

Techno-Economic Assessment of Petroleum Coke Production for Carbon and Graphite Electrodes Manufacturing

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ABSTRACT. The technical and economic aspects of the establishment of a delayed coking unit in the Arab world is investigated. Such a plant is to provide quality calcined coke for the production of carbon and graphite electrodes for the aluminum and steel Arab industries.

The Emirates and Libyan crudes, due to their low sulfur and metal contents (particularly vanadium and nickel), are deemed the best crudes for this purpose.

A single (on-its-own) delayed coker facility as well as a delayed coking complex are assessed. Both types of project implementation are considered profitable but the coker complex route is considered more realistic in view of the large investments and planning requirements needed to accommodate an independent coker inside an existing refinery.

A preliminary sensitivity analysis indicates that the coker project profitability is very sensitive to the hydrocarbon coproducts selling prices.

1. Introduction

Coking is a thermal cracking-type operation used to convert heavy petroleum residues (usually vacuum residuum) to lower boiling cracked products that can be processed catalytically (*e.g.*, in a FCC unit). The products thus obtained are gas, light and middle distillates and a coke residue known as "green coke". Figure 1 shows the role of coking in petroleum refining.

Two main types of petroleum coking processes are presently in commercial operation; delayed coking and fluid coking. Delayed coking (the oldest and most widely used process) is a cyclic batch operation, which uses multiple coking chambers to

allow semi-continuous feed processing. Unlike delayed coking, fluid coking is a continuous process similar in design to a fluid catalytic cracking unit.

2. Methods and Results

2.1 Calcination of Green Coke^[1]

Calcination (which can be done in electrical kilns, shaft kilns or horizontal rotating kilns) is reported to be necessary in electrode manufacture for the following reasons^[2] :

- 1) The green coke, when grounded cannot readily be found together into an electrode of a proper density.
- 2) Green coke is difficult to mold or extrude.
- 3) Green coke gives off its volatile matter during baking, thus yielding a very porous electrode.
- 4) Green coke is a poor conductor of electricity, therefore it has a much higher resistivity than the calcined material.
- 5) Calcination causes shrinkage of the carbonaceous substance, and thereby causes an increase in the specific gravity of the electrode.

Fluid coke is more difficult to calcine than delayed coke due to its structure of relatively imperious hard layers. For this reason fluid coke use is rather limited in the aluminum industry.

2.2 Calcined Coke Quality Specifications

The suitability of coke for use in aluminum smelters is largely determined by its metal (specifically vanadium and nickel) and sulfur contents. Table 1 shows the physical and chemical property requirements of calcined petroleum coke suitable for Arabian Gulf aluminum smelters. One approach to producing CPC (which meets such specifications) is to use vacuum residues, which are low in metals and sulfur content. It is worth noting that the alternative approach of hydrotreating the vacuum residue is economically justified when the primary purpose is the production of low sulfur fuel oil.

Arab crudes, in general, are of paraffinic or of mixed base with an appreciable amount of metals, sulfur and asphaltenes. These crudes, as such, are not suitable for the production of the required quality of calcined petroleum coke. However, Emirates, Libyan and Algerian crudes are paraffinic with a lower content of sulfur, asphaltenes and metals and are considered suitable for the production of regular as well as needle grade cokes.

2.3 Industrial Uses of Petroleum Coke

Calcined petroleum coke has two major uses; in the manufacture of carbon electrodes (also known as anodes) and graphite electrodes. These two types of electrodes are chemically similar, but differ in their physical properties of specific heat, electrical conductivity, thermal conductivity, strength and hardness. Table 2 summarises the industrial uses of CPC.

TABLE I. Calcined petroleum coke suitable to Arabian Gulf aluminum smelters^[3].

Testing Properties	Tyler Screen
+ 4	35% min.
4 - 14	30% min.
- 14	25% min.
Hardgrove grindability index	41 - 46%
Bulk density (gm/cm ³)	0.7% min.
Real density (gm/cm ³)	2.060% min.
Floating quantity on water	2.5% max.
Resistivity (ohm - cm ³)	6.78% max.
Chemical Analysis	
Dedusting oil	0.4% max.
Moisture	0.10% max.
Fe	0.030% max.
Si	0.0250% max.
S	3.0% max.
V	0.20% max.
Ti	0.0050% max.
Ni	0.020% max.
Mn	0.00150% max.
All other metals	0.020% max.
V CM	0.50% max.
Mixed carbon	99.00% min.
0 reactivity 450°C	3.0% max.
Ash	0.25% max.
Residual hydrogen	0.0% max.
Ca	0.40% max.

