A Techno-Economical Evaluation Study for Upgrading Sarir Oil Refinery and Maximizing Gasoline Production

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ABSTRACT

Oil refineries have become increasingly more efficient over time. Therefore, huge efforts are being made to invest in better processes and technologies that save energy and maximize the production of high-value products, particularly, gasoline. In this study, two scenarios are proposed to upgrade the Sarir Oil Refinery for increasing its capacity from 10,000 BPD to 120,000 BPD by adding new units of vacuum distillation and Delayed Coking or Fluid Catalytic Cracking (FCC) unit. The production rates of all units are obtained through material balance calculations. Finally, an economical evaluation is carried out to determine if the proposed projects meet the profitability criteria of the refinery and to decide which refinery scenario is techno-economically feasible and maximizes the production of gasoline more than the other. The observational results revealed that the best refinery scenario is the one that uses atmospheric distillation and FCC units as it has less payout time (3.6 years), higher internal rate of return (110%) and higher production of gasoline.

Keywords: Sarir Refinery; Gasoline production; Delayed coking; FCC unit; payout time; Rate of return.

1. Introduction

The rapid population growth has led to a huge increase in the global energy requirements, which will be doubled by 2050, leading to severe shortage in the fossil fuel supplies [1-3]. The demand on high-value petroleum products such as gasoline, middle distillates and lube oils is increasing, while the demand for low-value products such as fuel oil and residue based products is decreasing. Therefore, maximizing of liquid products yield from various processes and valorization of residues is of immediate attention to many oil producing countries [4-7].

Many small oil projects were made in Libya since the beginning of oil industry. However, these projects have not been developed since they were considered to be small and far from any existing facilities and therefore were judged as uneconomical projects. One of these projects is the Sarir Oil Refinery which is located in the southeast of Libya with a capacity of 10,000 BPD [8]. The refinery is currently supplying the nearby cities with gasoline and other fuels supplies. It also covers the fuel consumptions of all facilities in Sarir Oil Field, which is considered as one of the biggest oil fields in Africa (250,000 BPD). However, Libya still suffers from a severe shortage in the energy supplies and imports about 75% of its fuel needs. Therefore, new projects for increasing fuel production must be considered in the near future to meet the local consumption and regional demand of gasoline and other types of fuels. In the past, many techno-economical evaluation studies were reported by other researchers for upgrading such projects [9, 10].

The present study aims to upgrade the Sarir Oil Refinery and maximize the gasoline production by increasing the capacity of the refinery from 10,000 BPD to 120,000 BPD and adding new units to the refinery. This will be conducted in two different scenarios, by making material balance for all processing units that will be considered such as atmospheric distillation, reforming, vacuum distillation, delayed coking and FCC units. Then, analyzing the obtained technical data in order to select optimum scenarios and finally investigating the selected optimum scenario from a techno-economic point of view, taking into consideration the profitability, project payout time and the investment internal rate of return.

2. Material Balance Analysis

The material balance in any refining process is important for both ensuring its proper design and later for its proper operation. Mass balance is also useful in understanding the primary processing operations in various sub-processes and to estimate the flow rates of various intermediate streams and final product flow rates.

2.1 Material Balance of Atmospheric Distillation Unit

The operation of the atmospheric crude distillation is critical to the performance of the downstream units such as vacuum distillation, delyed coker and fluid catalytic cracking units. Mass balance analysis is conducted overall the refinery units to understand the primary and sub-processing operation units and to find the products flow rates. A set of qualitative and quantitative tests are also conducted in the laboratory of Sarir Oil Refinery in order to characterize the Sarrir-Messla crude oil sample. Details of these tests and their results are presented in **Table 1**.

In addition to the analytical testes reported in **Table 1**, a true boiling point (TBP) distillation test was conducted for analyzing the products of atmospheric distillation unit according to the ASTMD-2892 method. This was carried out by using 100 mL of the crude oil sample (Sarrir-Messla) in which the distillate fractions of light and medium products such as light/heavy naphtha, kerosene and gas oil are estimated according to their cut points in °C. Finally, the atmospheric residue is calculated by the difference between the original sample volume (100 mL) and the sum of products lighter than the atmospheric residue. All the product volume ratios in addition to the weight ratios are reported as shown in **Table 2** and according to these ratios, the volumetric and mass flow rates of the products are also calculated using the actual feed of Sarir Oil Refinery (10,000 BPD).

Using the TBP and other analyses results of Sarrir-Messla crude oil, a complete material balance is conducted over the upgraded atmospheric distillation unit assuming a crude oil feed rate of 120,000 BPD (15,979,500 kg/d). The production rates of all products of the new upgraded unit are reported as both volumetric and mass flow rates as shown in **Table 2**.

Table 1 Petroleum analysis of Sarrir-Messla crude oil sample

Test	Units	Methods	Results
Density	Kg/l	ASTM D-1298	0.8375
API gravity	°	Calculation	37.6°
Water and sediment content	vol. %	ASTM D-4007	0.050
Sulphur content	wt %	ASTM D-4294	0.128
Pour point	°C	ASTM D-97	+15
Asphaltenes content	wt %	IP 143	0.16
Conradson carbon residue	wt %	ASTM D-189	3.192

Table 2 Material Balance of current and upgraded atmospheric distillation unit of Sarir Refinery

Feed		**From ASTMD-2892**		**Current Refinery**			**Updated Refinery**		
		vol %	**wt %**	**L/d**	**Kg/d**	**BPD**	**L/d**	**Kg/d**	**BPD**
		١٠٠	١٠٠	1,590,000	1,331,625	10,000	19,080,000	15,979,500	120,000
Cut Point,°C	**Products**	-	-	-	-	-	-	-	-
–	*Gases & LPG*	1.55	1.03	24,645.0	13,715.7	155	295,740.0	164,588.9	1,860
5–70°C	*Light Naphtha*	7.18	5.60	114,162.0	74,571.0	718	1,369,944.0	894,852.0	8,616
70–175°C	*Heavy Naphtha*	17.94	16.07	285,246.0	213,992.1	1,794	3,422,952.0	2,567,905.7	21,528
175–235°C	*Kerosene*	9.82	9.31	156,138.0	123,974.3	982	1,873,656.0	1,487,691.5	11,784
235–350°C	*Atm. Gas Oil*	19.97	19.85	317,523.0	264,327.6	1,997	3,810,276.0	3,171,930.8	23,964
> 350°C	*Atm. Residue*	٤٣,٥٤	٤٨,١٤	692,286.0	641,044.3	4,354	8,307,432.0	7,692,531.3	52,248
Total		١٠٠	١٠٠	1,590,000	1,331,625	10,000	19,080,000	15,979,500	120,000

2.2 Material Balance of Reforming Unit

The catalytic reforming is one of the main downstream operation units that is used to convert the low-octane naphtha into high-octane reformates which can be blended to form premium gasoline. There are also some other by-products that could be produced from the reforming unit, these may include hydrogen and cracked light gases. The heavy naphtha feed is composed of four major hydrocarbon groups: paraffins, olefins, naphthenes, and aromatics (PONA). In order to estimate the values of H_2, C_1, C_2, C_3, C_4 products, it is necessary to find the value of C_5^+ which can be estimated through **Fig. 1** [11] using a given RON value of 94 and a solid line value calculated by **Equation 1** (~ 40) as follows:

$$\text{Solid line value} = N + 2A \quad (1)$$

Where N and A are the values of total vol% of Naphthenes and total Aromatics in the light naphtha, respectively.

