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FULL LENGTH ARTICLE

Economic evaluation and sensitivity analysis of some fuel oil upgrading processes

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Abstract Seven upgrading schemes, identified as high distillate production schemes have been proposed for upgrading of 3.50×10^6 t/y atmospheric residues. The seven schemes were evaluated using the discounting cash flow method. Economic parameters such as internal rate of return, **IRR**, payback period, **PBP** and net present value, **NPV** have been calculated for each option.

All studied schemes proved profitable with **IRR** ranging between **25.2** and **33.7**% with option 7 having the highest NPV, IRR and payback period. Sensitivity analyses were performed on this option. The parameters investigated are: sales price (Revenue); production rate (feed weight); feed cost; utilities cost; direct and indirect costs; tax% and discount rate%. Their impact on NPV and %IRR has been evaluated. Tornado diagrams were constructed to illustrate the effect of variation of different cost parameters on NPV and IRR. The single most effective input variable is Revenue on both NPV and IRR. With two-factor sensitivity analysis, the two most important input variables for NPV and IRR are revenue and utilities.

Spider charts for option 7 have been created to show how the model's outputs depend on the percentage changes for each of the model's input variables.

1. Introduction

World interest in upgrading fuel oil has been revived [1] this is being stimulated by;

- The rate of decline in size of the fuel oil market. In Europe, environmental regulations are restricting fuel oil utilization, leaving only bunker markets.
- The growing demand for transportation fuels, especially middle distillates. In Europe, for example, the deficit for road diesel is forecast to be around 45 million Tons by 2020. Also the USA is becoming more diesel-orientated because of the higher miles per gallon obtained and resulting reduction in CO_2 emissions.
- Tightening fuel specifications and facility emission controls.
- Improving refining margins.
- Growing confidence in residue upgrading technologies, based on commercial performance, technology development and capital cost reduction.
- The opportunity to produce the required, high quality transportation fuels by residue upgrading rather than additional crude processing.

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Egypt has the largest refining sector on the African continent with nine refineries and a combined crude oil processing capacity of 975,000 bbl/d.

The country currently has a large surplus of heavy fuel oil and a deficit of lighter products. As a result, Egypt has an unfavorable import–export balance, with expensive, lighter products being imported and heavy fuel oil being exported and sold to marine bunkers. Existing plans foresee expanding of upgrading refining capacity to produce more light products and distillates and cut heavy fuel–oil surplus.

The international price differential between distillate products and high sulfur fuel oil, coupled with the subsidizing cost to maintain the local market prices at a reasonable level, offers a good driving force to think of bottom of the barrel processing [2].

Crude atmospheric distillation residue AR (Fuel oil BP 320 °C+) and vacuum distillation residue VR (BP 550 °C+) are what we mean by ‘‘bottom of the barrel’’ or simply residual fractions.

Residue is the highest molecular weight and the lowest hydrogen content fraction of the crude oil. It is generally requested to obtain lighter and environmentally acceptable high value products from heavier, low value feed. Achieving these process goals requires that the residue molecules undergo a number of thermal and some catalytic reactions. Therefore, the objective of upgrading processes can be defined as:

- Convert high molecular weight residual components to distillates. This conversion requires the breakage of C–C bond and C–S bonds in the residue fraction.
- Improve the H/C ratio, moving from 1.5 in the feed to 1.8 mol/mole as suitable for transportation fuels.
- Remove the heteroatom down to environmentally acceptable levels. The main heteroatoms of interest are sulfur and nitrogen.

The heading ‘‘upgrading of residual fuel oil’’ has been tackled in many text books examples are Gray [3] and Gary and Handwork [4] and in the literature e.g. [5]. Significant advances have been made in these technologies over the last three decades [1,2,6].

Residue upgrading processes may be generally grouped into two general categories [3]: carbon rejection and hydrogen addition depending on the technique used to increase the hydrogen to carbon ratio. Solvent deasphalting, visbreaking, thermal cracking, coking and catalytic cracking are carbon rejection processes, while catalytic hydro-demetallization, hydrodesulphurization and hydrocracking, are typical hydrogen addition processes.

There are two families of VGO conversion processes that vary according to the production goals; gasoline, or middle distillates. When gasoline production is the main driver, a combination of VGO hydrotreating and FCC produces high yields of low sulfur gasoline. If, however, middle distillates production is the target, VGO hydrocracking is the most attractive option where the products have excellent characteristics. It is worth mentioning that if petro- chemical feedstock is the target then the newly developed deep fluid catalytic cracking can be used at very attractive economic indicators [7].

Several VR conversion processes are available that cope with different feedstock characteristics and process objectives. Fixed bed residue hydrotreating is suitable for feeds having low to medium metal contents and when moderate conversion levels are required. The unconverted residue is used as low sulfur fuel oil or as a feed to RCC or DC units.

Delayed coking or Flexi coking can be applied to any type of VR feedstock to produce the full spectrum of distillates while eliminating completely fuel oil. The main concern would be marketing of the produced coke.

When very high conversion is the objective, new slurry-phase residue hydrocracking processes can be of interest e.g. Eni slurry technology; **EST** [8]. These processes still lack industrial application.

Depending on **AR** characteristics, mainly metal and sulfur content, residue catalytic cracking, **RCC**, can be applied directly or after hydrodemetallizaton/hydrodesulphurization of the residue feedstock. The product would be rich in gasoline.

When feeds have high metal content, the use of guard hydrodemetallization reactors of the type On-stream Catalyst Replacement, **OCR**, [9] or Permutable Reactor System, **PRS** [10]. provide effective solutions to free the residue feedstock from metals prior to further processing. Alternatively, solvent deasphalting of **VR** using light hydrocarbons separates asphaltenes carrying metals from deasphalted oil which can be further processed. If high conversion is requested residue hydrocracking using one- or two-stage ebullated bed reactors can be used, [1].