The biggest consumer of amorphous carbon electrodes is aluminum industries, which consume 400-500 kg of carbon per ton of aluminum metal.

By far the largest use of graphite electrodes is in the manufacturing of steel by the electric arc furnace route at a rate of 3.5 to 8 kg per ton of steel.

Needle grade calcined petroleum coke, with low contents of sulfur (0.6%), vanadium and nickel (below 60 ppm each) is required for the production of ultra high power (UPH) electrodes which are used in electric steel making. The regular grade CPC with a sulfur content up to 1% and vanadium and nickel contents up to 200 ppm each is required for the production of regular power (RP) electrodes, which are used in the electrochemical industries, in which chlorine or chlorates are produced at the anode.

2.4 Expected Demand for Calcined Petroleum Coke in the Arab World

In order to study the economic viability of establishing a calcined coke facility in

the Arab world, an estimate of the expected demand for this product must first be made. On the basis of CPC input requirements^[3,4], it is estimated that the expected Arab world demand for calcined petroleum coke for carbon and graphite electrodes manufacture by the year 1995 will be 873,000 tons/year (see Table 3).

2.5 Preliminary Economic Assessment of Petroleum Coke Manufacturing in the Arabian Gulf Region

A preliminary economic appraisal of the viability of a delayed coker plant is investigated.

In making this economic assessment it is relevant to point out that there are two alternative ways of implementing such a project :

TABLE 2. Industrial uses of carbon and graphite^[3].

Use	Category*	Application
Metallurgical		
Aluminum	C	Electrodes
Steel	C or G**	Electrodes
Iron, ferroalloys, phosphorus and calcium carbide	C	Furnace lining
Foundry applications	C or G	Casting processes, moldfacings, crucibles, aluminum extrusion, etc.
Thermal		
Electric arc welding and	C or G	Electrodes
High temperature resistance furnaces	G	Heating elements
Solid fuel rockets	G	Rockets nozzles
Chemical		
Manufacture of chlorine/caustic soda	G	Anodes
Corrosion resistance process equipment	G	Heat exchangers, pumps, etc.
Electrical		
Motors and generators	C or G	Brushes
Circuit breakers	C or G	Contactors
Others	C or G	Battery electrodes current collectors
Mechanical		
Compressors, pumps, etc.	C or G	Seals, bearings, etc.
Nuclear		
Reactors	G	Moderator
Textiles and Fibers		
Reinforced plastics and heating elements	C or G	Various

*C for carbon, G for graphite.

**Open arc furnaces use graphite electrodes only. Submerged arc furnace can use carbon electrodes.

TABLE 3. Arab world calcined petroleum coke requirements by 1995 (units tons/year).

Industry	Capacity	Calcined petroleum coke requirement
Aluminum	1,940,000	776,000
Iron and steel	6,328,000	94,000
Caustic soda/chlorine	496,000	3,000
Total		873,000

a) Construct a delayed coker unit within a refinery. The coker would be owned by the refinery or an outside investor (*e.g.*, an aluminum company in the region). Prices of inputs (coker naphtha, gas oil and gas) will be agreed upon between the refinery and coker owners.

b) Build a coker complex within a refinery. Such a complex would comprise a vacuum distillation unit, a delayed coker, a fluid catalytic cracker, a coke calciner and gas compression and concentration units. The coker complex owners would buy long residue (*i.e.*, bottoms residue) from the refinery and can sell its slate of hydrocarbon products of gasoline, LPG, gas and fuel oil to the refinery (for inclusion in the refinery product pool) or directly to the market. Such a coker complex can also be constructed inside an aluminum smelter plant.

2.6 Alternative One: A Single Delayed Coker Unit

In this scenario the delayed coker is envisaged as an addition to a refinery in the United Arab Emirates, where crudes (specially Zakum crude) are best suited for quality petroleum coke production^[5].