Table 3 presents the obtained results for the conducted hydrocarbon analysis of the heavy naphtha sample using a gas chromatograph (GC) instrument. For a given value of feed research octane number (RON) equal to 94 and calculated value of **Equation 1** (~ 40), the C_5^+ volume percent (vol. %) is estimated to be 79% as illustrated in **Fig. 1**. The net hydrogen production in addition to the C_1, C_2, C_3 and C_4 productions of reforming process can be estimated based on the yield of reformate (C_5^+) as illustrated in **Fig. 2** However, the overall material balance of the reformer unit is presented in **Table 4**.

Table 3 Hydrocarbon analysis of heavy naphtha sample

Group Types	Vol %	Wt %	Mol. %
Total Aromatics	6.323	7.681	7.596
Total Iso–Paraffins	28.532	27.287	26.872
Total Naphthenes	27.193	29.114	28.231
Total Olefins	0.740	0.763	0.635
Total n-Paraffins	34.551	32.482	34.589
Total Unknowns	2.662	2.673	2.078
Total	100.00	100.00	100.00

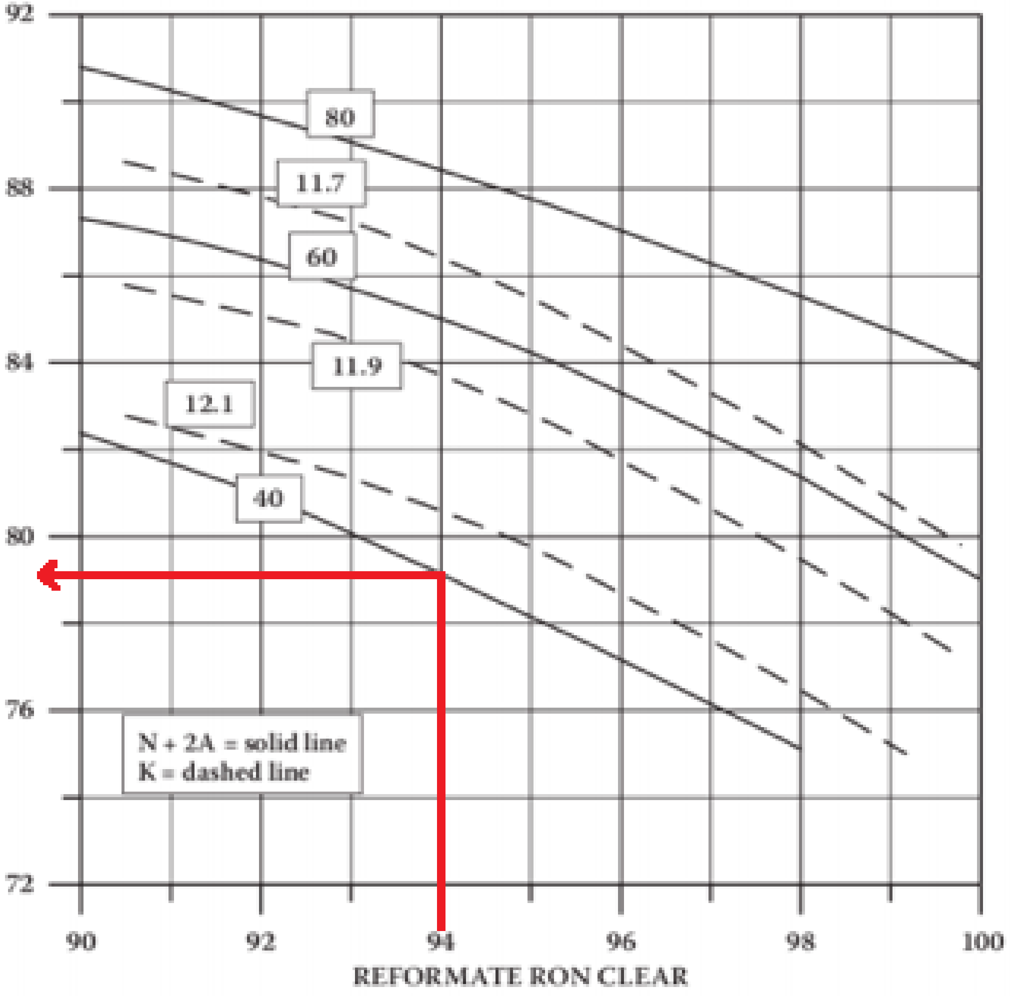

Fig. 1 The catalytic reforming yield correlations of C_5^+ vol. % for a given RON of 94 and a solid line value (~ 40) calculated by the equation N + 2A [11].

