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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

RESEARCH OF VARIOUS PROCESSING CASES AND SELECTION OF THE OPTIMAL DIRECTION FOR THE INTEGRATION OF CRUDE REFINING AND PETROCHEMICAL INDUSTRIES IN AZERBAIJAN

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GENERAL CHARACTERISTIC OF THE WORK

Relevance of the topic and extent of elaboration. The economic and geopolitical processes in the oil markets of the globalized world run concurrently with deep structural changes in processing sectors of the fuel and energy industry.[1] These changes have prompted the transition of the vehicle pool to new types of fuels due to the aggravation of the environmental situation as well as the processing of crude into the finished petrochemical stock, the latter for the purpose of both supplying the domestic market and satisfying the increasingly stringent environmental and economic requirements of foreign markets. The shift of demand focus from the fuel to the petrochemical sector creates the basis for product diversification and provides additional opportunities related to the lower operating costs due to synergy.[2] At this time, one of the main objectives set for the crude refining complex (REF) is to supply the petrochemical complex (PETR) with feedstock. It is known that until recent years, as much as 6-9% of refining products were supplied to the petrochemical facility, reflecting the low level of integration between the two facilities. On the other hand, the limited volume of crude involved in the refining turns the supply of straight-run naphtha, a feedstock for the production of both fuels (Catalytic Reforming) and petrochemicals (Steam Cracking), into an issue in our country. The integration of the oil and gas processing and petrochemical sectors is therefore considered a high priority dimension. Such integration calls for modernizing the crude refining complex and putting the crude processing facilities in the petrochemical operation mode. That will result in an improved quality of refining products; on the other hand, it will help create added value through both the production of valuable petrochemicals and the

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[1] Kelly Cui. Why crude-to-chemicals is the obvious way forward: [Electronic resource] / Wood Mackenzie, – April 27, 2020.
URL: https://www.woodmac.com/news/opinion/why-crude-to-chemicals-is-the-obvious-way-forward/

[2] Nasr, M.R, Sahebdelfar, S., Ravanchi, M.T., Beshelli, M.D. Integration of Petrochemical and Refinery Plants as an Approach to Compete in Hydrocarbon Market // 9th Iran Petrochemical Forum, – Tehran: – 21-22 May, – 2011, – p.5.

overall increase in the fuel and energy industry efficiency.

Although technological and economic aspects of refining processes have been studied separately, the integration of existing REF and PETR facilities has not been fully analyzed in terms of process and economics. Reinforced by the improved crude processing schemes and petrochemical processes, the creation and evaluation of integration projects between REF and PETR sectors and the ultimate selection of the optimal case have become a **pressing** matter.

Object and subject of the research. The fuel and energy industry encompassing the oil refining and petrochemical sectors has been selected as the object of the dissertation work; processing schemes of an integrated refining and petrochemical complex are its subject.

Goal and objective of the research: Development of effective refining cases towards the improvement of respective processes and intensification of integration opportunities between refining and petrochemical facilities as part of the national fuel and energy industry, and selection of the optimal case.

The following studies have been carried out to that end:

- Existing crude refining and petrochemical facilities were analyzed and development prospects studied.
- Various cases were developed for complex processing schemes and technical and economic calculations were performed to choose the optimal case in order to both upgrade the catalytic cracking (FCC) process, a source of petrochemical feedstock, and expand its feedstock pool by involving heavy petroleum stock.
- Steam cracking / pyrolysis plant improvement projects and energy consumption indicators were analyzed;
- Efficient processes were selected for processing of refinery gases and naphtha and complex processing schemes were built upon them.
- Development of various cases of crude processing schemes from the standpoint of integration between REF and PETR and selection of the optimal case on the basis of technical and economic calculations.

Research methods: Analysis of the physical infrastructure of the refining industry, assessment of processes, determination of energy and operating costs, and development and evaluation of processing schemes were carried out in line with the best industrial practice.

Main provisions put forward for defense: Development of processing schemes for a petrochemical-oriented oil refinery on the basis of state-of-the-art technology, creation of complex processing schemes for single refining and petrochemical facilities that provide integration with petrochemical enterprises, and the identification of an optimal case based on technical and economic calculations.

Scientific innovation of the research: For the first time, the theoretical and practical foundations of the integration of oil refining and petrochemical fields were studied, taking into consideration the activity and market structure of the processing enterprises in line with environmental and economic requirements and the use of energy resources of our country. On this basis, the conversion of crude into finished petrochemical stock was studied and various cases of a single integrated processing complex were developed, followed by the identification of the optimal case based on the technical and economic calculations:

- With the expansion of the FCC feedstock pool in mind, integrated processing scheme cases (6 in total) have been developed and evaluated in terms of both engineering and economics, which ensure the increase of the petrochemical feedstock pool.
- To intensify the integration of refining areas, different modes of the catalytic cracking process: conventional catalytic cracking (FCC), deep catalytic cracking (DCC), and steam cracking (SC) were analyzed; the advantages of the DCC process in the production of C_3-C_4 olefins were confirmed, and complex crude processing schemes were developed on that basis.
- With the upgrade of the EP-300 unit in mind, prospective processing schemes of the petrochemical sector (4 in total) were developed and evaluated from both the technical and economic standpoint.
- Various (a total of 4) cases of an integrated complex providing integration of refining and petrochemical sectors have been developed and the advantages of integration have been confirmed by calculations.

Theoretical and practical significance of the research: The integration of REF and PETR lays the foundation for improving the quality and efficiency of refining products and increasing the production volume of petrochemical products, improving the ecological situation in the country, boosting the national export potential, and improving the efficiency of the national fuel and energy industry as whole. The research outcomes can be used to ensure efficient investments in upgrading existing operating plants creating new complexes.

Validation and application: 19 scientific works, including 1 book, 7 full articles (2 without coauthoring), and 11 minor articles were published in respect of the dissertation.

The dissertation results were reported at the Scientific and Practical Conference "Statistics and Society" (Baku, 2011); the Republican Scientific and Practical Conference dedicated to the 100th anniversary of Academician S.J. Mehdiyev (Baku, 2014); the 9th Baku International Mammadaliyev Conference (Baku, 2016); the scientific conference dedicated to the 80th anniversary of the Academician M. Naghiyev Institute of Catalysis and Inorganic Chemistry of ANAS (Baku, 2016); the Russian conference "Relevant Issues of Petrochemical Industry" (Zvenigorod, 2016); the International Scientific and Practical Conference "Innovative Development Outlooks of Crude Refining and Petrochemistry" dedicated to the 110th anniversary of Academician V.S. Aliyev (Baku, 2018); the 13th International Scientific Conference for PhD and young researchers "Relevant Issues of Chemistry" dedicated to the 96th anniversary of National Leader Heydar Aliyev (2019); the conference dedicated to the 90th anniversary of Academician Sahib Aliyev (2023); and the conference dedicated to the 80th anniversary of Academician A.H. Azizov (2023).

Entity where the dissertation work was carried out: The dissertation work was carried out in the "Complex crude refining and technical-economic evaluation" laboratory pursuant to the scientific and research work plan prepared by the Academician Y.H. Mammadaliyev Institute of Petrochemical Processes of the Ministry of Science and Education of the Republic of Azerbaijan (state reg. No.

0114 Az 2007).

Personal participation of the author: The purpose of the dissertation work, the propositions put forward to the defense, the schemes and calculations, the analysis and summarization of the obtained results, plus the development of articles and conference theses have been carried out by the author himself**.**

Dissertation volume and structure: The dissertation work includes an introduction (8434 symbols), Chapter I (53178 symbols), Chapter II (42844 symbols), Chapter III (49418 symbols), Chapter IV (54962 symbols), the results (3770 symbols), and a 159-strong list of reference literature (20797 symbols). It also contains 29 tables, 46 pictures with graphs (212712 symbols, 156 pages).

The **introduction** lays out the issues faced by both the refining and petrochemical entities in Azerbaijan; the relevance of the dissertation work is justified, the purpose and scientific innovation of the work are explained, and the practical importance of research, the structure, and scope of the work are indicated.