The present paper is an update to the work presented by the authors in 2008 [11]. The reference work studied in detail the available technology alternatives to upgrade locally produced fuel oil to more valuable and lighter distillates, so as to fill the existing gap in the middle distillates. The final choice of the best alternative(s) was governed by techno-economic profitability analysis. In this communication, economic analysis of the seven previously studied cases is repeated after updating equipment, utility and crude oil and products’ prices. More over sensitivity analysis was performed to study the most influential factors that affect the net present value and the internal rate of return.

2. Cases studied for upgrading of atmospheric residue produced in Egyptian refineries

Seven upgrading schemes (Fig. 1), identified as high diesel production schemes [12] have been evaluated for a proposed plant capacity of 3.5 million t/y of the atmospheric residue produced in the Egyptian refineries. The Schemes evaluated are:

1. Atmospheric Residue hydrodemetallization/hydrodesulphurization + Residue Fluid Catalytic Cracking + Naphtha Hydrotreating, **ARDM/ARDS** + **RFCC** + **HDT**.
2. Vacuum distillation + Delayed Coker + High Pressure Hydrocraker + Hydrotreatment of Naphtha and Gasoil, **VDU** + **DC** + **HP-HCK** + **HDT**.
3. Vacuum distillation + Residue Hydrocraker + Delayed Coker + High Pressure Hydrocraker + Hydrotreaters for Naphtha and Gasoil, **VDU** + **RHCK** + **DC** + **HP-HCK** + **HDT**.

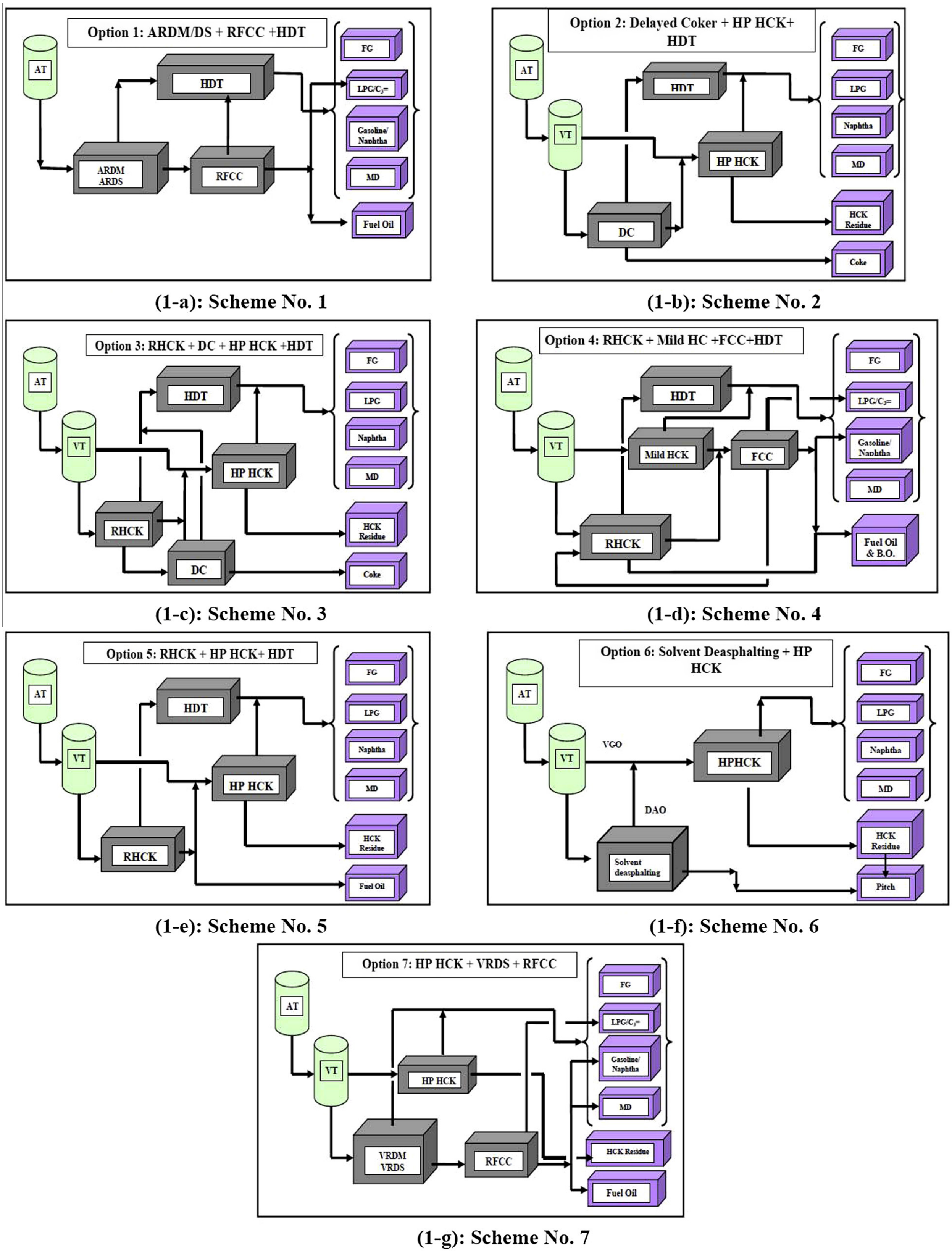

Figure 1 Block flow diagrams for scheme No. 1–No. 7.

4. Vacuum distillation + Residue Hydrocracker + Medium Pressure Hydrocracker + Fluid Catalytic Cracking + Hydrotreaters for Naphtha and Gasoil, **VDU** + **RHCK** + **MPHCK** + **FCC** + **HDT**.
5. Vacuum distillation + Residue Hydrocracker + High Pressure Hydrocracker + Hydrotreaters for Naphtha and Gasoil, **VDU** + **RHCK** + **HP-HCK** + **HDT**.
6. Vacuum distillation + solvent deasphalting + High Pressure Hydrocraker, **VDU** + **SDA** + **HP-HCK**.
7. Vacuum distillation + High Pressure Hydrocracker + Vacuum Residue Demetallization/Desulphurization + Residue Fluid Catalytic Cracking, **VDU** + **HP-HCK** + **VRDM/DS** + **RFCC**.