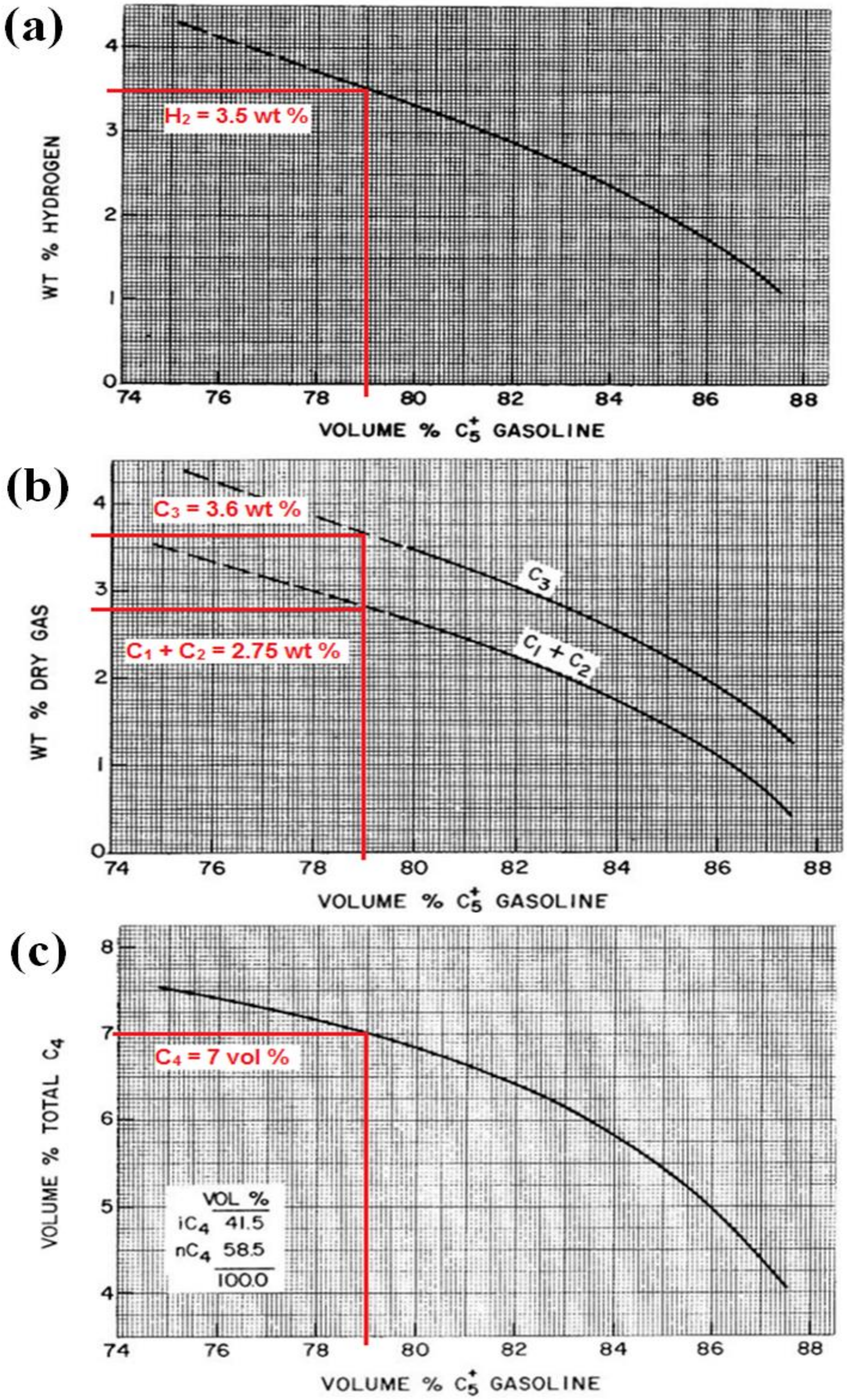

Fig. 2 The catalytic reforming yield correlations for **(a)** hydrogen wt %, **(b)** $C_1 + C_2$, C_3 wt % and **(c)** C_4 vol. % [11].

Table 4 Material Balance on the Reforming Unit

Feed	Vol. %	wt %	L/day	kg/day	BPD	Density
	100	100	3,422,952	2,567,906	21,528	–
Products	–	–	–	–	–	–
H_2	–	3.5	–	89876.7	–	–
C_1+ C_2	–	2.75	–	70617.4	–	0.328
C_3	–	3.6	–	92444.6	–	0.508
Total C_4	7	5.45	239,613	139950.9	1,507	0.584
C_5^+	–	84.7	–	2175016.4	–	
Total	–	100	–	2,567,906	–	–

2.3 Material Balance of Vacuum Distillation Unit

The atmospheric residue from the atmospheric distillation unit with a rate of 52,248 PBD is used as a feed to the column of the vacuum distillation unit in order to obtain vacuum gas oils and vacuum residue as top and bottom products, respectively. The production rates of vacuum gas oil and vacuum residue are estimated according to the volumetric and mass ratios obtained through the ASTM D-1160 vacuum distillation method and the results are presented in **Table 5**.

Table 5 Material Balance on the Vacuum Distillation Unit

Feed		Vol. %	wt %	L/d	Kg/d	BPD
		١٠٠	١٠٠	8,307,432	7,692,531	52,248
Cut point	**Products**	–	–	–	–	–
235–350°C	***Vac. Gas oil***	67.4	64.8	5,599,209	4,984,760	35,215
> 350°C	***Vac. Residue***	32.6	35.2	2,708,223	2,707,771	17,033
Total		١٠٠	١٠٠	8,307,432	7,692,531	52,248

2.4 Material Balance of Delayed Coker Unit

The delayed coker is mainly used to minimize refinery yields of residual liquid products such as vacuum residue from the vacuum tower and produce wet gas (C_4), gasoline, gas oil and coke. When the Conradson carbon residue (CCR) is known, all the yields (wt%) of gas (C_4), gasoline, gas oil and coke can be predicted using **Equations (2-5)** reported by Gary and Handwerk [11]:

$$\text{Coke wt \%} = 1.6 \times (\text{wt \% CCR}) \quad (2)$$

$$\text{Gas } (C_4) \text{ wt \%} = 7.8 + 0.144\ (\text{wt \% CCR}) \quad (3)$$

$$\text{Gasoline wt \%} = 11.29 + 0.343\ (\text{wt \% CCR}) \quad (4)$$

$$\text{Gas oil wt \%} = 100 - (\text{coke wt \%} + \text{gas wt \%} + \text{gasoline wt \%}) \qquad \textbf{(5)}$$

The Conradson carbon residue (CCR) of the vacuum residue is found to be 21.46 wt% and hence, a material balance of the coking process is conducted and presented in **Table 6**. It can be seen from the obtained results that the gasoline yield was 18.65 wt% while the coke yield reached up to 34.34 wt% with the use of vacuum residue feed of 2,707,771 Kg/d.

Table 6 Material Balance on the Delayed Coking Unit

Feed	**wt %**	**Kg/d**	**L/d**	**BPD**
	١٠٠	2,707,771	2,708,223	17,033
Products	–	–	–	–
Coke	٣٤,٣4	929,849	–	–
Gas(C_4)	١٠,٨٩	294,876	–	–
Gasoline	١٨,٦٥	504,999	–	–
Gas Oil	٣٦,١٢	978,047	–	–
Total	100	2,707,771	–	–

2.5 Material Balance of Fluid Catalytic Cracking Unit

The fluid catalytic cracking (FCC) is one of the most efficient secondary processes to increase gross refinery margin (GRM) and hence increasing the profitability as it converts low-priced heavy feed stock into lighter, more valuable hydrocarbons such as liquefied petroleum gas (LPG) and gasoline. The main feedstock used in the FCC unit is the gas oil with a boiling ranging from 316 and 566 °C (600 and 1050°F). There are also some other possible feed stocks such as atmospheric distillates, coking distillates, visbreaking distillates, VGO, atmospheric residue and vacuum residue. However, in this study the FCC feed will be a mixture of atmospheric and vacuum gas oils (**Table 7**) produced from the atmospheric distillation unit (3,171,930.8 Kg/day) and the vacuum distillation unit (4,984,760 Kg/day).

Table 7 Feed composition of Fluid Catalytic Cracking Unit

Stream	**BPD**	**API**	**kg/day**
AGO	23,964	40	3,171,930.8
VGO	35,215	28.75	4,984,760
Total	59,179	34.375	8,156,690.8

The FCC product yields can be estimated using equations of yield correlations [12] illustrated in **Table 8** and the obtained results are presented in **Table 9**. It is worth mentioning that these simplified yield correlations are only approximations and not specific for any catalyst, operating parameters, or process configuration. The actual yields are functions of reactor pressure, catalyst type, activity, and feed quality.

Table 8 Yield correlations of Fluid Catalytic Cracking Unit

Products	Correlation	Result	Equation
Gases, wt %	0.0552 × CONV. + 0.597	4.74	**(6)**
C_3 LV, %	0.0436 × CONV. – 0.8714	2.4	**(7)**
$C_3^=$ LV, %	0.0003 × $(CONV.)^2$ + 0.0633 × CONV. + 0.0143	6.45	**(8)**
iC_4 LV, %	0.0007 × $(CONV.)^2$ + 0.0047 × CONV. + 1.40524	5.7	**(9)**
nC_4 LV, %	0.0002 × $(CONV.)^2$ + 0.019 × CONV. + 0.0476	2.6	**(10)**
$C_4^=$ LV, %	0.0993 × CONV. – 0.1556	7.3	**(11)**
Gasoline LV, %	0.7754 CONV. – 0.7778	57.4	**(12)**
LGO, vol. %	0.0047 × $(CONV.)^2$ – 0.8564 × API + 53.576	15.8	**(13)**
HGO, wt %	100 – CONV. – (15.7835)	9.2165	**(14)**
Coke, wt %	0.05356 × CONV. – 0.18598 × API + 5.966975	3.6	**(15)**
CONV.	$\text{CONV. \%} = \left(\frac{\text{volume of oil feed} - \text{volume of cycle stock}}{\text{volume of oil feed}}\right) \times 100$	75%	**(16)**

Table 9 Material Balance on the Fluid Catalytic Cracking Unit

Products	Vol. %	wt %	BPD	Kg/day
Light gases	–	4.74	–	386627.1
$C_3^=$	6.45	–	3817	–
C_3	2.4	–	1420.3	–
$C_4^=$	7.3	–	4320	–
i-C_4	5.7	–	3373.2	–
n-C_4	2.6	–	1538.7	–
Gasoline	57.4	–	33968.7	–
LGO	15.8	–	9350.3	–
HGO	6	9.2165	3550.7	751761.4
Coke	–	3.6	–	293640.9

Using all the obtained material balance data, two different scenarios of multi-unit refineries are proposed and economically investigated in this study. **Fig. 3** and **4** demonstrate complete schematic illustrations for all the operation units in the two proposed refinery scenarios.