Chapter I presents the current situation and development prospects of the problem of the integration processes in the development of the world's renewable energy sources, the analysis of advanced global liquefied gas and olefin technologies, a literature review on production and consumption forecasts by region, and, based on it, the integration directions between the national oil refining and petrochemical sectors are determined.

Chapter II presents information on the establishment and development of the national petrochemical industry and analyzes its physical infrastructure and feedstock resources. Methods of technical and economic evaluation of integrated processing schemes and projects are presented.

Chapter III analyzes the possibilities of using the catalytic cracking process in different modes and introducing new processes, such as deasphalting and hydrocracking, into the processing scheme of the refinery in order to expand the feedstock pool of the petrochemical industry. The technical characteristics and energy consumption of individual processes in the petrochemical industry are analyzed and their development prospects determined.

Chapter IV provides various cases of integrated processing schemes of the refining (as the primary source of petrochemical feedstock) and petrochemical sectors, as well as their technical and economic evaluation. With the application of selected technologies in mind, distinct cases of a single integrated refining and petrochemical complex were developed, and technical and economic calculations were conducted to pick an efficient case.

The dissertation work concludes with the results and references.

MAIN CONTENTS OF THE WORK

The oil industry of our country is characterized by 4 core dimensions: oil and gas production, transportation, refining/processing, and production of petrochemicals. It is their harmonious convergence that forms the basis of the success – not only in the petroleum industry, but in the national economy as a whole. With trade and economic relations becoming increasingly globalized, Azerbaijan becomes deeper involved in the world economy, including integration in the refining/processing sector. Local refining development prospects, in line with latest global trends, include increasing the conversion depth, upgrading products, and ensuring integration between the refining and the petrochemical sectors. The effective development of the fuel and energy industry as stemming from the four production dimensions is determined by the mutually aligned activity of industries, and the main focus is on creating added value and increasing the efficiency of plants by using the synergy opportunities and possible advantages between petrochemical and refining facilities. Based on the good world practice, this dissertation analyzes various aspects of that problem and presents the creation of an integrated crude refining and petrochemical complex as a solution.

A comparative analysis of the national physical infrastructure against global technologies shows that both ways to develop the petrochemical sector in Azerbaijan – the creation of a new gas-based petrochemical production and the reconstruction of the naphtha-based petrochemical production by using the existing refining infrastructure – could be evaluated. As the industry sees the rapid transition to alternative types of energy, the trends of vehicles going electric do shift the demand from gasoline to petrochemical products. This, in turn, renders critical the integration of crude refining and petrochemical fields.

Overall, refining and petrochemical complexes fall into 3 categories:

- Low to average integration - 5 to 10% of products are petrochemicals.
- High integration - 10 to 20% of products are petrochemicals.
- Petrochemical-oriented REF - 40-50% and more products are petrochemicals.

The integration between REF and PETR plants could fall in one of four categories:

- Process-wise integration: coordination of feedstock and semi-finished products
- Utilities-wise integration: heat, hydrogen, water, steam, electricity
- Fuel gas production: use of hydrogen and hydrocarbons as petrochemical feedstock
- Ensuring energy efficiency: specialized solutions are applied.

Currently, on average 65% of steam cracking plants and 85% of aromatics production facilities worldwide are located in the same area as crude refineries, and companies do their best to install grassroot facilities as close as practicable to such areas. The integration level in both Europe and the Middle East is higher compared to other regions. To improve integration, possible petroleum product flows were investigated and their potential for use in both the refining and petrochemical sectors was evaluated (Table 1).

Table 1

Hydrocarbon flows: Production and Consumption

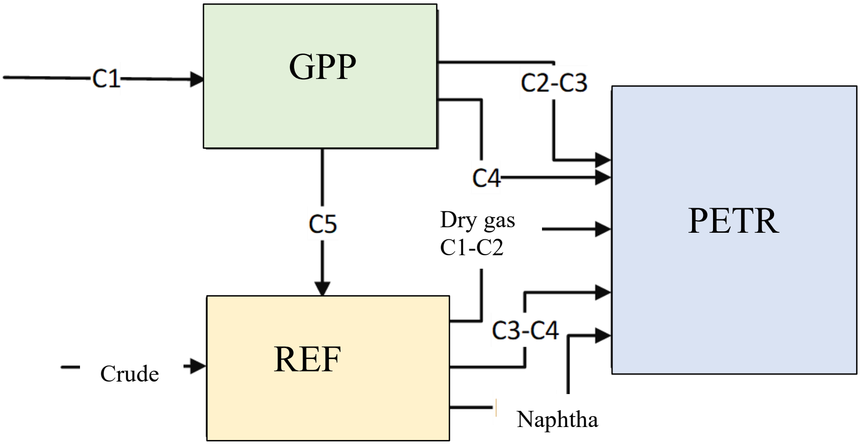
Product flow	Source	Use in refining	Alternative use (petrochem)
Dry gas	Primary processing, process units	Refinery fuel system	Petrochemical feedstock (ethylene)
Ethylene	FCC, DCU, Visbreaker	Refinery fuel system	Main link of petrochemical value chain (ethylene)
Propylene	FCC, DCC, Visbreaker	Alkylation	Main link of petrochemical value chain (polypropylene, cumene, isopropanol, oligomers)
Propane	Primary processing, conversion units	Refinery fuel system	Petrochemical feedstock (propylene, ethylene)
Butane	Primary processing, conversion units	Gasoline blending	Petrochemical feedstock (ethylene, methyl-ethyl ketone)
Naphtha	Primary processing, conversion units	CCR feedstock	Petrochemical feedstock (propylene, ethylene, others)
Reformate	CCR	Gasoline blending	Production of aromatics (orthoxylene, paraxylene)
Benzene and hydrogen	CCR	Gasoline blending	Cyclohexane
Kerosene	Primary processing, conversion units	Refining product	n-paraffins
Light gasoil	FCC	Diesel blending	Naphthalene

The petrochemical complex and its feedstock base can be conditionally divided into four groups:

- Hydrocarbon (oil and gas) feedstock
- base intermediates
- petrochemical monomers and intermediates
- finished petrochemical stock (polymers, synthetic rubber etc.)

Since the most important integration opportunities are olefin-related, the family scheme of olefin technologies was investigated.

As part of the study of the national oil refining and petrochemical infrastructure, the existing facilities were analyzed; besides, an attempt was made to increase the efficiency of the petrochemical complex through the intensification of the integration processes by looking into their technical and economic performance. The processing of refinery gases and naphtha at the petrochemical complex was taken as the basis when choosing the optimal integration case for the country. The feedstock supply for the prospective oil and gas processing and petrochemical complex in our country is described in the following graph (see Fig. 1)



From GPP: C3/C4s
From REF: Naphtha, dry gas, and spent C3/C4s

Figure 1. Feedstock supply to petrochemical complex

As the volume of crude refining goes down, meeting the increasing demand for petrochemical feedstock becomes quite an issue. In such conditions, studies related to ensuring stable supply of feedstock to PETR by increasing the FCC feedstock pool were conducted in two directions:

1. To increase the feedstock pool of the catalytic cracking unit:
   - In CDU/VDU, achieving a VGO cut range of 350-540 °C increases the FCC feedstock volume by 5%, thereby ensuring a 35% supply.
   - Incorporating a VR deasphalting unit into the refinery's processing scheme could help yield additionally 70% of quality FCC feedstock.
2. With the upgrade of the FCC unit (2.5 MTA capacity), new related processes, such as deep catalytic cracking (DCC) or steam cracking (SC), create the basis for increasing the yield of petrochemical products (Table 2).

The DCC technology has been recognized as an optimal case, as it ensures the highest yield of liquefied gas (465 kt) subject to the feedstock type and operating conditions.