2.1. Economic evaluation for the proposed fuel oil upgrading schemes

The seven different processing schemes under consideration are evaluated using the discounting cash flow method. Economic parameters such as internal rate of return, **IRR**, payback period, **PBP**, and net present value, **NPV**, are calculated for each option.

The feed for all schemes is 3.5×10^6 t/y atmospheric residue which is considered as fuel oil (3% S). Material loss is taken as 6% of the feed. Product distributions in wt.% for all the investigated schemes are given in Table 1. Estimated capacities for upgrading units required by different options are given in Table 2. Upgrading equipment costs per bbl/d of feed to the unit as well as utility, hydrogen and catalyst consumptions are compiled and given in Table 3. The cost for shipping of equipment from Europe to the refinery location in Egypt is taken as 5% of installed equipment cost. Equipment cost was corrected to the year 2012 using the cost indexes found in Chemical Engineering Magazine. Sales prices of petroleum products for the year 2012 is given in Table 4.

The bases for economic evaluation are given in Table 5. Using these data Microsoft Excel was used to calculate the annual Net Cash flow, **NCF**, **NPV**, and **IRR**. The calculated economic parameters are presented in Table 6 for all the investigated schemes. **PBP** was found for each case by investigating the cumulative cash flow column. The payback period is the year at which the cumulative cash flow changes its sign from negative to positive.

2.2. Discussion

Table 6 summarizes the results obtained for the different cases studied. As regards diesel, options No. 3 and No. 6 produce nearly the same weight, this is roughly two millions t/y. Besides this high production rate of middle distillate, option No. 3 produces as well the highest weight of LPG among the seven investigated options in addition to 260,000 t/y of base oil stock. On the other hand option 6 is poor in other distillate products, and around 30% of the feed is separated as a low value product, namely pitch resulting from the deasphalting unit. Moreover, the economic indicators of option 6 rank it as the least profitable option. It has the lowest realized NPV over the project life time, the least IRR, only 25.2 and consequently the longest PBP, 7 years, among the investigated options.

The next highest production rates of middle distillates are those produced by option No. 5 and No. 2. Despite the difference in the processing schemes, options 2 and 5 have very close product distribution except that option 2 produces coke as a byproduct and option 5 produces nearly an equivalent weight of 1% S fuel oil. As regards the economic indicators, option No. 2 offers slightly better indicators than option No. 5.

Comparing option No. 2 and option No. 3, the insertion of a vacuum residue hydrocracking unit before the Delayed Coker in option No. 3 resulted in an increase in the total liquids + LPG production over option No. 2 where vacuum residue goes directly to the Delayed Coker. As a result the Delayed Coker in option 2 has a capacity double that of option 3 and so is the product coke.

If we consider the sum of middle distillates (diesel + base oil) + LPG as the criterion for the selection of the process scheme, then ranking of the three options left would be, option No. 4 > option No. 7 and finally comes option No. 1. Both of options 7 and 1 use RFCC. While in option No. 1 atmospheric residue is introduced directly after removing the contaminants to the RFCC unit, option 7 uses a vacuum distillation tower to separate heavy vacuum residue from the lighter VGO fraction. Vacuum residue is then subjected to an HDM/HDS treating step before being directed to RFCC unit. VGO is subjected to high pressure hydrocracking.

The effect of the separation and Hydrocracking steps in option No. 7 is reflected as an increase in the middle distillate product fraction as compared to option No. 1. Both options

Table 1 Product distribution for different options.

Product wt%	Option No.						
	1[a]	2[a]	3[a]	4[a]	5[a]	6	7[a]
LPG	1.69	4.8	5.31	3.57	4.3	2.43	3.13
Propylene	4.06	–	–	2.43	–	–	2.31
Naphtha	3.38	18.4	19.65	5.35	17.22	–	11.39
Gasoline	46.79			29.66		5.95	23.43
Middle distillates	32.26	52.0	61.03	38.57	53.75	60.80	46.04
Base oil	–	7.36	7.89		7.34	–	5.61
Fuel oil	11.82	–	–	20.42	17.38	–	8.09
Pitch	–			–		30.82	–
Coke	–	17.44	6.12	–	–		–
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00

[a] Estimated from data of Plain [12].

Table 2 Estimated capacities of upgrading units required for different options.

Unit, bpsd.	Opt.1	Opt.2	Opt.3	Opt.4	Opt.5	Opt.6	Opt.7
ARDS/DM	70,000	–					
VDU	–	70,000	70,000	70,000	70,000	70,000	70,000
RCC	70,000	–	–	–	–	–	30,000
MP BCK	–	–	–	40,000	–	–	–
HP HCK	–	60,000	65,000		60,000	66,000	40,000
RHCK	–	–	30,000	30,000	30,000	–	–
VRDM/DS	–	–	–	–	–	–	30,000
Deasphalting	–	–	–	–	–	30,000	–
FCC	–	–	–	40,000	–	–	–
DC	–	30,000	15,000	–	–	–	–
FRNS	–			30000			50,000
GHT	40,000	15,000	15,000	15,000	15,000		
MDHT	26,000	45,000	45,000	55,000	40,000		
Sulfur unit T/d	100	100	100	100	100	100	100

Table 3 Residue upgrading equipment costs and utilities, hydrogen and catalyst requirements.