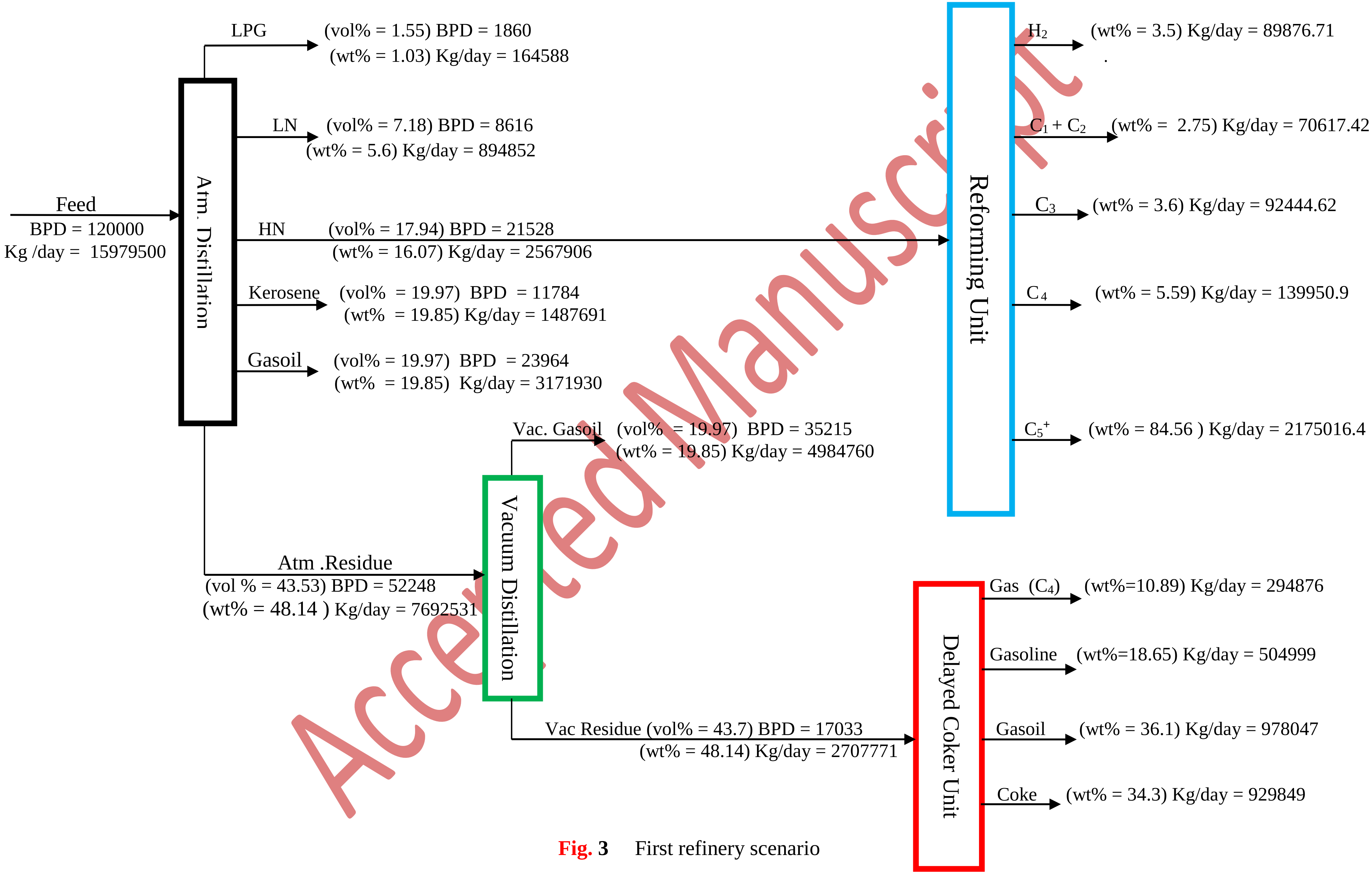

Fig. 3 First refinery scenario

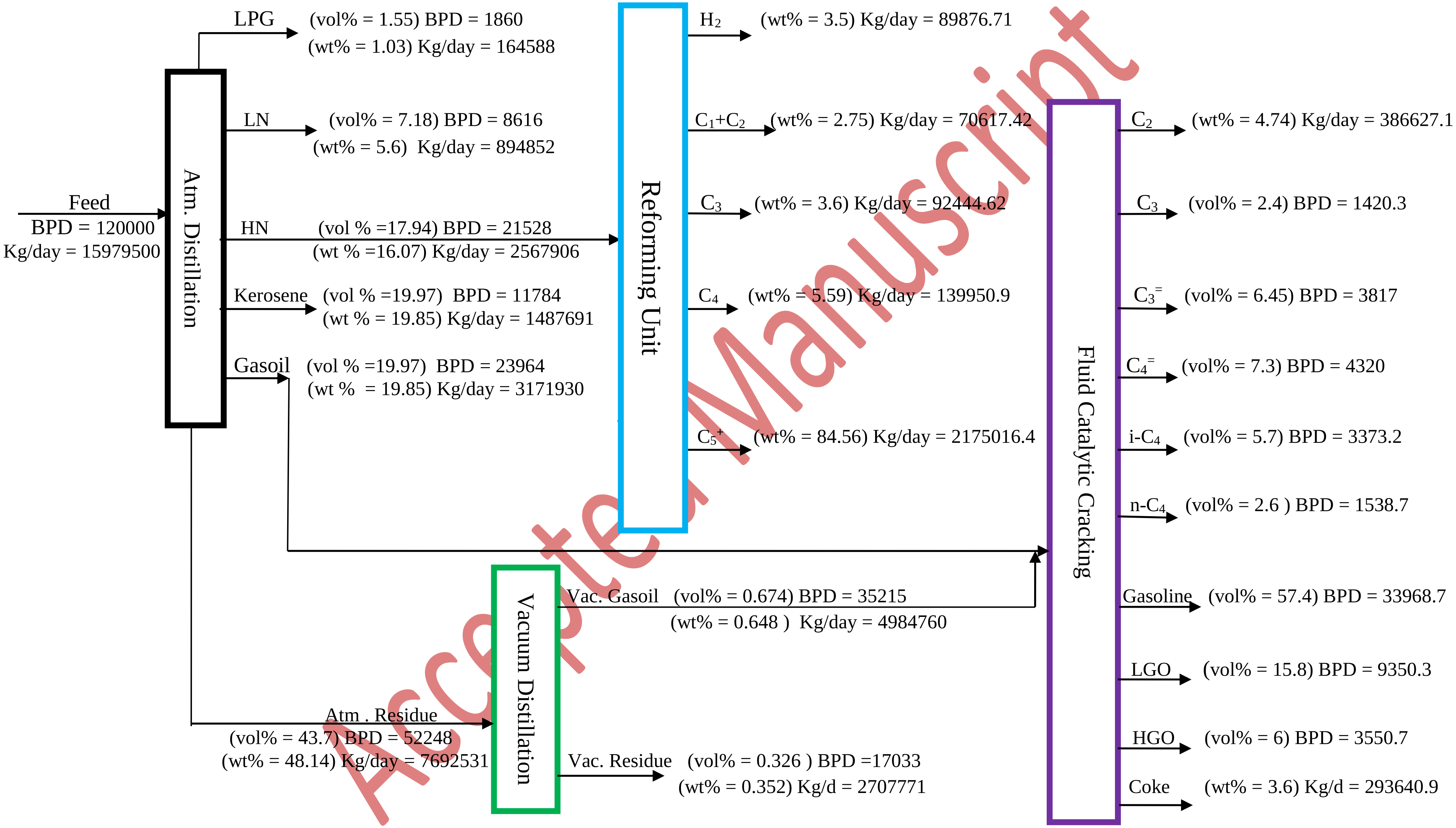

Fig. 4 Second refinery scenario

3. Economic Evaluations

An economic evaluation is carried out to determine if the proposed investment meets the profitability criteria of the refinery and to compare both refinery scenarios, this is going to be conducted in several steps demonstrated in the following sections. However, there are some terms that are going to be used in this study and need to be explained as presented in **Table 10**.

Table 10 Terms used in this study with their abbreviations and definitions

Term	Abbreviation	Definition
Revenue	-	The money received throughout a project. It is calculated by multiplying the annual production by its forecasting selling price.
Net Cash Flow	NCF	The money received minus the money spent during a certain period which is usually assumed to be one year.
Payout Time	POT	The time needed to recover the investment (refinery). The shorter the payout time, the more attractive the project becomes.
Net Present Value	NPV	The present value of the entire cash flow discounted at a specified discount rate.
Internal Rate of Return	IRR	The internal rate of return or discounted cash flow return on investment is the discount rate at which the net present value is equal to zero.

3.1 Estimation of annual revenue

In this section we are going to calculate the annual revenue of the two project scenarios by using the sum of products quantities and the average estimated product prices as illustrated in **Table 11**. The prices are the average global prices during the year of 2023, however some products are considered as by-products like vacuum residue and its price is historically estimated to be about 70% of the price of crude from which it was produced [11].

3.2 Estimation of revenue for the 25 years period

In this section the revenue for each year of project life is calculated by multiplying the products quantity by the new year's prices for each product. The future prices are estimated using an inflation factor (**Equation 17**) at a specified inflation rate of 3% [11]. The revenue results of the two refineries are illustrated in **Tables 12** and **13**.