Table 2

Comparison of material balances of FCC, DCC, and SC units

Yields (vol%)	**Catalytic cracking (FCC)**		**Deep catalytic cracking (DCC)**		**Steam cracking (SC)**	
	%	kt	%	kt	%	kt
Hydrogen	0.1	2.5	0.2	5.0	4.5	15.0
Dry gas (C1-C2)	**4.0**	**100.0**	**5.1**	**127.5**	**13.0**	**130.0**
Liquefied gas (LPG), including	**14.0**	**350.0**	**18.6**	**465.0**	**57.0**	**570.0**
C2 olefins	1.2	30.0	1.2	30.5	24.6	246.0
C3 olefins	**4.3**	**107.5**	**9.4**	**235.5**	**13.6**	**136.0**
C4 olefins	**8.5**	**212.5**	**8.0**	**200.5**	**9.5**	**95.0**
Naphtha	**50.0**	**1250.0**	**42.8**	**1070.0**	**3.3**	**33.0**
Light Gasoil	14.5	362.5	5.1	127.5	18.3	183.0
Heavy Gasoil	10.0	250.0	18.1	460.0	5.8	58.0
Coke	5.0	125.0	7.0	175.0	-	-
Losses	2.4	60.0	3.0	75.0	1.1	11.0
Total:	100	2500.0	100	2500.0	100	1000.0

Petrochemical process upgrade projects

In standard ethane or naphtha-based olefin plants, approximately 70% of production expenses are energy costs. With that in mind, the energy losses in the existing processes, as well as the energy saving potentials offered by state-of-the-art improvements and alternative processes, have been analyzed from both the ecological and economic standpoint. As part of the study, the energy efficiency of the pyrolysis unit was looked into in two stages:

1. energy consumption in existing processes
2. potential energy efficiency improvements through the application of new technologies

Energy integration of the steam cracking unit with another industrial process can also provide an opportunity for energy savings. Integrated cooling brings together the cryogenic natural gas condensate unit, natural gas condensate fractionation unit, and the ethylene unit into a single unit. A simplified energy profile of conventional steam cracking and catalytic olefin production processes is presented in Figs. 2,4.

In identifying the modifications suggested for the pyrolysis unit, three distinct factors were considered. These factors are:

- Possibility of processing the feedstock supplied to REF,
- the target throughput, and
- resolving bottlenecks in current operation.

Energy consumption analyzes reveal the most energy-consuming sections; one of them is the pyrolysis section, which accounts for ~65% of the total available energy (exergy) consumption and ~75% of the total energy loss. As far as conventional steam cracking is concerned, catalytic olefin technologies can bring savings in activation energy consumption.

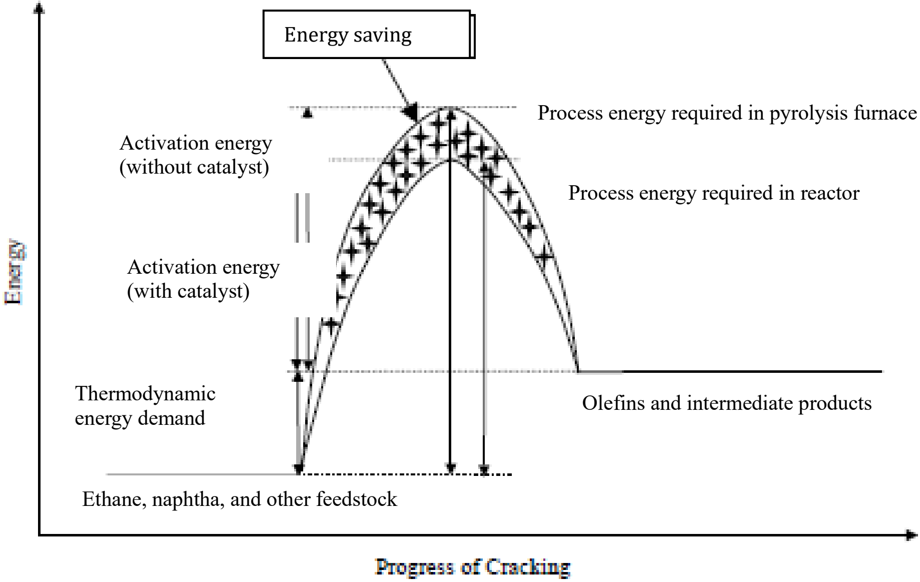


Figure 2. Energy profile of different technologies

The steam cracking (pyrolysis) unit includes three sections as shown: pyrolysis, primary fractionation / compression, and product recovery/separation.

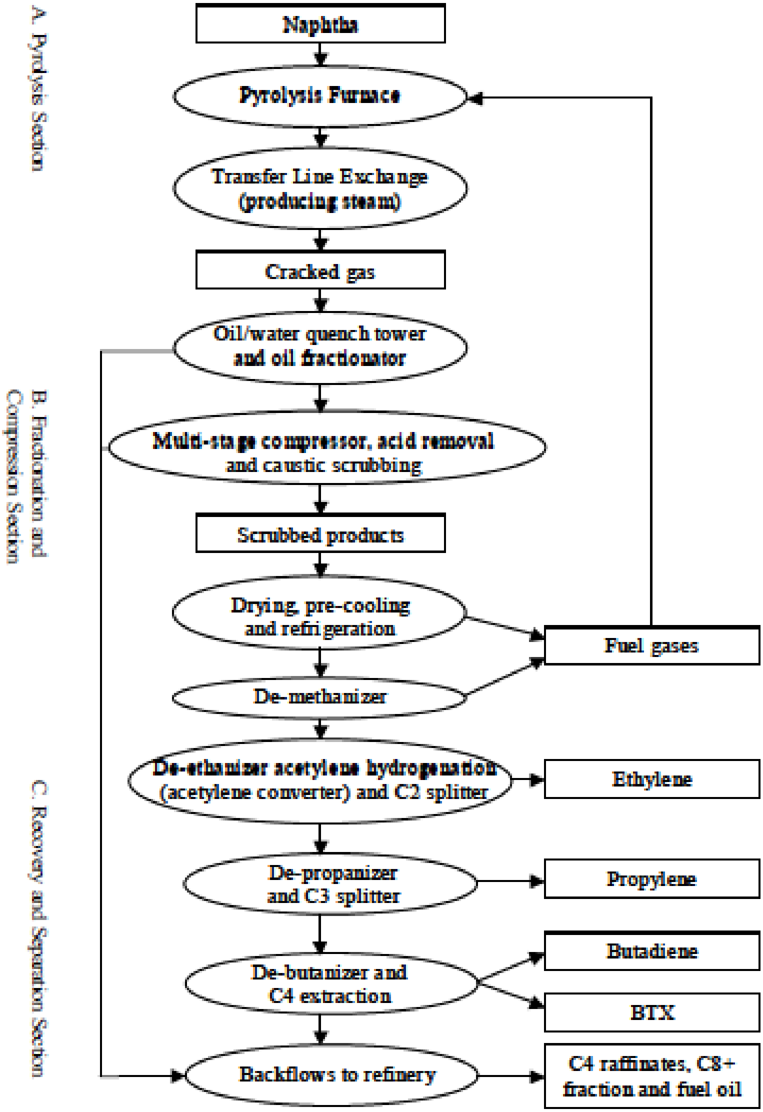


Figure 3. Pyrolysis unit

As far as conventional steam cracking is concerned, catalytic olefin technologies can bring savings in activation energy consumption (Table 3). Certain achievements have been made to tackle these issues in cutting-edge catalytic technologies.