Equipment name	Cost \$/bsd	Utilities/bsd feed to the unit					
		C Wm^3	Fuel kWh	Elec. kW	St kg	H_2 \$	Cat. \$
VDU	698	1	–	.005	1.362	–	–
ARDS/DM[a]	1800	120	18.078	5.1	–	4.0	1.6
VRDS[a]	3100	100	24.759	14	+31.78[c]	5.4	1.6
HPHC[a]	3500	100	45.195	23	+16.12[c]	9.8	1.8
MPHC[a]	2300	100	18.078	5.1	–	3.5	0.9
Ebullated bed[b]	2200–6500	100–240	22–45.195	8–23	+16.12–36.18[c]	8.0	4.0
Delayed Coker[b]	2500–4000	180–270	43.23–56.985	3–3.9	+6.81–18.16[c]	–	–
Fluid Coker[a]	3100	N.A.	N.A.	N.A.	N.A.	–	–
Fluid catalytic cracker, RFCC[b]	1950–2800	500	39.3	0.7–1.0	+18.16–90.8[c]	–	3.0
Slurry phase hydrocraker	4200	58	71.526	10–17	4.36–35.41	–	–
Naphtha splitter	650	–	–	–	–	–	–
Sulfur plant	500,000 \$/t	–	–	–	–	4.0	1.6

[a] Sapre et al. [13].
[b] Ref Hydrocarbon Processing's Refining Processes'98 [14].
[b] The plus(+) sign indicates the processes are producing steam.

Table 4 International prices of petroleum products for the year 2012.[a]

Product	Price, \$/tonne
LPG	848.1
C3	1200[b]
Naphtha	845.48
Gasoline (MOGAS 95)	886.78
Middle distillates (diesel euro 10 ppm)	866.49
Base oil	1097
Fuel oil 3% S	400[b]
Fuel oil 1% S	422.9
Pitch	150[b]
Coke high sulfur	100[b]
Coke low sulfur	250[b]

[a] EGPC (2012).
[b] International net prices.

are characterized by the presence of propylene in the gaseous product which has a high selling price that improves the process economics. In option No. 4 the presence of the hydro-cracking and the FCC steps and the recycle of heavy cycle oil eliminated completely the production of fuel oil. Despite the high capital and operating expenses required by this option, it has favorable economic indicators due to the high sales Revenue realized.

According to the economic indicators option No. 7 has the best indicators overall. It has the highest IRR% (33.7) and a NPV of **\$MM** 3089.248.

3. Sensitivity analysis

Because of the volatile oil prices and their consequent reflections on other costs such as utility, machinery, and interest rates, it is thought necessary to study the sensitivity of the economic parameters to the variation of the factors affecting the economic situation.

The actual cash flows achieved in any year will be affected by changes in raw material costs and other operating costs and will be very dependent on the sales volume and price. A sensitivity analysis is a way of examining the effects of uncertainties in the forecasts on the viability of a project.

Table 5 Economic Bases for Fuel Oil Upgrading Processes.

Parameter	Value
Upgrading plant capacity	3.5 MM tonne/y
Work days/year	350 days
Manufacturing plant life	25 years
Depreciation schedule	15 years (straight line)
Plant construction period	3 years
Spending profile	25%, 50%, 25%
Plant stream day production profile	50% first year, 100% years 2–25
Working capital model	15 days product sales
Buildings + off-sites	40% of total equipment cost
Maintenance	3% of total equipment cost/year
Indirect costs	10% of direct costs
Contingency	10% of (direct + indirect) costs
Taxes	34% of net profit
Year of starting taxation	Year 6 after starting production
Discount rate	10%
Material losses	6%
Price of utilities	
Fuel	2.0 $/MM Btu (393 kWh)
Electricity	0.08 $/kWh
High pressure steam	30 $/1000 lb (454 kg)
Cooling water	0.34 $/m^3

To carry out the analysis, the investment and cash flows are first calculated using what are considered the most probable values for various factors; this establishes the base case for analysis. Various parameters in the cost model are then adjusted, assuming a range of errors for each factor in turn. This will show how sensitive the cash flows and economic criteria are to errors in the forecast figures. A sensitivity analysis gives some idea of the degree of risk involved in making judgments on the forecast performance of the project. Sensitivity analysis involves recalculating the NPV or IRR for different values of major input variables, where they are varied one at a time. Combinations of changes in values can also be investigated. The results of a sensitivity analysis are usually presented as tables and plots of an economic criterion such as **NPV** or %**IRR** vs. the parameter(s) studied [15].

In this study various aspects of sensitivity analysis have been investigated for option 7 as it has the highest values of NPV and %IRR and at the same time produces more LPG and middle distillates as compared to option No. 1 which has the second highest NPV and %IRR.

The purpose of sensitivity analysis is to identify those parameters that have a significant impact on project viability over the expected range of variation of the parameter. Typical parameters investigated and the range of variation that is usually assumed [15], are given in Table 7.

Sensitivity analysis methods can be classified in a variety of ways as: (1) mathematical; (2) statistical; and (3) graphical [16]. In this work we concentrate on the graphical representation.

Graphical methods give representation of sensitivity in the form of graphs, charts, or surfaces. Generally, graphical methods are used to give visual indication of how an output is affected by variation in inputs. It can be used as a screening method before further analysis of a model or to represent complex dependencies between inputs and outputs.

3.1. Tornado diagram

Tornado diagram is a special type of Bar chart [15], where the data categories are listed vertically instead of the standard horizontal presentation, and the categories are ordered so that the largest bar appears at the top of the chart, the second largest appears second from the top, and so on. This diagram is named as tornado as the final chart appears to be one half of a tornado. Tornado diagrams are highly effective for sensitivity analysis and risk management analysis by comparing the relative importance of variables as it summarizes graphically one-parameter sensitivity analyses (NPV or IRR) on every model input or combinations of. This lets one evaluate the risk associated with the uncertainty in each of the variables or combinations of variables that affect the outcome. The sensitive variable is modeled as uncertain value while all other variables are held at baseline values. Then the values are plotted in a ***bar chart***. The uncertainty in the parameter associated with the largest bar, the one at the top of the chart, has the maximum impact on the result, with each successive lower bar having a lesser impact. Tornado diagrams are easy to construct and

Table 6 Products and economic parameters for different upgrading options.