$$\textit{Inflation factor} = (1 + 3\%)^n \qquad \textbf{(17)}$$

Where n is the number of the year.

Table 11 Estimation of the annual revenue for Delayed Coking and FCC Refineries

Delayed Coking Refinery							
Product	**Total quantity**	**density (Kg/L)**	**L/Year**	**Kg\Year**	**Ton/Year**	**Price**	
LPG	1,860 BPD	—	107,945,100	60,074,949	60,075	1451 $/Ton	87
Light naphtha	8,616 BPD	—	500,029,560	326,620,980	326,621	951 $/Ton	31
Kerosene	11,784 BPD	—	683,884,440	543,007,398	543,007	1381 $/Ton	74
Gasoil (Atm. & Vac.)	9,134,737.8 Kg/d	0.8350	3,993,029,098	3,334,179,297	3,334,179	1.1 $/L	4,3
H_2	89,876.71 Kg /d	—	—	32,804,999	32,805	3.7 $/Kg	12
$C_1 + C_2$	70,617.42 Kg /d	0.3280	78,583,409	25,775,358	25,775	2600 $/Ton	6
C_3	92,444.62 Kg/d	0.5080	66,421,823	33,742,286	33,742	940 $/Ton	3
C_4	434,827 Kg/d	0.5840	271,766,875	158,711,855	158,712	960 $/Ton	15
Gasoline	2,680,015 Kg/d	0.7650	1,278,699,967	978,205,475	978,205	2186 $/Ton	2,1
Coke	929,849 Kg/d	—	—	339,394,885	339,395	200 $/Ton	6
Total	—	—	—	—	—	—	**8,1**
FCC Refinery							
Product	**Total quantity**	**density (Kg/L)**	**L/Year**	**Kg\Year**	**Ton/Year**	**Price**	
LPG	1,860 BPD	—	107,945,100	60,074,949	60,075	1451 $/Ton	87
Light naphtha	8,616 BPD	—	500,029,560	326,620,980	326,621	951 $/Ton	31
Kerosene	11,784 BPD	—	683,884,440	543,007,398	543,007	1381 $/Ton	74
Gasoil (light & heavy)	12901 BPD	0.8350	748,709,535	625,172,461.7	625,172	1.1 $/L	82
H_2	89,876.71 Kg /d	—	—	32,804,999	32,805	3700 $/Ton	12
$C_1 + C_2$	457,244.5 Kg /d	0.3280	508,823,932	166,894,250	166,894	2600 $/Ton	43
C_3	577,985 Kg/d	0.5080	370,369,251	188,147,579	188,148	940 $/Ton	17
C_4	997188.2 Kg/d	0.5840	264,639,600	363,973,693	363,974	960 $/Ton	34
Gasoline	6,306,799.22 Kg/d	0.7650	3,009,126,425	2,301,981,715	2,301,982	2186 $/Ton	5,0
Vac. Residue	2,707,771 Kg/d	—	988,510,155	988,336,415	988,336	330 $/Ton	32
Coke	293,640.9 Kg/d	—	—	107,178,929	107,179	200 $/Ton	2
Total	—	—	—	—	—	—	**8,4**