Table 3

Catalytic and alternative olefin technologies on conventional and heavy feed

	Gas flow technologies	**Ethane oxidative dehydrogenation**	**Propane oxidative dehydrogenation**	**Catalytic cracking of naphtha**	**Hydropyrolysis of naphtha**	**Upgrade of intermediates**	**Catalytic pyrolysis process (CPP)**
Feedstock	Ethane and other gaseous feeds	Ethane and oxygen	Propane and oxygen	Naphtha	Naphtha	C4–C9 (ex SC, REF etc.)	Crude oil, heavy oil ex REF, residues, AGO, VGO
Olefins	Ethylene	Ethylene	Propylene	Ethylene/Propylene	Ethylene	Propylene	Ethylene/Propylene
Reactor	Acoustic wave, flue gases; synthesis gas; plasma etc.	Mixture catalyst reactor with additional hydrogen feedstock	Steam reforming and oxy-reactor or cyclic stationary reactor with compressed fluid bed	Compressed fluid bed	Reactors with additional hydrogen feed but less steam	Stationary or with compressed fluid bed	Lift and transfer reactor
Catalysts	N/A	Mordenite zeolite	Zinc and calcium aluminate-based	Zeolite (or various metal oxides)	N/A	Zeolite	Acidic zeolite
T (^{0}C) Total energy consumption	625–700 Shockwave: ≈8–10 GJ/t ethylene/HVC	900–1100 Dow: ≈10–12 GJ/t ethylene/HVC	550–600 Uhde: ≈8–10 GJ/t propylene; ≈8–10 GJ/t HVC	600–650 KRICT: ≈19 GJ/t ethylene and ≈10 GJ/t HVC	785–825 Blachownia :≈16–20 GJ/t etylene and ≈10–13 GJ/t HVC	580–650 No data	600–700 CPP: ≈35 GJ/t ethylene and ≈12 GJ/t HVC
Yield (wt%)	Shockwave: highest ethylene yield ≈90%	Dow: ethylene mass yield ≈80%	Uhde: propylene mass yield ≈84%	KRICT: ethylene 38%, propylene 17–20%, aromatics 30%, and HVC 73%	Blachownia: ethylene yield 36–40% and HVC yield 70%	UOP: SC propylene yield 30% and HVC yield 85%	CPP: ethylene 21%, propylene 18%, C4 11%, aromatics 15%, and HVC 60%
Status	**Lab**	**Lab**	**Commercial**	**Pilot plant**	**Commercial**	**Commercial**	**Lab**

A steam cracker has a large, tubular fired furnace; the feedstock is heated indirectly; no catalyst is used in the process; temperature 750–1100 °C is achieved; hydrogen and oxygen are not required. For an average naphtha-based cracking technology, the process energy is about 9 GJ per ton of naphtha.

Ethane dehydrogenation - Ethylene yield for one process cycle is about 30%.

Ethane dehydrogenation - Propylene yield for one process cycle is about 30-40%.

Propane steam cracking has a specific energy consumption of 20–25 GJ/t ethylene and 15–18 GJ/t HVC (with 42% ethylene yield and 11% propylene yield).

Catalytic cracking of naphtha - Other processes: LG claims 10% saving on specific energy consumption in naphtha-based cracking with 20% yield of ethylene and 10% of propylene. AIST: total ethylene/propylene yield of 60–70% and energy savings of 20% per ton of ethylene and propylene. VNIIOS: yields of ethylene and propylene are 30-34/5 and 18-20%, respectively; Asahi: 22% ethylene and 20-40% propylene.

Hydropyrolysis - this process is used at the Blachownia Chemical Plant in Poland, with a 20% increase in average ethylene yield and about 30% less energy consumption claimed.

Another industrial process is metathesis, an olefin conversion where ethylene and butane-2 are converted to propylene. It mainly compliments naphtha-based cracking to increase the yield of propylene.

The specific energy consumption for ethane cracking is 17–21 GJ/t ethylene and 16–19 GJ/t HVC. The specific energy consumption for naphtha cracking is 26–31 GJ/t ethylene and 14–17 GJ/t HVC. The state-of-the-art naphtha cracking boasts specific energy consumption in a range of 20–25 GJ/t ethylene and 11–14 GJ/t HVC; ethane cracking has an ethylene yield of 81%. Ethylene yield of naphtha cracking is 30% and propylene yield is 15%.

Additionally, we have analyzed the results of available energy-oriented studies of the naphtha cracking process. The formula $E_m=h-h_0-T_0(s-s_0)$ is used to calculate the available energy unit of each material flow Em for both sources. Here, $h_0$is the initial enthalpy, h is the flow enthalpy, s_0 is the initial entropy, and s is the flow entropy. The initial conditions are assumed to be ambient conditions, i.e. at the temperature $T_0 = 250$C and pressure of 1 bar. Available energy units of air, water and CO_2 are assumed to be equal to 0. In this study, we sought to locate exergy losses in order to discover the process appreciable exergy savings could be achieved at.

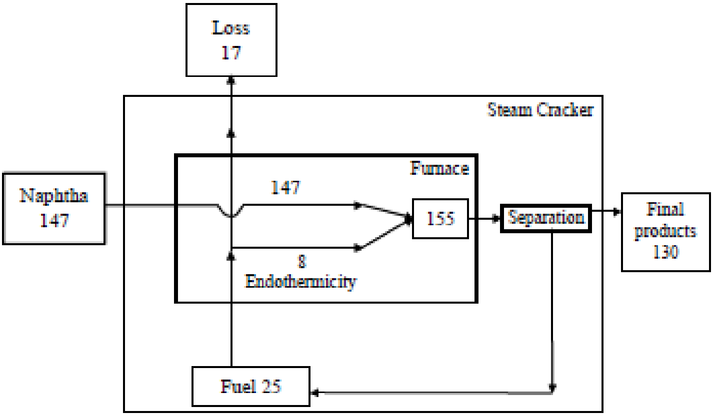


Figure 4. Energy flow in steam cracking (GJ/t of ethylene)

As part of the study, the energy consumption of naphtha and ethane cracking has been analyzed. A standard specific energy consumption (SEC) level has been defined to compare the total energy consumption in steam cracking. Then, a distribution table of energy consumption and exergy losses for standard naphtha-based steam cracking was presented. Then the issue of energy integration was reviewed and possible savings opportunities were investigated as resulting from the improvement. It has been established that additional respective savings of up to 20%, 15%, and up to 20% can be achieved in the furnace, in the compression and separation units, and in catalytic olefin technologies.

An analysis of modern naphtha-based cracking technologies shows that about 20% saving in current energy consumption is attainable. As can be seen, the main integration opportunities in the current situation focus on steam cracking and FCC units, and the primary objective here is to ramp up both the feedstock pool for the two units and the economic efficiency of different petrochemical chain products as well as their possible application nationwide.

Development of various processing schemes

Researches on the intensification of the integration processes of the refining and petrochemical sectors in the context of the national fuel and energy industry were conducted in several directions:

- REF processing schemes (a total of 6) were created and subjected to technical and economic evaluation
- PETR prospective development schemes (a total of 4) were created
- Various cases of integrated refining and petrochemical complexes were created

Being the main source of petrochemical feedstock, the crude refining facility in any configuration includes: CDU/VDU (primary processing unit), FCC (a unit that ensures the required conversion rate), DCU and BBU, Diesel and Kerosene Hydrotreaters (to upgrade the respective fuels), CCR (to produce gasolines), MTBE, Isomerization, FCC Gasoline Hydrotreater, as well as hydrogen production and sulfur recovery units. For the sake of comparison, both the existing process configuration and the crude throughput (6.5 MTA) of the refinery were assumed to be constant (Case 1). It is known that reconstruction works are underway at the Heydar Aliyev Oil Refinery to create the production of environmentally compliant fuel. As part of these works delivered in phases and accompanied by capital investments, the modernization of existing units and the installation of new plants (MTBE, DHT, Isomerization, HPU, SRU, FCC Gasoline Hydrotreatment, etc.) are planned. In this regard, the introduction of isomerization and other units in the process configuration is foreseen in the following cases (2,3). Thereafter, the hydrocracking (HC) process is added to the configuration to enable the refining of sour and paraffinic crudes (Case 4). In the next case, the FCC unit in the refinery configuration is replaced with the HCU (Case 5). The hydrocracking process has been calculated for 2 cases depending on the feedstock:
a) VGO-based
b) VR, py-resin, and FCC heavy slurry oil-based

Out of hydrocracking products, naphtha is supplied to PETR, diesel fraction to the commodity park, and residue is the FCC process as a feedstock. The presented scheme provides 96.6% crude conversion rate and adds 470 kta worth of petrochemical output. According to Case 4, no increase in the yield of HC naphtha is observed if only a limited part of VGO is fed to the HCU. Therefore, a VR mix replaces VGO as a feedstock in another case. Another case

(5) only includes the HCU plant for conversion of heavy ends, which ensures the operation in diesel mode. This time, the process can be used for either advanced production of diesel fuel, advanced production of jet fuel, or advanced production of lubricants. This can be achieved by adjusting the catalyst and/or the operating mode. Subject to the cases, the produced VGO (or VR) is fed to HCU together with HCGO and py-resin. As a result, the maximum production of petrochemical feedstock (970 kta) and diesel fuel (2,784 kta) on the basis of hydrocracking naphtha is ensured. The gasoline production, however, is at a minimum level (712 kta), with quality ensured by reforming and isomerization processes.