Products 1000 t/y	Opt. 1	Opt. 2	Opt. 3	Opt. 4	Opt. 5	Opt. 6	Opt. 7
LPG	55.601	157.92	174.639	117.453	141.7	79.947	102.977
C3 =	133.574	0	0	79.947	0	0	75.999
Naphtha	111.202	605.36	646.485	176.015	566.538	0	374.731
MOGAS 95	1539.391	0	0	975.814	0	195.758	770.847
Diesel Euro 10 ppm	1061.351	1710.9	2007.887	1268.953	1768.375	2000.32	1514.716
Base oil	0	242.144	259.586	671.818	241.486	0	184.569
Fuel oil 1% S	388.878	0	0	0	571.802	0	266.161
Pitch	0	0	0	0	0	1013.975	0
Coke	0	573.77	201.348	0	0	0	0
Total	3290	3290	3290	3290	3290	3290	3290
Products Revenue $ MM/y	2,750.673	2,451.152	2,769.664	2,593.345	2,637.982	2,126.749	2806.451
Fixed capital investment $MM	1567.620	1314.519	1705.794	1544.099	1485.297	916.597	1479.373
Production costs $MM/y	1852.438	1744.975	1911.361	1782.414	1878.650	1720.594	1900.780
NPV $MM	2974.212	2255.727	2650.196	2565.592	2360.597	1131.436	3089.248
IRR%	32.0	30.2	28.7	29.7	29.0	25.2	33.7
PBP years	6	6	6	6	6	7	6

Table 7 Sensitivity analysis parameters [15].

Factor investigated	% of base value
Sales price	−20 to +20
Production rate	−20 to +20
Feed cost	−10 to +30
Utilities cost	−50 to +100
Direct and indirect costs	−20 to +50
Taxes%	−20 to +20
Discount rate%	−20 to +20

can include a large number of parameters without becoming crowded.

3.2. One-way sensitivity analysis

One-way sensitivity analysis allows a reviewer to assess the impact that changes in a certain parameter will have on the model's conclusions. This is performed by varying the value of the one concerned input variable in the model by a given amount, while keeping all the other variable parameters at their base values, and examine the impact that the change has on the model's results. This sensitivity analysis has been performed for the various specified ranges of the input variable parameters depicted in Table 7 and the results are recorded as shown in Table 8 indicating the low and high output values of NPV and %IRR with their swing values which is the difference between the high and low output values, together with the corresponding input variables. The output results, Fig. 2(a and b) are arranged downward from largest swing down to smallest swing, and presented as tornado charts for the NPV and %IRR single-factor sensitivity analysis for option 7. Fig. 3(a and b) shows the output results arranged by downside risk, while Fig. 4(a and b) depicts the results sorted by upside potential.

- From the one-factor analyses, we note that the input variables associated with maximum swing are total sale price, utilities, feed price for both NPV and IRR, followed by feed weight, discount rate, direct and indirect costs and taxes% in case of NPV while for %IRR direct and Indirect costs come before feed weight and taxes%. The single-factor downside-risk tornado chart shows the same order for both NPV and IRR.
- The single-factor upside potential tornado chart shows that the highest Present Worth is for the sale price and utilities followed by feed weight, discount rate, feed price, direct and indirect costs and taxes. While the highest %IRR it is for the sale price followed by direct and indirect costs, feed weight, feed price and taxes%.
- It could be concluded that the sale price and utilities are the most influential single input variables for both NPV and %IRR.

3.3. Two-way sensitivity analysis

This approach involves changing of two key input parameters simultaneously, showing the results for each potential combination of values within a given range. If N is the number of input variables, there are N * (N − 1)/2 pairs to evaluate. In this study combination of pairs of five input variables namely total sales price, utilities, feed price, feed weight and direct and

Table 8 Single-Factor Sensitivity Analysis for Option 7.

	Corresponding input value			NPV output value, $ million			IRR% output value		
	Low output	Base	High output	Low	Base	Swing	Low	High	Swing
Input variable parameters									
Total sale price, $million	312.5	5866.0	5553.5	13.11	48.44	35.3	2245.2	2806.5	3367.7
Utilities, $million	727.6	4270.1	3542.5	16.80	40.47	23.7	949.2	474.6	237.3
Feed price, $/ton	999.2	3785.9	2786.7	19.06	37.77	18.7	520.0	400.0	360.0
Feed weight, ton/year	2178.2	4000.3	1822.1	27.90	38.83	10.9	2.8E6	3.5E6	4.2E6
Direct and indirect costs, $million	2476.5	3334.3	857.8	24.15	39.82	15.7	2017.3	1344.9	1075.9
Taxes%	2870.1	3308.4	438.3	33.13	34.16	1.0	40.8	34.0	27.2
Discount rate%	2407.5	3985.6	1578.1	33.66	33.66	0.0	12.0	10.0	8.0

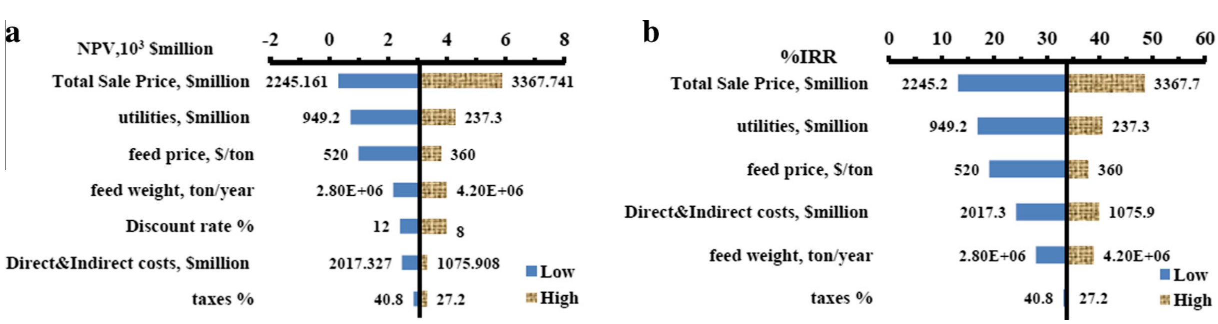

Figure 2 (a) NPV single-factor tornado chart sorted by swing for option 7. (b) %IRR single-factor tornado chart sorted by swing for option 7.

