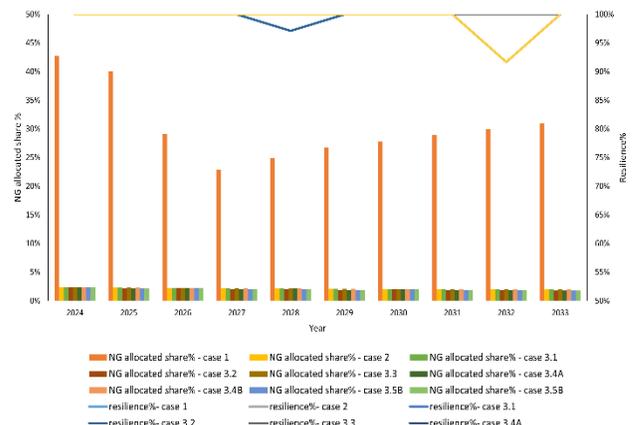
As the methanol infrastructure in Qatar is limited and constrained by smaller scale plants, the natural gas allocated share to the methanol process was the lowest as shown in Figure 7 wherein less than 1% of the available natural gas was allocated to the methanol process. Additionally, the model allocated even less natural gas to the methanol process in case 1 in the absence of input market data and upper operational limits. Instead, the available natural gas was diverted to other processes, such as Haber-Bosch and liquefaction. For the resilience%, a value of around 85% was achieved throughout the planning period for all cases, except for case 3.4B and case 3.5B where the resilience dropped from 100% at year 2024 and 2025 to 85% at year 2026. This is attributed to the expansion of the liquefaction capacities wherein additional available natural gas share was allocated to produce LNG.

## CONCLUSION

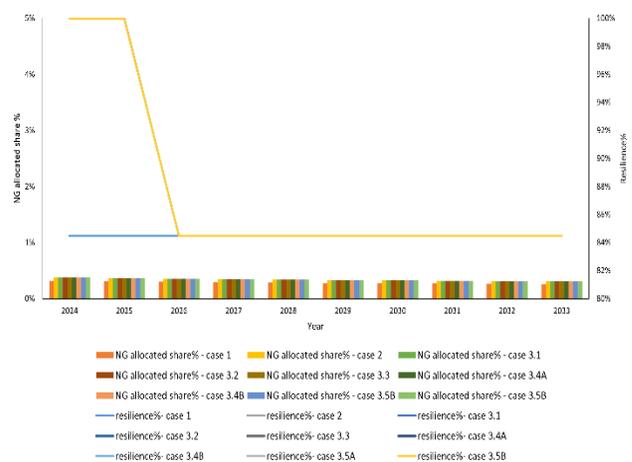
This study highlighted the industry's vulnerability to both market fluctuations and operational disruptions, emphasizing the need for proactive planning and flexible resource allocation. Findings showed that the liquefaction process received the highest allocated natural gas share for all optimised case studies due to the established infrastructure, while the methanol process had the lowest due to smaller plant capacities. Integrating operational and market data in cases 2-3.5B improved overall network resilience from 74% to at least 82%, reinforcing the value of adaptive strategies. Additionally, allowing

surplus natural gas feed diversion during planned and unplanned shutdowns enhanced the economic profitability by approximately 8% and improved resilience by around 4% from case 3.4A to case 3.4B and from case 3.5A to case 3.5B. Yet, further resilience enhancements could be achieved by increasing the available natural gas feed to ensure the full utilisation of existing infrastructure.

Overall, the results emphasise the importance of resilience-based strategies in infrastructure planning and management. A dynamic natural gas approach enhanced system stability, optimises resource utilisation, and improves economic outcomes. As the global energy landscape evolves, integrating flexibility into decision-making will be key to ensuring resilience, long-term sustainability and profitability of the natural gas industry from the perspective of suppliers.



**Figure 6.** Annual natural gas allocated share% and resilience% to the Haber-Bosch process to produce ammonia.



**Figure 7.** Annual natural gas allocated share% and resilience% to the methanol process to produce ammonia.

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