To load the FCC to the capacity (2.5 MTA) in the conditions of limited (6.5 MTA) crude throughput, a deasphalting unit is introduced (Case 6). Deasphalted oil (DAO) produced at a yield of 70% in a VR-based deasphalting unit is considered a valuable feedstock for both the FCC and HCU. DAO is fed to both FCC and HCU, while the pitch product received with a 20% yield is sent as feedstock to DCU, BBU, or some integrated facilities where complex heavy residues are processed. The crude conversion rate in this case is the highest at 96.57%. To increase feedstock reserves for PETR, introduced in the configuration is the Delayed Coker for the processing of heavy petroleum stock together with the FCC and the HCU (Case 7). This case, however, stipulates that the Coker will be running in the flexcoking mode. In this very configuration, the crude conversion rate is 96.54% and the production rate of petrochemical feedstock is 642.4 kta.

The maximum production of gasoline (1,918 kta) is observed if a deasphalting unit is included (Case 6). In this case, the supply of feedstock to FCC increases, hence the high gasoline production. At the same time, such a refining configuration makes it possible to produce lubes: Lubes with a high viscosity index (>120) could be produced by α-olefin alkylation of HCU residue. With the national demand in mind, the jet fuel and diesel outputs for all cases are fixed at 560 kta 2.4-2.7 MTA, respectively. Thus, meeting the national demand for motor fuels has been taken into account. The loading of devices in the schemes by cases is presented in Table 3.

A comparative analysis of refining cases shows that the introduction of new energy- and capital-intensive units increases the total production cost. However, at this time, the production of high quality and value fuels leads to a higher income from the sale of products. As a result, the profit rises to 2.02 billion AZN. In the short outlook, Case 3-based crude refining in our country is considered rather fit for purpose (Table 4). The refinery will be in the position to make 2,022 million AZN worth of profit from the processing of 6.5 million tons of crude per annum.

Table 4

Loading of units by cases

Process units	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
CDU/VDU	+	+	+	+	+	+	+
CCR	+	+	+	+	+	+	+
FCC	+	+	+	+	–	+	+
HCU	–	–	–	+	+	+	+
MTBE	–	+	+	+	–	+	+
ISOM	–	–	+	+	+	+	+
DHT	+	+	+	+	+	+	+
Merichem	+	+	+	+	+	+	+
DCU	+	+	+	+	+	+	+
Flexicoking	–	–	–	–	–	–	+
Integrated combined cycle gasification plant	–	–	–	–	–	+	–
Deasphalting unit	–	–	–	–	–	+	–

As results from the application of different technological schemes, the feedstock types that can be obtained for petrochemical purposes have been different. In parallel, the issue of meeting the national demand for motor fuels was investigated. It bears mentioning that each scheme includes gas purification and hydrogen production. In the drawing up of the schemes, the quantitative indicators of the fuel are intended to meet the national demand, and the production quality shall satisfy the applicable environmental requirements.

Table 5

Technical and economic figures by refining cases

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Production rate (kt)	**6,500**	**6,500**	**6,500**	**6,500**	**6,500**	**6,500**	**6,500**
Incl. gasoline (kt)	1,265.5	1,399.4	1,599.3	1,561.729	**587.08**	1,791.1	1,552.9
A-92					**125.5**		
A-95	-	125.5	125.5	127.400	558.4	127.4	127.4
Jet fuel	491.8	558.4	558.4	558.4	2,784.3	558.4	558.4
Diesel fuel	2,395.8	2,713.4	2,708.2	2,664.3		2,427.6	2,664.2
Petrochemical feedstock	669.1	636.8	462.6	470.8	**970.4**	478.5	642.4
Conversion	***94.31***	***96.48***	***96.13***	***96.61***	***95.61***	***96.57***	***96.54***

Some processing schemes are provided below:

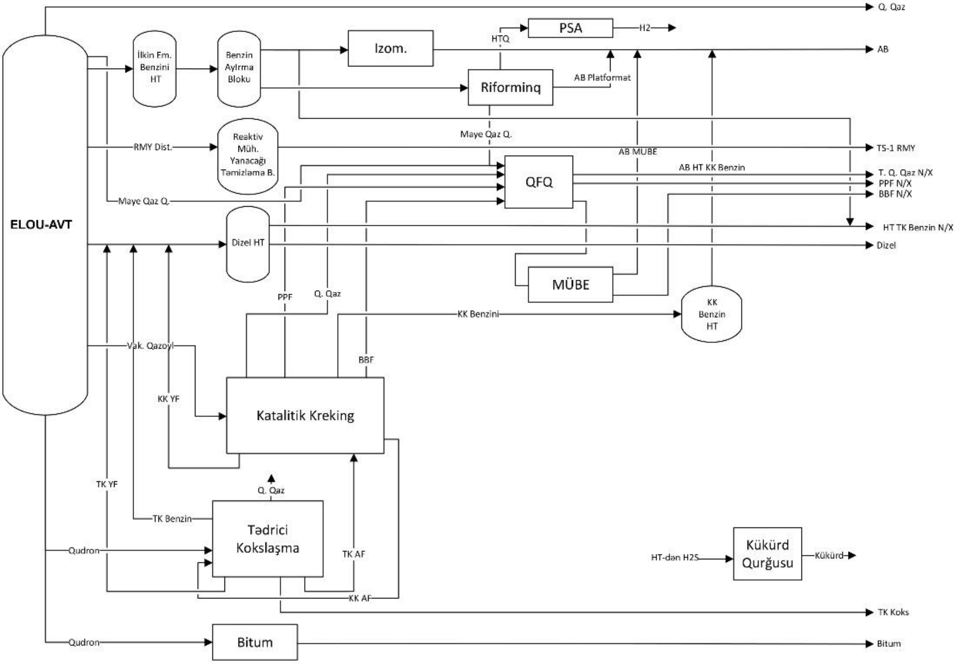


Figure 5. Post-modernization processing scheme of the Refinery (Cases 2,3)

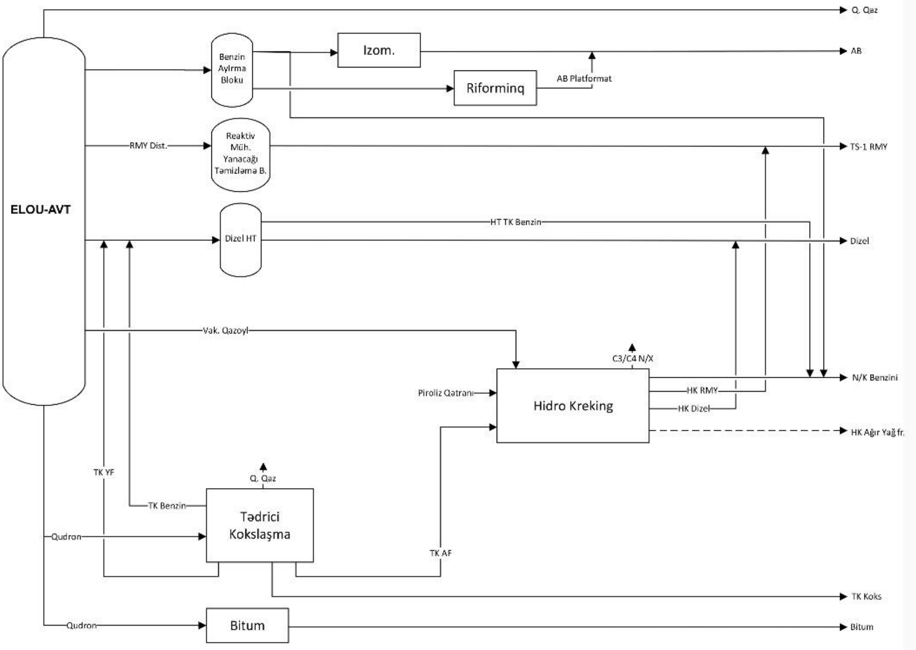


Figure 6. FCC replaced with hydrocracking (Case 5)