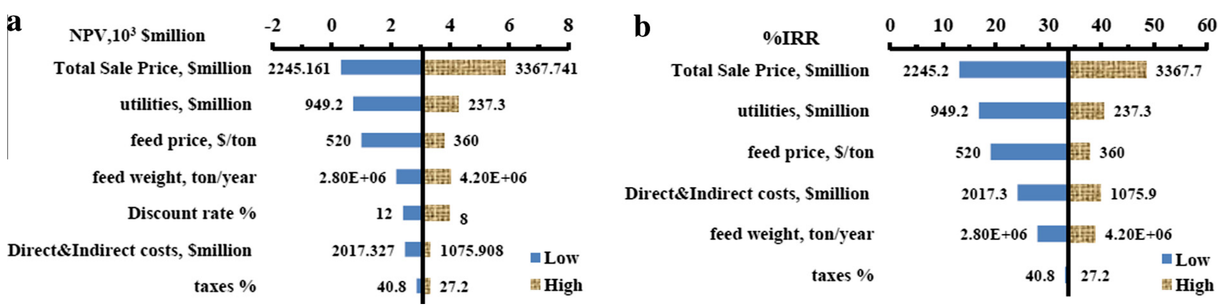

Figure 3 (a) %IRR downside single-factor tornado chart for option 7. (b) %IRR downside single-factor tornado chart sorted by swing for option 7.

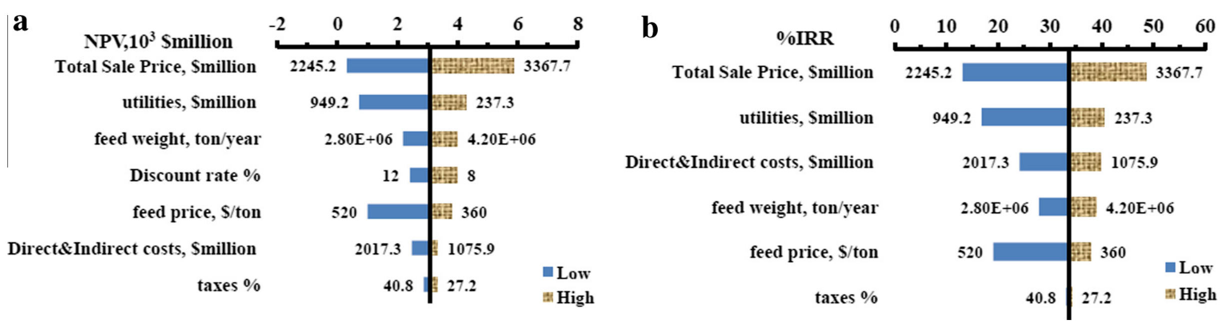

Figure 4 (a) NPV upside single-factor tornado chart for option 7. (b) %IRR upside single-factor tornado chart sorted by swing for option 7.

Table 9 Two-factor sensitivity analysis for option 7.

	Corresponding input value			NPV output value, $ million			IRR% output value		
Input variable parameters	Low output	Base	High output	Low	High	Swing	Low	High	Swing
Direct and indirect costs, $million and feed weight, ton/year	2017.3, 2.8E+06	1344.9, 3.5E+06	1075.9, 4.2E+06	1565.5	4245.4	2679.9	19.5	45.6	26.1
Direct and indirect cost and Sales price, $million	2017.3, 2245.2	1344.9, 2806.5	1075.9, 3367.7	−300.2	6111.1	6411.3	7.8	56.3	48.5
Direct and indirect costs, $million and feed price, $/ton	2017.3, 520	1344.9, 400	1075.9, 360	386.5	4031.0	3644.5	12.6	44.4	31.8
Direct and indirect costs and utilities, $million	2017.3, 949.2	1344.9, 474.6	1075.9, 237.3	114.9	4515.2	4400.3	10.8	47.4	36.6
Sales price and utilities, $million	2245.2, 949.2	2806.5, 474.6	3367.7, 237.3	−2049.2	7046.8	9096.0	0.0	53.9	53.9
Sales price, $million and feed price, $/ton	2245.2, 520	2806.5, 400	3367.7, 360	−1777.6	6562.7	8340.3	0.0	51.7	51.7
Sales Price, $million and feed weight, ton/year	1796.1, 2.8E+06	2806.5, 3.5E+06	4041.3, 4.2E+06	−43.2	7332.4	7375.6	9.5	54.9	45.4
Feed weight, ton/year and feed price, $/ton	2.8E+06, 520	3.5E+06, 400	4.2E+06, 360	506.2	4836.3	4330.1	14.9	43.3	28.4
Feed weight, ton/year and utilities, $million	2.8E+06, 759.3	3.5E+06, 474.6	4.2E+06, 284.7	288.9	5417.3	5128.4	12.9	46.3	33.4
Utilities, $million and feed price, $/ton	949.2, 520	474.6, 400	237.3, 360	−1362.5	4966.8	6329.3	0.0	44.1	44.1

indirect costs have been investigated so there are 10 pairs to evaluate. For each pair the NPV and %IRR has been calculated varying simultaneously the values of the pair variables at the low and high extreme ends as indicated in Table 9 while the other input variables are kept at their Base Case values. The results are recorded as shown in Table 9 indicating the low and high output values of NPV and IRR together with the swing values and the corresponding input variables.