On the basis of the estimated Arab world demand of about 870,000 tons/year of calcined petroleum coke (equivalent to about 1058 tons/year of green coke*) by 1995, it is proposed that a 500,000 tons/year green coke plant will be justified.

2.7 Estimation of Capital Investment Requirements

A 500,000 tons/year green coke facility (requiring 47,000 barrels per operating day of vacuum residue as input) is estimated to require a total capital investment of \$75 million in the US Gulf Coast in 1982^[6]. Adjusting this figure for the Emirates location (assuming a differential location factor of 1.3 between the two locations) and a time basis of 1992 (using the relevant chemical engineering cost indices of 932.6 and 764.6), the fixed capital investment for the Emirates in 1992 is \$118.92 million (excluding steam plant).

Table 4 shows the basis on which the original estimates of the total capital investment were made^[6].

*The yield of calcined petroleum coke from green coke is 0.822^[5].

TABLE 4. Delayed coking units^[6].

<p>Costs Included</p> <ol style="list-style-type: none"> 1. Coker fractionator to produce naphtha, light gas oil and heavy gas oil. 2. Hydraulic decoking equipment. 3. Coke dewatering, crushing to - 2" and separation of - 1/4" from + 1/4" 4. Three days covered storage for coke. 5. Coke drums designed for 50 to 60 psig. 6. Blowdown condensation and purification of waste water. 7. Sufficient heat exchange to cool products to ambient temperatures. <p>Costs Not Included</p> <ol style="list-style-type: none"> 1. Light ends recovery facilities. 2. Light ends sulfur removal. 3. Product sweetening. 4. Cooling water, steam, and power supply. 5. Off gas compression.
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2.8 Estimation of Total Product Cost

The total product cost is the sum of manufacturing costs (also known as operating or production costs) and general expenses. Manufacturing costs are subdivided into :

- a) Direct production costs (such as raw materials, operating labor and supervision, utilities and maintenance).
- b) Fixed charges (such as depreciation and taxes).
- c) Plant overhead costs (such as medical, safety, packaging, ... etc.).

In order to estimate the manufacturing costs, the following estimates and assumptions are made :

The coker feed is vacuum residue. The Al-Ruwais refinery in Abu Dhabi has a vacuum distillation unit with a throughput of 1.7 million tons per year. The vacuum residue from this unit can be used as a feedstock to a coker/calcliner project.

The Zakum vacuum is reported to have the following product distribution^[3] :

Green coke	21.5 wt %
Gas oil/fuel oil	46.0 wt %
Gasoline/naphtha	24.0 wt %
Gas	8.5 wt %
	<hr/> 100 %

On the above basis and on the basis of coker products shown in Fig. 1, it is estimated that the feed requirements and yields from the proposed 500,000 tons/year delayed coker will be as follows :

Vacuum residue charge stock (on the basis of a coke yield of 21.48 wt% from fresh feed^[7]) = 2.327×10^6 tons/year.

Products :