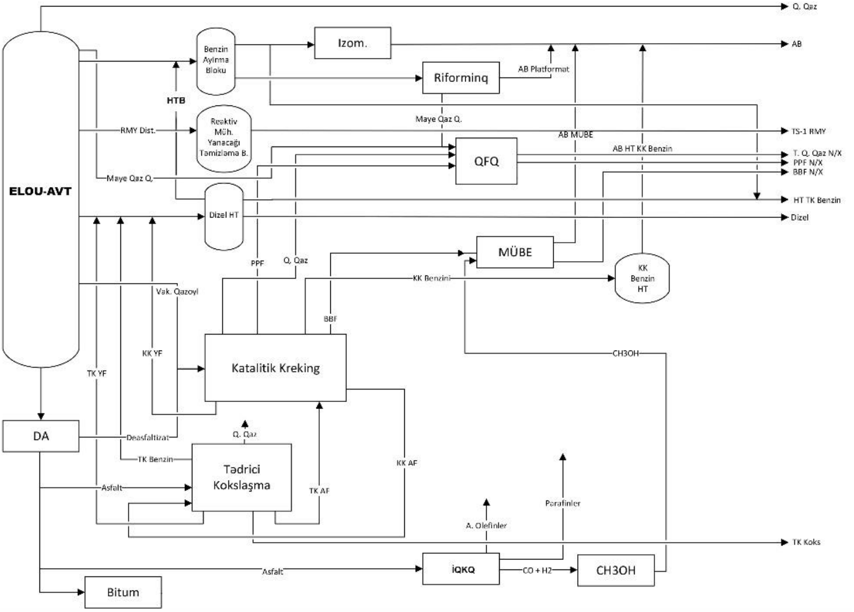


Figure 7. Process diagram with FCC and deasphalting units (Case 6)

Development of efficient processing schemes for petrochemical complex

66% of ethylene production worldwide is provided by pyrolysis, 30% by refineries, and 4% by the propane dehydrogenation process. The main product derived from ethylene is PE (mainly HDPE), as well as ethylene oxide and ethylene glycol, ethylbenzene, α-olefins, ethyl alcohol, etc. 67% of propylene production accounts for pyrolysis, 30% for catalytic cracking, and the remaining 3% for other processes.

Ensuring the production of high added value petrochemical products, the petrochemical sector works to boost the efficiency of both individual processing sectors and the broader fuel and energy industry. Under the developed integrated refining schemes, it is planned to process 6.5 million tons of crude annually, subject to meeting the demand for both refining and petrochemical products. The petrochemical feedstock composition by cases is presented in Table 6. For the sake of comparison it is assumed that the petrochemical units will be running at the same load.

Table 6.

Petrochemical feedstock composition by cases (kta)

Case / Composition	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Crude refining	6,500	6,500	**6,500**	6,500	6,500	6,500	6,500
Petrochemical feedstock	669.0	636.7	**462.5**	470.8	**970.4**	478.5	642.4
Including:							
HT Gasoline	377.7	342.3	**167.8**	158.6	**809.6**	112.0	301.4
PPF	91.4	88.1	**88.2**	88.2	-	108.9	101.5
BBF	161.1	129.9	**130.1**	147.6	160.8	163.3	151.5
Dry gas	38.8	76.4	**76.4**	76.4	-	94.3	88.0

Dry gas, PPF, BBF, and SR naphthas are supplied to the petrochemical production facilities as a feedstock. The PPF is first fractionated, and the resulting propane and propylene are respectively fed to the SC and the PP. Our country produces LDPE and HDPE from ethylene, PP, isopropyl alcohol, and diisopropyl ether from propylene. BBF is primarily fed to MTBE production, while spent BBF servs as feedstock for Steam Cracker; in turn, MTBE goes to gasoline blending.

The ethane-ethylene fraction from the steam cracker is fed to the fractionation plant, from where ethane and ethylene are respectively fed to the Steam Cracker and polyethylene units (LDPE and HDPE) (Case 8). Some portion of ethylene could also be fed to Butene-1 production unit (Case 9); The production of various grades of alpha-olefins can be created on that basis in the future. Setting up linear alpha-olefin production facilities beside ethylene-based plants will enable to both increase the Steam Cracker efficiency and boost the production of wide range linear alpha olefins (C_6-C_8, C_8-C_{12}, and C_{12}-C_{16}). C_6-C_8s (with a 50% yield) are used to make monomers and elastomers in PE production, C_{10}-C_{12} are used in the production of poly-alphaolefin oils, and C_{12}-C_{16} can be used in the production of biodegradable synthetic detergents. The next scheme envisages the ethylene-based production of alpha olefins (Case 10).

It makes it possible to create the production of semi-synthetic lubricants and sulfanol, which is a strategic product and the main component of synthetic detergents. And finally, the processing of C_4s will enable to create the rubber production in the country. BBF-based production of polyisobutylene rubber (with high-purity isobutylene obtained by MTBE decomposition) could be created (Case 11).

In the future, it will be possible to organize the production of ethyl benzene with the involvement of ethylene-derived benzene; ethyl benzene can be dehydrogenated to make styrene and eventually polystyrene. In that case, benzene could be either produced from heavy pyrolysis fractions or imported. The presented scheme will create a basis for producing a broader slate of products, diversifying the finished stock, and ultimately protecting the independence of our country when the entire world is crippled by sanctions. The four processing cases created in respect of the petrochemical complex development include: modernization of petrochemical production, addition of butene-1 production (Case 9), alpha-olefin production (Case 10), and rubber production (Case 11) (Table 7,8).

Table 7

Loading cases for proposed petrochemical units

Process Case	Case 8	Case 9	Case 10	Case 11
PE	+	+	+	+
PP	+	+	+	+
Butene-1	-	+	-	-
IPS	+	+	+	+
α -olefins	-	-	+	+
Polyisobutylene rubber	-	-	-	+
Polybutadiene rubber	-	-	-	+

The presented cases account for the limited amount of pyrolysis feedstock (naphtha, liquefied C_3, C_4, and dry gas) (Cases 8,9) and the involvement of an additional 538 thousand tons of gaseous feedstock as required to increase the process load of the plant to 1.0 MTA (Cases 10,11).