Table 12 Estimation of the total revenue of Delayed Coking refinery for 25 years

Product		LPG	L. naphtha	Kerosene	Gas oil	H_2	$C_1 + C_2$	C_3	C_4	Gasoline	Coke	**Total re**
Quantity, Ton		60,075	326,621	543,007	3,334,179	32,805	25,775	33,742	158,712	978,205	339,395	
Year	**Inflation factor**	**Price ($)**										
2024	1.000	1451.0	951.0	1381.0	1317.4	3700.0	2600.0	940.0	960.0	2186.0	200.0	8,118,7
2025	1.030	1494.5	979.5	1422.4	1356.9	3811.0	2678.0	968.2	988.8	2251.6	206.0	8,362,2
2026	1.061	1539.4	1008.9	1465.1	1397.6	3925.3	2758.3	997.2	1018.5	2319.1	212.2	8,613,1
2027	1.093	1585.5	1039.2	1509.1	1439.5	4043.1	2841.1	1027.2	1049.0	2388.7	218.5	8,871,5
2028	1.126	1633.1	1070.4	1554.3	1482.7	4164.4	2926.3	1058.0	1080.5	2460.4	225.1	9,137,6
2029	1.159	1682.1	1102.5	1601.0	1527.2	4289.3	3014.1	1089.7	1112.9	2534.2	231.9	9,411,8
2030	1.194	1732.6	1135.5	1649.0	1573.0	4418.0	3104.5	1122.4	1146.3	2610.2	238.8	9,694,1
2031	1.230	1784.5	1169.6	1698.5	1620.2	4550.5	3197.7	1156.1	1180.7	2688.5	246.0	9,985,0
2032	1.267	1838.1	1204.7	1749.4	1668.8	4687.0	3293.6	1190.8	1216.1	2769.2	253.4	10,284,5
2033	1.305	1893.2	1240.8	1801.9	1718.9	4827.7	3392.4	1226.5	1252.6	2852.2	261.0	10,593,0
2034	1.344	1950.0	1278.1	1855.9	1770.4	4972.5	3494.2	1263.3	1290.2	2937.8	268.8	10,910,8
2035	1.384	2008.5	1316.4	1911.6	1823.5	5121.7	3599.0	1301.2	1328.9	3025.9	276.8	11,238,2
2036	1.426	2068.8	1355.9	1969.0	1878.2	5275.3	3707.0	1340.2	1368.7	3116.7	285.2	11,575,3
2037	1.469	2130.8	1396.6	2028.0	1934.6	5433.6	3818.2	1380.4	1409.8	3210.2	293.7	11,922,6
2038	1.513	2194.8	1438.5	2088.9	1992.6	5596.6	3932.7	1421.8	1452.1	3306.5	302.5	12,280,2
2039	1.558	2260.6	1481.6	2151.6	2052.4	5764.5	4050.7	1464.5	1495.6	3405.7	311.6	12,648,7
2040	1.605	2328.4	1526.1	2216.1	2114.0	5937.4	4172.2	1508.4	1540.5	3507.9	320.9	13,028,1
2041	1.653	2398.3	1571.9	2282.6	2177.4	6115.5	4297.4	1553.7	1586.7	3613.1	330.6	13,419,0
2042	1.702	2470.2	1619.0	2351.1	2242.7	6299.0	4426.3	1600.3	1634.3	3721.5	340.5	13,821,5
2043	1.754	2544.3	1667.6	2421.6	2310.0	6488.0	4559.1	1648.3	1683.4	3833.2	350.7	14,236,2
2044	1.806	2620.7	1717.6	2494.2	2379.3	6682.6	4695.9	1697.7	1733.9	3948.2	361.2	14,663,3
2045	1.860	2699.3	1769.1	2569.1	2450.7	6883.1	4836.8	1748.7	1785.9	4066.6	372.1	15,103,2
2046	1.916	2780.3	1822.2	2646.1	2524.2	7089.6	4981.9	1801.1	1839.5	4188.6	383.2	15,556,3
2047	1.974	2863.7	1876.9	2725.5	2599.9	7302.3	5131.3	1855.2	1894.6	4314.3	394.7	16,022,9
2048	2.033	2949.6	1933.2	2807.3	2677.9	7521.3	5285.3	1910.8	1951.5	4443.7	406.6	16,503,6

Table 13 Estimation of the total revenue of FCC refinery for 25 years

Product		LPG	L. naphtha	Kerosene	Gas oil	H_2	$C_1 + C_2$	C_3	C_4	Gasoline	Vac. residue	Coke	**To**
Quantity (Ton)		60,075	326,621	543,007	625,172	32,805	166,894	188,148	363,974	2,301,982	988,336	107,179	
Year	**Inflation factor**	**Price ($)**											
2024	1.000	1451.0	951.0	1381.0	1317.4	3700.0	2600.0	940.0	960.0	2186.0	330.0	200.0	8,1
2025	1.030	1494.5	979.5	1422.4	1356.9	3811.0	2678.0	968.2	988.8	2251.6	339.9	206.0	8,6
2026	1.061	1539.4	1008.9	1465.1	1397.6	3925.3	2758.3	997.2	1018.5	2319.1	350.1	212.2	8,9
2027	1.093	1585.5	1039.2	1509.1	1439.5	4043.1	2841.1	1027.2	1049.0	2388.7	360.6	218.5	9,2
2028	1.126	1633.1	1070.4	1554.3	1482.7	4164.4	2926.3	1058.0	1080.5	2460.4	371.4	225.1	9,4
2029	1.159	1682.1	1102.5	1601.0	1527.2	4289.3	3014.1	1089.7	1112.9	2534.2	382.6	231.9	9,7
2030	1.194	1732.6	1135.5	1649.0	1573.0	4418.0	3104.5	1122.4	1146.3	2610.2	394.0	238.8	10,0
2031	1.230	1784.5	1169.6	1698.5	1620.2	4550.5	3197.7	1156.1	1180.7	2688.5	405.9	246.0	10,3
2032	1.267	1838.1	1204.7	1749.4	1668.8	4687.0	3293.6	1190.8	1216.1	2769.2	418.0	253.4	10,6
2033	1.305	1893.2	1240.8	1801.9	1718.9	4827.7	3392.4	1226.5	1252.6	2852.2	430.6	261.0	11,0
2034	1.344	1950.0	1278.1	1855.9	1770.4	4972.5	3494.2	1263.3	1290.2	2937.8	443.5	268.8	11,3
2035	1.384	2008.5	1316.4	1911.6	1823.5	5121.7	3599.0	1301.2	1328.9	3025.9	456.8	276.8	11,6
2036	1.426	2068.8	1355.9	1969.0	1878.2	5275.3	3707.0	1340.2	1368.7	3116.7	470.5	285.2	12,0
2037	1.469	2130.8	1396.6	2028.0	1934.6	5433.6	3818.2	1380.4	1409.8	3210.2	484.6	293.7	12,3
2038	1.513	2194.8	1438.5	2088.9	1992.6	5596.6	3932.7	1421.8	1452.1	3306.5	499.2	302.5	12,7
2039	1.558	2260.6	1481.6	2151.6	2052.4	5764.5	4050.7	1464.5	1495.6	3405.7	514.1	311.6	13,1
2040	1.605	2328.4	1526.1	2216.1	2114.0	5937.4	4172.2	1508.4	1540.5	3507.9	529.6	320.9	13,5
2041	1.653	2398.3	1571.9	2282.6	2177.4	6115.5	4297.4	1553.7	1586.7	3613.1	545.4	330.6	13,9
2042	1.702	2470.2	1619.0	2351.1	2242.7	6299.0	4426.3	1600.3	1634.3	3721.5	561.8	340.5	14,3
2043	1.754	2544.3	1667.6	2421.6	2310.0	6488.0	4559.1	1648.3	1683.4	3833.2	578.7	350.7	14,7
2044	1.806	2620.7	1717.6	2494.2	2379.3	6682.6	4695.9	1697.7	1733.9	3948.2	596.0	361.2	15,2
2045	1.860	2699.3	1769.1	2569.1	2450.7	6883.1	4836.8	1748.7	1785.9	4066.6	613.9	372.1	15,6
2046	1.916	2780.3	1822.2	2646.1	2524.2	7089.6	4981.9	1801.1	1839.5	4188.6	632.3	383.2	16,1
2047	1.974	2863.7	1876.9	2725.5	2599.9	7302.3	5131.3	1855.2	1894.6	4314.3	651.3	394.7	16,6
2048	2.033	2949.6	1933.2	2807.3	2677.9	7521.3	5285.3	1910.8	1951.5	4443.7	670.8	406.6	17,1

3.3 Estimation of the Net Cash Flow (NCF)

In this section the net cash flow (NCF) of both refineries is estimated by calculating the difference between the total revenue of each year and the sum of Capital Expenditure (CAPEX) and Operating Costs (OPEX). The results are demonstrated in **Table 14**. However, the following assumptions were made to construct the net cash flow tables:

- The OPEX for both refineries is 2,000,000,000 \$/year.
- No tax is considered (100% owned to National Oil Corporation).
- The CAPEX for the Delayed Cocking refinery is 3,924,552,788 \$.
- The CAPEX for the FCC refinery is 3,491,661,619 \$.
- The production will start after the 3 years of building.