Gas	197,690 tons/year
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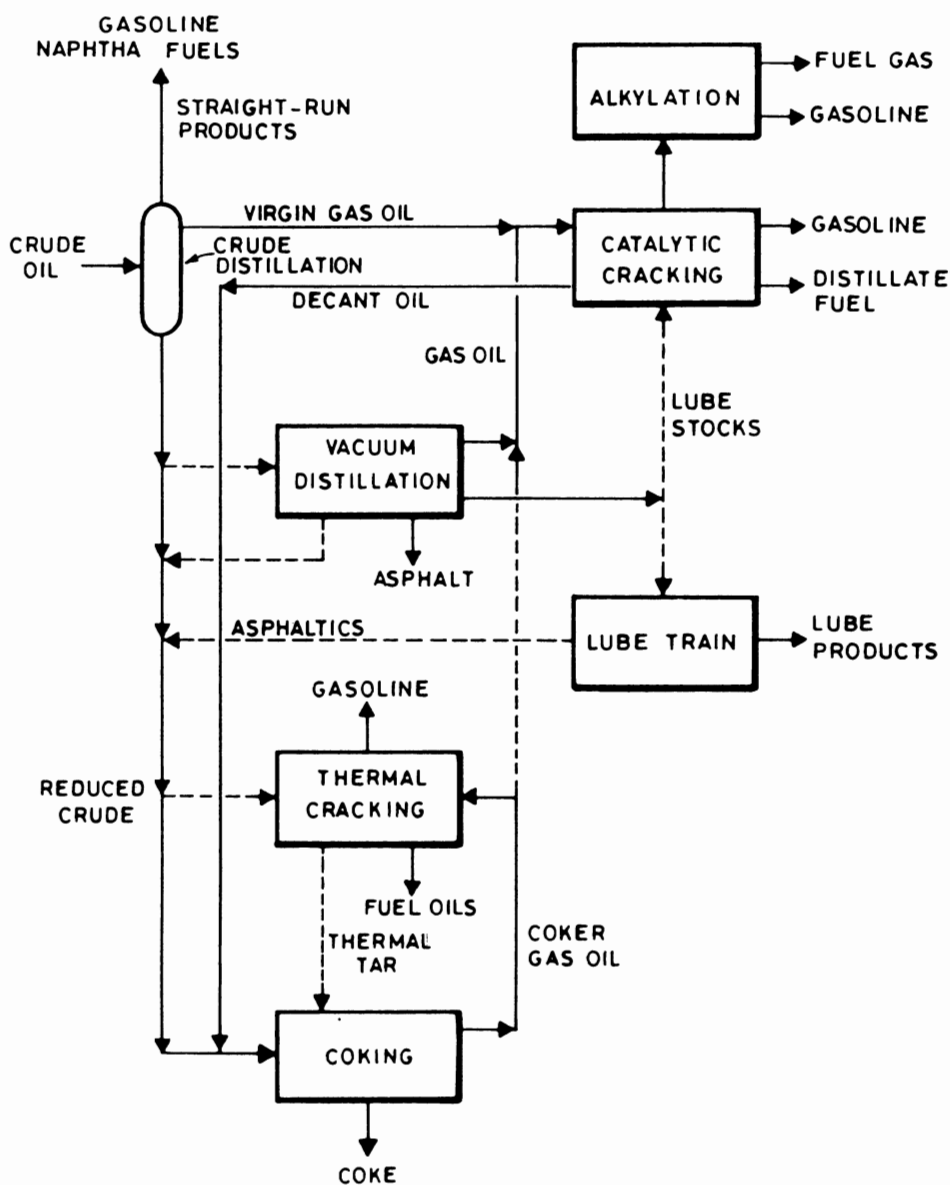


FIG. 1. Schematic diagram for the role of coking in petroleum refining.

Unstabilized naphtha	558,178	tons / year
Gas oil	718,325	tons / year
Fuel oil	351,521	tons / year

For the purposes of manufacturing cost estimation the assumed prices of the above feed and product items are as follows :

	Cost in \$/ton
Vacuum residue ⁽¹⁾	108
Gas (valued as fuel with a gross heating value of 52.7×10^6 Btu/ton)	26.35
Unstabilized naphtha ⁽²⁾	148.35
Gas oil ⁽³⁾	172.6
Fuel oil ⁽⁴⁾	106.1

⁽¹⁾Valued at 0.72 times crude price at refinery head of 150 \$/ton.

⁽²⁾The coker naphtha is valued as virgin naphtha designated for fuel use.

⁽³⁾Valued as high sulfur light gas oil designated for fuel use.

⁽⁴⁾Valued as 3% sulfur residual fuel oil designated for use as bunker fuel oil.

The coker utility requirements and their unit costs are shown in Table 5.

TABLE 5. The coker utility requirements and their unit costs^[5].

Utility	Consumption / ton of coke	Cost \$/unit
Steam*	0.227 tons	8.0
Power	40 kWh	0.0154
Cooling water (30°F)	13.66 m ³	0.04
Fuel	5 MMBtu	0.5

*Because of the high consumption rate it is recommended that a steam generation facility be established in the refinery area. An investment cost of \$100 per lb/hr of steam generation capacity is recommended^[5]. On this basis the capital investment of the steam plant would amount to 3.15 million dollars. The capital charges of steam production from this facility would be \$7.7 per ton of steam. Allowing for a water make up for the boilers of about 10% of the steam generated, the cost of steam is estimated at about \$8.0 per ton.