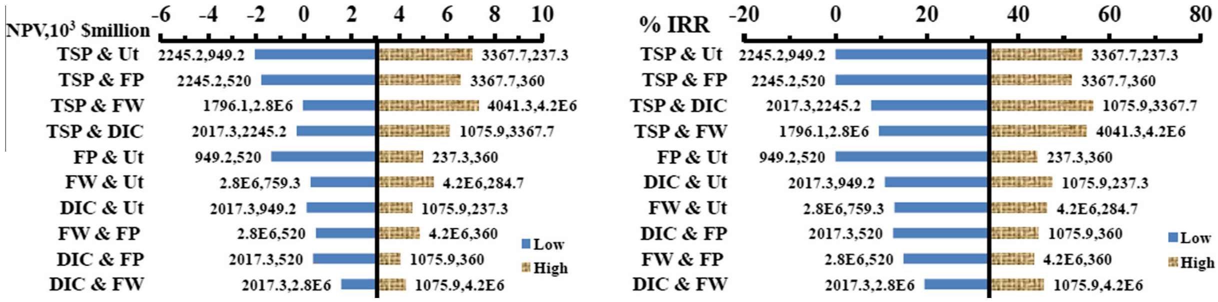

Figure 5 NPV two-factor tornado chart for option 7. %IRR two-factor tornado sorted downward by swing chart for option 7.

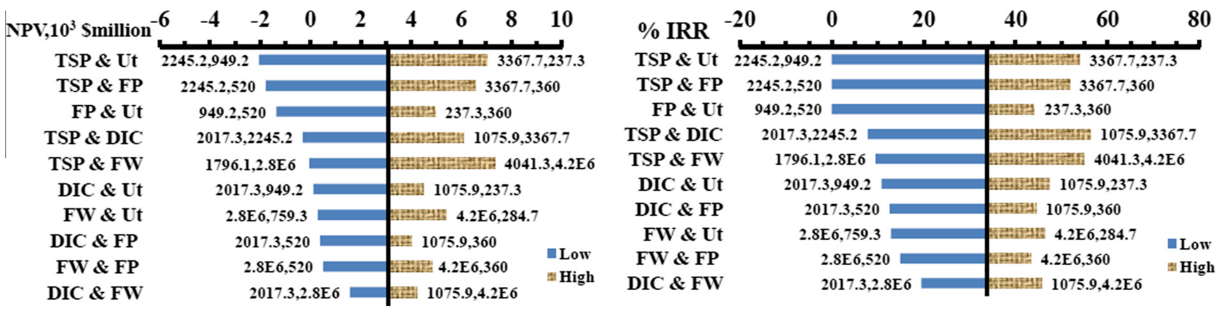

Figure 6 NPV two-factor downside risk tornado chart for option 7. %IRR two-factor downside risk tornado chart for option 7.

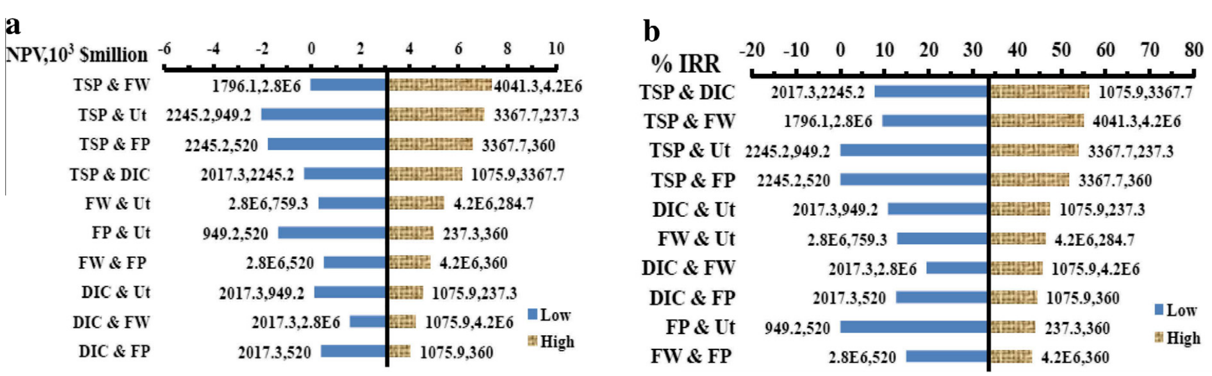

Figure 7 (a) NPV two-factor upside potential tornado for option 7. (b) %IRR two-factor upside potential tornado for option 7.

Fig. 5(a and b) show the two-factors sensitivity analysis tornado charts for the NPV and %IRR for option 7, arranged downward according to the swing values. Fig. 6(a and d) show the output results arranged by downside risk, while Figs 7(a and b) depict the results sorted by upside potential.

- The two-factor analysis shows that the following order of combinations: total sales price, TSP and utilities, Ut > total sales price and feed price, FP > total sales price and feed weight, FW > total sales price and direct and indirect costs, DIC have the maximum swing and downside risk for NPV. So it is particularly important to find a way to avoid the low Revenue and high utilities cost, feed price and direct and indirect costs combinations. As regards the %IRR we have the following order of combinations: total sales price and utilities > total sales price and feed price > total sales price and direct and indirect costs > total sales price and feed weight for the swing and downside risk.
- As for upside potential the two-factors analysis shows that the combinations of total sales price and feed weight > total sales price and utilities > total sales price and feed price > total sales price and direct and indirect costs in that order could produce the highest value for NPV. As for the %IRR a different order was found as the combinations of total sales price and direct and indirect costs > total sales price and feed weight > total sales price and utilities > total sales price and feed price have the maximum influence. So increasing total sales price and feed weight will have the most positive effect on NPV while increasing total sales price and decreasing direct and indirect costs will have the most positive effect on %IRR.