Finally, the payout time (POT) of both Delayed Coking and FCC refineries is found by drawing the relationship between the cumulative NCF versus time as shown in **Fig. 5 (a)**. Although the payout time for the two refineries is very close, there is a slight difference of about two months, in which 3.75 and 3.6 years payout times were exhibited by the Delayed Coking and FCC refineries, respectively.

3.4 Estimation of the Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) gives a good indication of whether the project is profitable or not and it is calculated by plotting a graph of cumulative net present values (NPV) versus different discount rates. As illustrated in **Table 15**, the present value is calculated by multiplying the NCF by the discount factor which is given by **Equation 18** [11]. The cumulative net present values are calculated at different discount rates of 0, 10, 15, 30, 60, 70, 90, 100, 120 and 140%.

$$\textit{Discount factor} = 1 / (1+ \text{D. Rate})^{n} \qquad \textbf{(18)}$$

Where n is the number of the year,

Fig. 5 (b) shows very high IRR values for both investigated refineries in this study, which are 100% for the Delayed Coking refinery and more than 110% for the FCC refinery, indicating the attractiveness of these projects.

Table 14 Estimation of the cumulative net cash flow (CUM. NCF) of Delayed Coking and FCC Refineries

Year	Delayed Coking refinery					FCC refinery				
	Total Revenue	CAPEX	OPEX	NCF	CUM. NCF	Total Revenue	CAPEX	OPEX	NCF	CU
1 (2024)		500,000,000		500,000,000-	500,000,000-		500,000,000		500,000,000-	50
2 (2025)		1,000,000,000		1,000,000,000-	1,500,000,000-		1,000,000,000		1,000,000,000-	1,5
3 (2026)		2,424,552,788		2,424,552,788-	3,924,552,788-		2,042,528,313		2,042,528,313-	3,5
4 (2027)	8,871,545,257		2,000,000,000	6,871,545,257	2,946,992,469	9,214,479,147		2,000,000,000	7,214,479,147	3,6
5 (2028)	9,137,691,615		2,060,000,000	7,077,691,615	10,024,684,084	9,490,913,521		2,060,000,000	]7,430,913,521	11,
6 (2029)	9,411,822,363		2,121,800,000	7,290,022,363	17,314,706,448	9,775,640,927		2,121,800,000	7,653,840,927	18,
7 (2030)	9,694,177,034		2,185,454,000	7,508,723,034	24,823,429,482	10,068,910,155		2,185,454,000	7,883,456,155	26,
8 (2031)	9,985,002,345		2,251,017,620	7,733,984,725	32,557,414,207	10,370,977,459		2,251,017,620	8,119,959,839	34,
9 (2032)	10,284,552,416		2,318,548,149	7,966,004,267	40,523,418,475	10,682,106,783		2,318,548,149	8,363,558,635	43,
10 (2033)	10,593,088,988		2,388,104,593	8,204,984,395	48,728,402,870	11,002,569,987		2,388,104,593	8,614,465,394	51,
11 (2034)	10,910,881,658		2,459,747,731	8,451,133,927	57,179,536,797	11,332,647,086		2,459,747,731	8,872,899,355	60,
12 (2035)	11,238,208,108		2,533,540,163	8,704,667,945	65,884,204,742	11,672,626,499		2,533,540,163	9,139,086,336	69,
13 (2036)	11,575,354,351		2,609,546,368	8,965,807,983	74,850,012,725	12,022,805,294		2,609,546,368	9,413,258,926	79,
14 (2037)	11,922,614,981		2,687,832,759	9,234,782,223	84,084,794,947	12,383,489,453		2,687,832,759	9,695,656,694	88,
15 (2038)	12,280,293,431		2,768,467,741	9,511,825,689	93,596,620,637	12,754,994,136		2,768,467,741	9,986,526,395	98,
16 (2039)	12,648,702,234		2,851,521,774	9,797,180,460	103,393,801,097	13,137,643,960		2,851,521,774	10,286,122,187	109
17 (2040)	13,028,163,301		2,937,067,427	10,091,095,874	113,484,896,971	13,531,773,279		2,937,067,427	10,594,705,852	119
18 (2041)	13,419,008,200		3,025,179,450	10,393,828,750	123,878,725,721	13,937,726,478		3,025,179,450	10,912,547,028	130
19 (2042)	13,821,578,446		3,115,934,833	10,705,643,613	134,584,369,333	14,355,858,272		3,115,934,833	11,239,923,439	141
20 (2043)	14,236,225,799		3,209,412,878	11,026,812,921	145,611,182,254	14,786,534,020		3,209,412,878	11,577,121,142	153
21 (2044)	14,663,312,573		3,305,695,265	11,357,617,309	156,968,799,563	15,230,130,041		3,305,695,265	11,924,434,776	165
22 (2045)	15,103,211,950		3,404,866,122	11,698,345,828	168,667,145,390	15,687,033,942		3,404,866,122	12,282,167,819	177
23 (2046)	15,556,308,309		3,507,012,106	12,049,296,203	180,716,441,593	16,157,644,960		3,507,012,106	12,650,632,854	190
24 (2047)	16,022,997,558		3,612,222,469	12,410,775,089	193,127,216,682	16,642,374,309		3,612,222,469	13,030,151,840	203
25 (2048)	16,503,687,485		3,720,589,143	12,783,098,341	205,910,315,023	17,141,645,538		3,720,589,143	13,421,056,395	216

Table 15 Estimation of the cumulative present values of Delayed Coking and FCC Refineries at different discount rates