The bases for capital charges estimate is shown in Table 6. Table 7 gives the break down of manufacturing costs. The plant life time is 10 years.

Sales revenue from green coke and by-product credits (in 1000 \$/year)

Gas	15135
Unstabilized naphtha	83113
Gas oil	123983
Fuel oil	37296
Green coke (valued at 80 \$/ton)	40000
	<u>299527</u>

Net profits = \$91,180,000

Total capital investment* = \$143,612,000

∴ Simple rate of return on total capital investment = 63%

However this high ROI will have to be viewed in the light of the following observations :

*A working capital of 15% of total capital investment is assumed.

TABLE 6. Bases for capital charges estimate^[5].

	Percent of total facilities investment per year
Direct	
Process labor	2.0
Maintenance	2.0
Repair materials	1.6
Operating material (5% process labor)	0.1
Miscellaneous	0.5
Total direct	6.2
Indirect	
Supervision (25% process labor)	0.5
Plant overhead costs (40% process labor)	0.8
Insurance, taxes, interest on working capital	11.2
Depreciation	8.3
Miscellaneous	1.0
Total indirect	21.8
Total capital charges	28.0

TABLE 7. Total product cost estimate (in 1000 \$/year).

Direct Production Costs	
Raw materials (vacuum residue)	60,311
Process labor	2,378
Utilities	
Steam	905
Power	308
Cooling water	275
Fuel	1,250
Maintenance	2,378
Repair materials	1,903
Operating materials	119
Miscellaneous (Lab charges, patents and royalties, ... , etc.)	595
Fixed Charges	
Supervision	595
Plant overhead costs	951
Insurance, taxes, interest on working capital	13,319
Depreciation	9,871
Miscellaneous	1,189
Total	96,347

a) The coker capital investment does not include some important subsidiary units such as light ends recovery facilities and sulfur removal, product sweetening, cooling water and power supply, and off gas compression (see Table 4). It is assumed that the refinery will build such units or already has some excess capacity in the refinery of such facilities. The second alternative of building a coker complex solves this problem at an extra investment. However, an added value is realized from the improved product quality, which offsets the extra investment requirement.

b) The coker requires a feed of 558,439 tons per year of vacuum residue from the refinery. The question is, can the refinery supply this feedstock? Or should it build a vacuum distillation unit to convert bottoms residue into vacuum residue? Or should the coker investor be responsible for building a vacuum distillation unit within the refinery area. It is felt that such questions cannot be properly answered at this preliminary stage of project assessment and can be better handled at a subsequent stage of project development.

2.9 Sensitivity Analysis

The three major cost variables are: The cost of feedstock (*i.e.*, vacuum residue), the capital related cost items (*i.e.*, the capital charges (see Table 6)) and the sales revenue. A sensitivity analysis of the impact of adverse changes in the three cost items on ROI are given in Tables 8, 9, and 10.

TABLE 8. Sensitivity analysis of unfavourable changes in vacuum residue prices on ROI (alternative one).

Increase in vac. res. price		
ROI	+ 10 %	+ 20 %
	59 %	55 %

TABLE 9. Sensitivity analysis of increases in capital investment on ROI (alternative one).

Increase in capital investment		
ROI	+ 10 %	+ 20 %
	55.7 %	39 %

TABLE 10. Sensitivity analysis of decreases in total sales revenue from hydrocarbon products (gas, naphtha, gas oil and fuel oil) (alternative one).

Decrease in total hydrocarbon sales revenue		
ROI	- 10 %	- 20 %
	45.5 %	27.5 %

From the above sensitivity analysis it is evident that the project profitability is most sensitive to hydrocarbon products prices. A twenty percent decrease in these prices results in the decrease of ROI from 63% to 27.5%. In fact, by far the major contribution to revenues is from hydrocarbon sales rather than from green coke itself.