3.4. Multiway sensitivity analysis

This method is sometimes used to assess the confidence around all parameters. It is to undertake extreme sensitivity analysis,

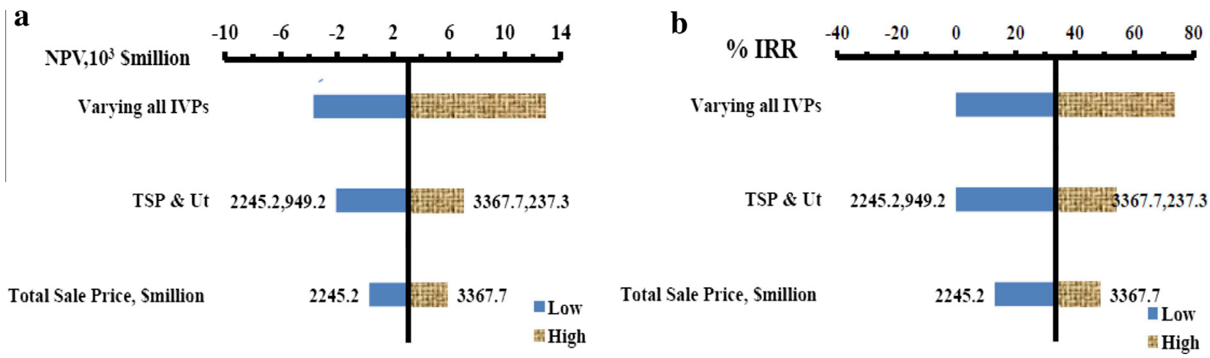

Figure 8 (a) Comparison of variation of NPV output values for option 7. (b) Comparison of variation of %IRR output values for option 7.

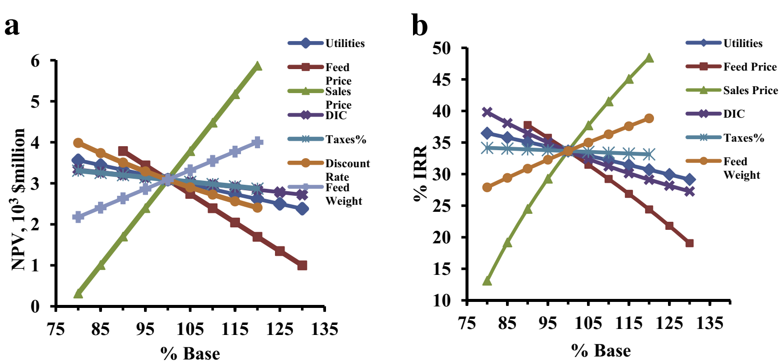

Figure 9 (a) NPV spider chart for option 7. (b) %IRR spider chart for option 7.

by varying all of the parameters in a model simultaneously to their 'best' and 'worst' case. Fig. 8(a and b) show the multiway sensitivity analysis tornado charts for the NPV and %IRR for option 7, arranged downward according to the swing values.

3.5. Many inputs, one output spider plots

Many inputs, one output option creates a consolidated chart called a spider plot to show how the model's output depends on the percentage changes for each of the model's input variables. It is a visual presentation showing the impact of uncertainty in each parameter on the variable in question, all on the same graph [17]. The center of the spider plot is the NPV or %IRR when all the variables are at their baseline values. The curves on the spider chart show how the NPV or %IRR changes as the values of each variable change, all others being held equal. The lengths of the spider lines vary because each variable has its own plausible range within which it can change. A spider plot shows the particular functional response of the output to each parameter on a common scale, so one needs a common metric to represent changes in all of the parameters. Here, we use percentage of the nominal or base values. Spider plots are a little harder to construct than tornado diagrams. However, they provide a more complete view of the relationships between each parameter and the performance measure. In particular, a spider plot reveals the non-linear relationships and the relative sensitivity of the performance measure to (percentage) changes in each variable.

In the present work the Spider values have been obtained using the same base case and extreme input values as the single-factor sensitivity analysis for the tornado chart, and specifying a Step Percent for evaluating the model at intermediate values. The results, Fig. 9(a and b) are shown with each input value expressed as a percentage of the base case input value for the horizontal axis and the vertical axis is the associated model output value.

Spider charts reveal a linear relationship for the NPV vs.% base of the various Input Variable Parameters except that with discount rate. However, for the %IRR the relationship is non linear with all variables except that with% taxes. These charts also reveal that increasing the sales price has a more pronounced positive effect than increasing the feed weight. The other Input Variable Parameters have a negative effect on both NPV and %IRR and increasing the feed price has the most negative effect.

4. Conclusions

In this study seven different schemes for the upgrading of atmospheric residue produced in the Egyptian refineries were studied. All the studied cases were identified as high diesel producing alternatives. The discounted cash flow method was used for the economic evaluation of the studied options.

The economic parameters; net present value, NPV, internal rate of return, IRR, and payback period were evaluated for each case. All the studied options are profitable. Similar results have been reported by Plain [12] and El-Temtamy and Gendy [11].

The option that has the most favorable economic indicators is option No. 7, followed by option No. 1. A common feature of these schemes is that they contain either FCC or RFCC units which produce propylene a high sales value component besides other distillate products which improves the economics.

Sensitivity analyses have been performed on the most profitable scheme, No. 7 to study the most influential factors that affect the project profitability manifested in %IRR and NPV. Graphical representations using single factor, two-factor and multiway Tornado diagrams were used to illustrate the effect of variation of individual factors, two combined factors and all the factors simultaneously on the model output respectively. Another way of graphical representation namely, the Spider chart was also used. All methods of analyses showed that the product sales price is the most influential factor for the project profitability.

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