Discount factor with 15% rate	Delayed Coking refinery			FCC refinery		
	NCF	Present Value	CUM. Present Value	NCF	Present Value	CUM. Present Valu
1.00000000	–500,000,000	–500,000,000	–500,000,000	–500,000,000	–500,000,000	–500,000,000
0.86956522	–1,000,000,000	–869,565,217	–1,369,565,217	–1,000,000,000	–869,565,217	–1,369,565,217
0.75614367	–2,424,552,788	–1,833,310,237	–3,202,875,454	–2,042,528,313	–1,544,444,849	–2,914,010,067
0.65751623	6,871,545,257	4,518,152,549	1,315,277,094	7,214,479,147	4,743,637,148	1,,627,081
0.57175325	7,077,691,615	4,046,693,152	5,361,970,247	7,430,913,521	4,248,648,924	6,078,276,005
0.49717674	7,290,022,363	3,624,429,519	8,986,399,766	7,653,840,927	3,805,311,645	9,883,587,649
0.43232760	7,508,723,034	3,246,228,178	12,232,627,943	7,883,456,155	3,408,235,647	13,291,823,296
0.37593704	7,733,984,725	2,907,491,324	15,140,119,268	8,119,959,839	3,052,593,666	16,344,416,962
0.32690177	7,966,004,267	2,604,100,925	17,744,220,193	8,363,558,635	2,734,062,153	19,078,479,116
0.28426241	8,204,984,395	2,332,368,655	20,076,588,848	8,614,465,394	2,448,768,711	21,527,247,827
0.24718471	8,451,133,927	2,088,991,056	22,165,579,904	8,872,899,355	2,193,245,020	23,720,492,847
0.21494322	8,704,667,945	1,871,009,381	24,036,589,285	9,139,086,336	1,964,384,670	25,684,877,516
0.18690715	8,965,807,983	1,675,773,619	25,712,362,904	9,413,258,926	1,759,405,400	27,444,282,916
0.16252796	9,234,782,223	1,500,910,285	27,213,273,189	9,695,656,694	1,575,815,271	29,020,098,187
0.14132866	9,511,825,689	1,344,293,560	28,557,566,749	9,986,526,395	1,411,382,373	30,431,480,561
0.12289449	9,797,180,460	1,204,019,449	29,761,586,198	10,286,122,187	1,264,107,691	31,695,588,252
0.10686477	10,091,095,874	1,078,382,637	30,839,968,835	10,594,705,852	1,132,200,801	32,827,789,053
0.09292589	10,393,828,750	965,855,753	31,805,824,588	10,912,547,028	1,014,058,109	33,841,847,162
0.08080512	10,705,643,613	865,070,805	32,670,895,393	11,239,923,439	908,243,350	34,750,090,512
0.07026532	11,026,812,921	774,802,547	33,445,697,940	11,577,121,142	813,470,131	35,563,560,643
0.06110028	11,357,617,309	693,953,586	34,139,651,526	11,924,434,776	728,586,291	36,292,146,934
0.05313068	11,698,345,828	621,541,038	34,761,192,564	12,282,167,819	652,559,895	36,944,706,829
0.04620059	12,049,296,203	556,684,581	35,317,877,145	12,650,632,854	584,466,689	37,529,173,518
0.04017443	12,410,775,089	498,595,756	35,816,472,901	13,030,151,840	523,478,861	38,052,652,379
0.03493428	12,783,098,341	446,568,372	**36,263,041,273**	13,421,056,395	468,854,979	**38,521,507,358**

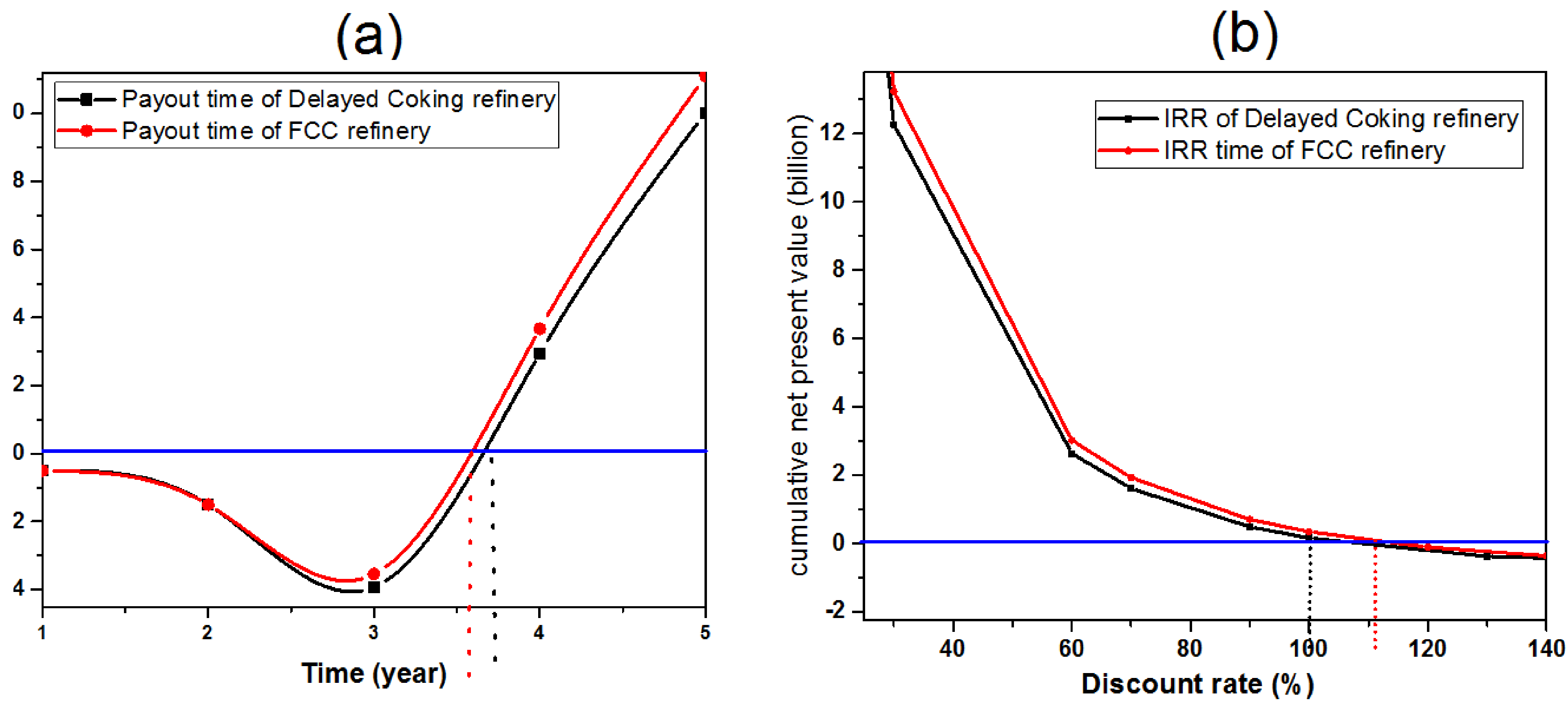

Fig. 5 **(a)** The payout time of delayed coking and FCC refinery. **(b)** The internal rate of return of delayed coking and FCC refinery.

4. Conclusions

Small undeveloped projects particularly refineries, exist in Libya and with a good economic evaluation these projects can be developed to be economically profitable. Sarir Oil Refinery is one of these economically attractive projects. Therefore, an economical evaluation was conducted over two upgraded refinery scenarios in this study and the following conclusions were made:

- Both proposed refinery scenarios are economically profitable. However, the observational results showed that the best refinery process scheme is the one that uses atmospheric distillation and FCC units since it is aimed for more maximizing of gasoline yield and reducing the capital cost.
- The payout time of the Delayed Coking refinery was calculated to be about 3.75 years while for the FCC refinery it was 3.6 years.
- The IRR results exhibited very high values for both refineries, which are 100% for the Delayed Coking refinery and more than 110% for the FCC refinery, indicating the attractiveness of this project. The high values of the IRR are due to the fact of that no tax was applied and deducted from the profits since the refinery belongs to the National Oil Corporation, making this project very profitable.
- The atmospheric residue in the old refinery which is about 52% is distilled to produce more valuable products like gasoline and gas oils by upgrading the refinery and adding a new vacuum distillation unit and a Delayed Coking unit or FCC unit.
- Compared to the Delayed Coking refinery, the FCC refinery produces more than 2 times gasoline and costs less as well. Moreover, only 18% of the crude feed is converted into gasoline in the Delayed Cocking refinery, where as for the FCC refinery it was more than 43%.
- The proposed project also gives a large variety of products like H_2, C_1, C_2, C_3 and C_4, which have high demand in the local and global markets.

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Graphical Abstract