2.10 Alternative Two: A Complex Delayed Coker Plant

In this alternative the viability of a self-contained coker complex is investigated. Such a complex can be an addition to the refinery or as part of an aluminum smelter complex. In either case bottoms crude oil (*i.e.*, long residue) is bought from the refinery and the hydrocarbon product mix of gasoline, LPG and fuel gas can be sold directly to the market or sold to the refinery for subsequent sale and distribution through the refinery market outlets.

Figure 2 shows a schematic flow diagram of the envisaged coker complex plant.

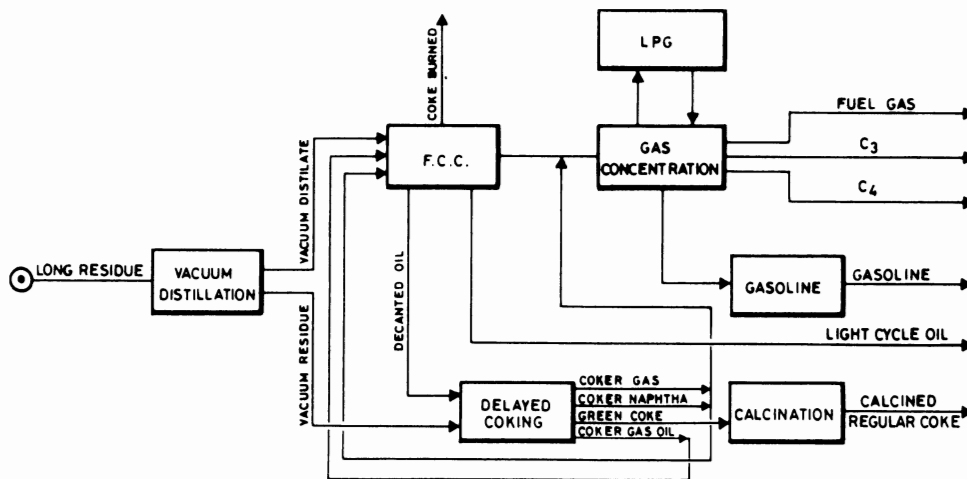


FIG. 2. Flow diagram of petroleum coker complex.

For comparison purposes the coker complex will also have a green coke production rate of 500,000 tons/year. Table 11 gives the material balance breakdown of such a complex^[5].

2.11 Capital Investment Requirements

The total capital investment of a coker complex of a production capacity of 170,000 tons per year of calcined coke (130,000 tons/year anode grade CPC and 40,000 tons/year regular graphite CPC) in 1982 in Libya was estimated at about \$308 million^[5]. The proposed complex in this study will, therefore have an estimated total capital investment of, $308 \times (932.6/764.6) (411/170)^{0.6} = \638.04 million.

2.12 Production Costs

The estimated production costs of the 170,000 tons/year complex in 1982 was about \$166 million. This sum comprised variable costs (*i.e.*, cost of feedstock,

TABLE 11. Coker complex material balances.

	In 1000 tons/year
Input	
Long residue (bottoms crude)	2,862
Output	
LPG	435
Gasoline	1,343
Gas oil	266
Fuel gases	155
Calcined Petroleum Coke	
Anode grade	314
Regular graphite grade	97

utilities, catalyst and chemicals), fixed costs (management and repair, labor, repair supplies), depreciation (at 6.67% on a straight line basis) as well as interest on investment and working capital^[5].

In order to estimate the production costs of the 411,000 tons/year complex in 1992, we make the following adjustments:

The capital related costs (see Table 6) are corrected from 28% of total capital investment to become 26.37% to allow for the allowance of 6.67% for depreciation instead of the 8.3% shown in Table 6.

On this basis the total capital related costs will amount to,

$$0.2637 \times 638.04 = \$168.25 \text{ million}$$

The variable costs in the 170,000 tons/year complex were therefore,

$$0.7363 \times 308 = \$22.678 \text{ million}$$

Assuming that the cost of the variable cost items in Libya in 1982 and the Emirates in 1992 are comparable, the variable production costs of the coker complex of 411,000 tons per capacity will be,

$$22,678 \times 411/170 = \$54.828 \text{ million}$$

Therefore, the total annual production costs of the 411,00 tons per year coker complex in the Emirates in 1992 are,

$$168.25 + 54.828 = \$223.078 \text{ million}$$

The total annual sales are 489.776 million dollars (see Table 12).