Some processing schemes are provided below:

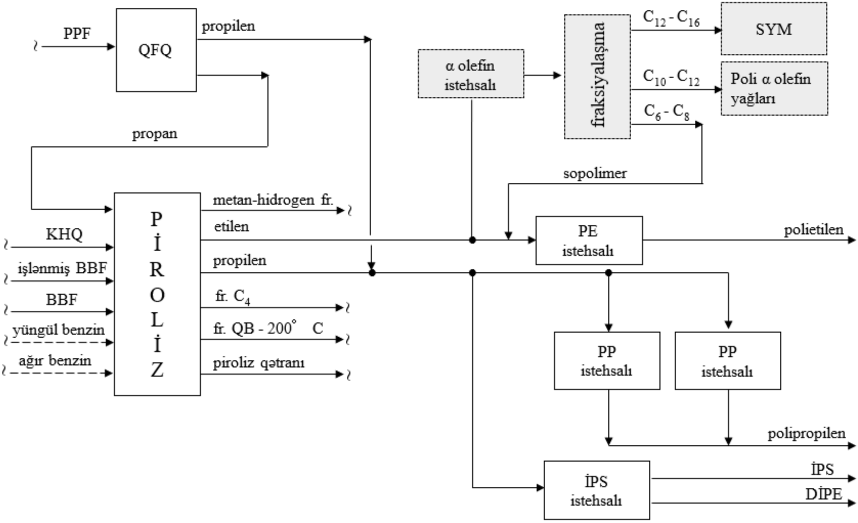


Figure 8. Petrochemical complex development scheme (Case 9)

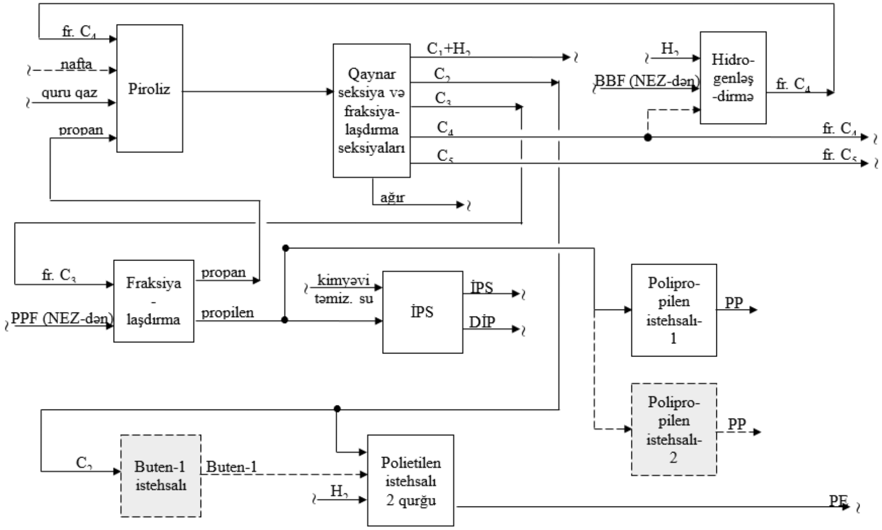


Figure 9. Petrochemical complex development scheme (Case 10)

The presented cases account for the limited amount of pyrolysis feedstock (naphtha, liquefied C_3, C_4, and dry gas) (Cases 8,9) and the involvement of an additional 538 thousand tons of gaseous feedstock as required to increase the process load of the plant to 1.0 MTA (Cases 10,11).

Table 8

Production of stock by petrochemical cases

	Case 8	Case 9	Case 10	Case 11
Feedstock (kt)				
REF	462.0	462.0	462.0	462.0
NG-based feedstock	-	-	538.0	538.0
Yields:				
PE	130.2	130.2	240.0	240.0
PP	100.0	100.0	143.8	143.8
IPS	23.5	23.5	30.0	30.0
α -olefins	-	-	143.3	143.3
Butene-1	-	30.5	-	-

Development of integrated refining and petrochemical complexes

Based on the integration of refining and petrochemical complexes through product integration, product flows (naphtha, liquefied gases, etc.) in crude refineries have traditionally been directed to the production of motor fuels. However, more products (polymers, plastics, rubbers, stabilizers, etc.) could be obtained by processing those streams in the petrochemical facility. A few schemes have been developed showing product flows in the prospective PETR complex in our country based on the demand for petrochemical products and the development of the national petrochemical infrastructure and the advantages of its integration with the crude refinery.

The main integration indicator is obviously the ethylene-to-propylene ratio. It is recommended to operate the refinery FCC unit in a petrochemical mode that ensures maximum production of propylene. The produced PPF and BBF could be fed to PETR and converted into polypropylene and isopropyl alcohol, while spent BBF originated at MTBE production plant could be used to produce rubber (polyisobutylene, polybutadiene, etc). It is also possible to supply aromatic hydrocarbons from the oil refinery to the petrochemical complex, thereby making it possible to create the production of PETR benzene-based ethylbenzene with the involvement of ethylene, and the production of styrene by way of its dehydrogenation. Production of butadiene styrene rubber can be created on the basis of styrene with the involvement of polystyrene and butadiene. On the other hand, we could indicate methanol (which is mainly used in the production of MTBE) as well as Steam Cracker products: isobutylene, isopropyl alcohol and diisopropyl ether (DIPE), which is a by-product of the latter and serves a high-octane component (oxygenate) in the production of gasolines, and olefins used in the production of synthetic and semi-synthetic high-viscosity lubes and additives to fuels and lubricants. On the other hand, heavy pyresin from the steam cracking process, which is very difficult in disposal, could be fed to the DCU and/or the HCU.

In order to determine the economic advantages of the integration of processing areas, economic performances of oil refining and petrochemical facilities have been studied separately. If we compare the operation of a single integrated complex with that of the individual processing areas, the refinery feedstock throughput is 6,500 thousand tons per annum of crude, whereas the steam cracking unit processes

1.0 million tons of feedstock annually, including 462 thousand tons of feedstock mixture supplied from the refinery and 538 thousand tons of natural gas. According to the presented Case 3 (refinery), the profit obtained from the production and consumption of the product amounts to 2,022 million AZN. In this case, petrochemical feedstock is valuated at the company's internal price (AZN 256/t). If we consider that the profit obtained from the feedstock processing in the petrochemical facility as per that case is 198.6 million AZN, the total profit received in the processing sector makes up 2,220.6 million AZN.

In the evaluation of the integrated refining and petrochemical complex, the transformation of petrochemical feedstock into final stock (polymers, rubbers, etc.) was taken into account, and the averaged price of finished petrochemical stock (765 AZN/t) was evaluated. As a result, the profit from the production and consumption of the produced stock is 2,305.6 million AZN. Thus, the integrated complex brings a benefit in the amount of 85 million AZN as compared to the individual activities of enterprises (Table 9). The studies once again confirm the ecological, technological, and economic advantages the integration of the processing areas brings, and at the same time lay the foundation for gaining income from the consumption of petrochemical products rather than losing them as a result of changes in market conditions.

Table 9

Comparison of individual and joint operations of refining and petrochemical facilities

	Crude refining	Petrochemical production	Total	Integrated refining/petrochemical facility
Feedstock:				
Crude oil (kt)	6500	-	6,500	6,500.0
Petrochemical feedstock (kt), incl.	-	1,000.0	1,000	1,000.0
natural gas	-	538.0	538.0	538.0
Total product: (million AZN)		337.4		
- profit (million AZN)	2,022	198.6	2,220.6	**2,305.6 difference - 85 million AZN)**

In addition, added value is created in production and the company's competitiveness is increased by centralizing inter-enterprise management, optimizing costs, and applying state-of-the-art digital tools. The integration of oil refining and petrochemical industries in a single hub presents great opportunities; integrated facilities promise higher operating margins due to efficient planning. It facilitates consistent strategy and forward-looking development in terms of growth and strategic planning and brings business excellence due to shared best practices in operations, maintenance, and supply chain.

More efficient management of spare parts, flexibility, and development of personnel capacity are therefore ensured, bringing increasingly effective maintenance, resource allocation, and economies of scale.

The integration of oil refining and petrochemical industries increases overall profitability. As the extent of integration increases, so does profitability:

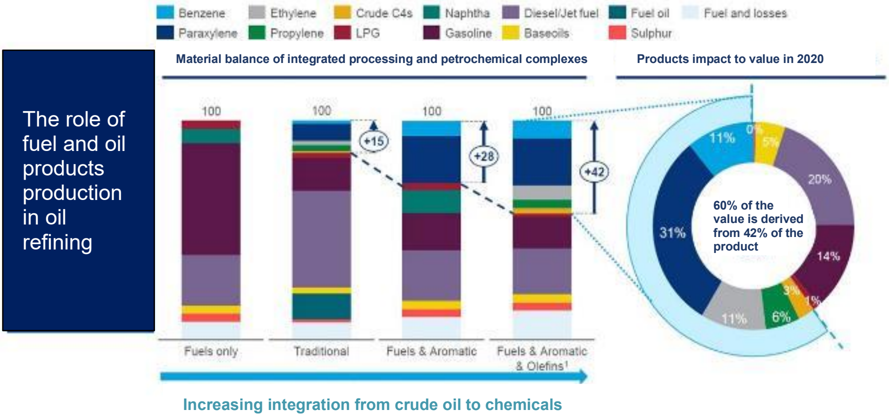


Figure 10. Material balance of integrated refining/petrochemical complex

Integrated businesses boast lower costs and higher profit potential than those specializing in one single area. A performance comparison between integrated and non-integrated sites is provided below:

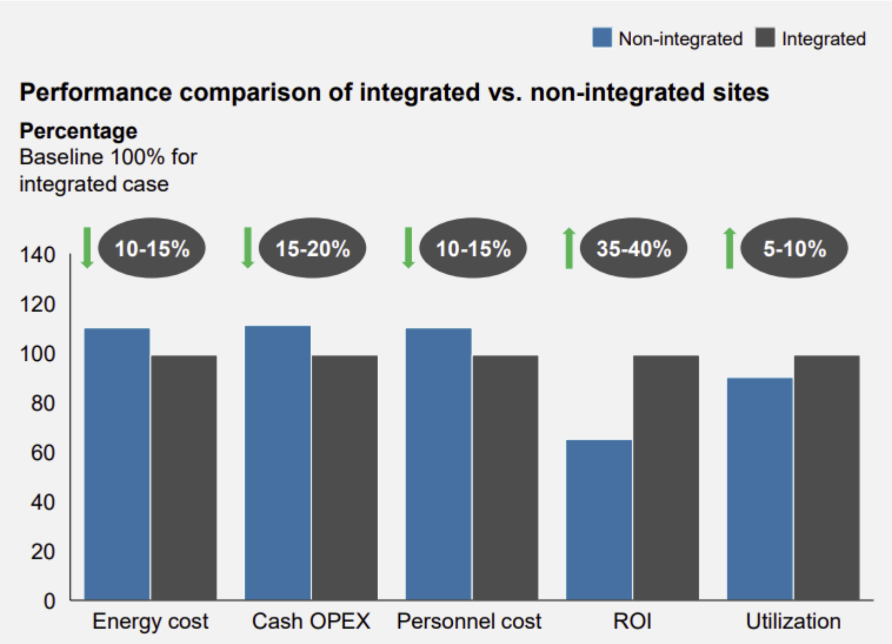


Figure 11. Baseline figures for integrated enterprise case

Each presented scheme can be used in both the creation of new complexes and the reconstruction of existing plants. As a result of the conducted research, it can be noted that the creation of a single combined refining and petrochemical complex will enable efficient use of investments, as well as create savings to a certain extent. Apparently, the dissertation work is not in the position to provide solutions for all problems. However, should this effort be taken as a step towards the development of processing sectors in our country, we will consider our mission accomplished.

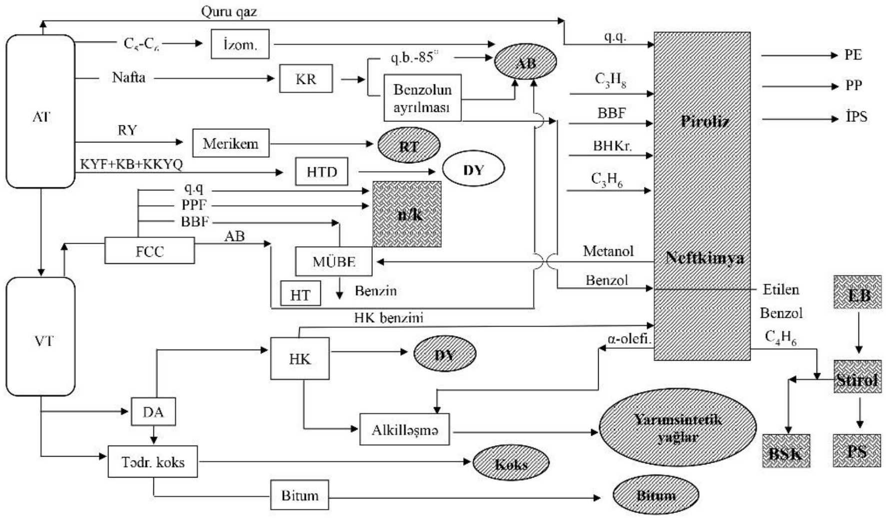


Figure 12. Integrated refining/petrochemcial complex processing scheme (Case 14)

RESULTS

The following results were obtained in the complex studies conducted towards of increasing the integration capabilities of refining and petrochemical enterprises and covering environmental, technological, and economic challenges:

1. Based on the study of the national petrochemical infrastructure, the creation and development dynamics of integration processes with the crude refining industry have been analyzed [1,2,15,9].
2. As a result of the study of the possibilities of increasing the yield of liquefied gases by running the catalytic cracking unit (FCC) in different modes (a total of 3), it has been determined that the operation of the unit in the deep catalytic cracking mode both doubles the output of C_3 olefins (from 107.5 to 235.0 kt) and increases the output of butylene from 212.5 to 237 kt [3,4,14].
3. To expand the FCC feedstock pool, various modifications have been applied to the processing scheme [5,14,17].

- By increasing the FBP of VGO to 540C in the CDU/VDU, it becomes possible to increase the output by 5% to 35%.
- With heavy residue processing facilities (deasphalting, integrated gasification unit (IGU), etc.) introduced in the configuration, integrated processing schemes have been created and evaluated from both the technical and economic standpoint. It has been determined that the application of the presented scheme allows increasing the feedstock supply of the pyrolysis unit by 8-10% [6-8].

4. The technical characteristics and energy consumption of individual processes in the petrochemical industry have been analyzed and their development prospects determined [18, 19].
5. With the introduction of new units, various cases (a total of 6) of integrated processing schemes with a crude throughput of 6.5 MTA have been developed and evaluated technically and economically. Maximum petrochemical feedstock (970.4 kta) could only be provided in Case 5, which features the hydrocracking process. The national gasoline demand, however, cannot be met in this case. From an economic point of view, Case

3 - which brings profits in the amount of 2,022 million AZN per year - is considered optimal, and petrochemical feedstock is provided by the FCC Unit [10-13].

6. Integrated petrochemical processing schemes (4 cases in total) were created with the application of advanced technologies; it was determined that the processing of 462.0 thousand t/year of feedstock yields 130.2 thousand tons of PE, 100.0 thousand tons of PP, and 23.5 thousand tons of isopropyl alcohol annually. The profit obtained from the sale of this finished stock is AZN 198.6 million/year [11].
7. The potential supply of utilizing an additional 538,000 tons of natural gas has been studied in view of increasing the duty of the steam cracker. It was determined that the full loading of the unit increases PE production two-fold (up to 140 kt) and PP production by 44 kt, thereby creating the basis to produce an additional 140 thousand tons of alpha-olefins and helping expand the production capabilities of synthetic and semi-synthetic lubes and synthetic detergents nationwide [6].
8. Various cases (a total of 4) of processing schemes for a unified refining and petrochemical complex have been developed. While the total profit received from the individual activities of the processing areas is 2,220.6 million AZN (2,022.0 million AZN from the refining and 198.6 million AZN from the petrochemical sector), the unified (integrated) refining and petrochemical complex yields a profit of 2305.6 million AZN by processing the very same feed. Such a complex therefore represents an estimated economic benefit of around 85 million AZN [5,15].
9. If the construction of a larger-scale petrochemical complex in line with modern standards is foreseen in the country, it is recommended to consider setting up an oil-gas processing and petrochemical cluster controlled from a single center. This approach will help build a more competitive production chain and optimize costs in the long run. It will also help monetize the valuable petrochemical feedstock contained in the gases produced locally [16].

The studies once again confirm the ecological, technological, and economic advantages the integration of the processing areas brings, and at the same time lay the foundation for gaining income from the consumption of petrochemical products rather than losing them because of changing market conditions.

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