Therefore, the simple return on investment for the envisaged coker complex would be,

$$\text{Net profits/Total capital investment} = (266.698 \times 10^6 / 638.04 \times 106) \times 100 = 41.8\%$$

Tables 13 and 14 show a sensitivity analysis of the impact of unfavourable changes

in total capital investment and hydrocarbon sales revenue on the projects profitability.

TABLE 12. The sales from the product mix of the coker complex (in \$ million/year).

	Quantity ton/year	Unit price (\$)	Sales revenue
LPG	435	180	78.300
Gasoline	1343	185	248.455
Gas oil	266	172.6	45.912
Fuel gases	155	26.35	4.084
Anode CPC*	314	275	86.350
Regular graphite CPC	97	275	489.776
Total			489.776

*It is assumed that the calcined petroleum coke is of the regular type (price \$275/ton) and not needle grade (CPC price \$450/ton).

Tables 13 and 14 show a sensitivity analysis of the impact of unfavourable changes in total capital investment and hydrocarbon sales revenue on the projects profitability.

TABLE 13. Sensitivity analysis of unfavourable changes in the total capital investment on the project ROI (alternative two).

Increase in TCI		
ROI	+ 10 %	+ 20 %
	35.6 %	30.4 %

TABLE 14. Sensitivity analysis of decreases in hydrocarbon products prices on the project ROI (alternative two)

Decrease in hydrocarbon products prices		
ROI	- 10 %	- 20 %
	22.4 %	17 %

Again as in the single coker project, the project profitability is particularly sensitive to decreases in hydrocarbon products prices, which are in fact the major products and not by-products. Calcined coke is a by-product as far as sales revenues are concerned.

3. Conclusion

The combined Arab world aluminum and steel industries are now large enough to justify the establishment of upstream diversifications in the form of the construction of calcined petroleum coke, and carbon and graphite electrode industries. In this paper, the construction of a 500,000 tons per year green petroleum coke facility (which can produce about 411,000 tons per year calcined anode and graphite grade petroleum coke) was investigated on a preliminary basis. Crude qualities in terms of low sulfur, vanadium and nickel contents are necessary for such an industry. The United Arab Emirates and Libyan crudes are considered to be the most suitable crudes in this respect.

Two different scenarios were investigated: The first envisages the construction of a delayed coker without subsidiary supporting units inside a refinery. Such an arrangement is estimated to achieve a ROI of 63% on the basis of a 143 million dollar total capital investment. However, such an arrangement raises questions regarding the availability of the required subsidiary units (with enough excess capacity) in the refinery or the willingness of the refinery management to construct the required units if they do not exist.

The second scenario, which is considered more realistic, proposes the establishment of a self-sufficient coker complex as an addition to the refinery or as part of an aluminum smelter plant. The total capital investment for such a complex is about 638 million dollars and is expected to have a 41.8% return on the investment.

Both types of project are particularly sensitive to fluctuations in hydrocarbon products prices. In fact, these hydrocarbons are the major source of plant revenues and not the petroleum coke.

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دراسة تقنية اقتصادية لإنتاج الفحم البترولي لتصنيع أقطاب الكربون والجرافيت

أنيس حمزة فقيها ، وكامل محمد الحسن وقيع الله ، ومحمد عز الدهشان

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المستخلص . هذا البحث دراسة تقنية واقتصادية لإقامة وحدة تفحيم بطيء في العالم العربي . والهدف من إنشاء مثل هذه الوحدة هو توفير فحم محمص بنوعية ممتازة لإنتاج أقطاب الكربون والجرافيت المستخدمة في صناعة الألومنيوم والفولاذ العربية . يعتبر البترول الخام في كل من الإمارات العربية المتحدة وليبيا هما أفضل المواد الخام في هذا الصدد ، نظرًا لقلّة مكوناتها من الكبريت والفلزات (وبوجه خاص الفاناديوم والكبريت) . وقد شملت الدراسة بالتحليل إقامة وحدة تفحيم مستقلة بذاتها أو مجمع تفحيم . وأظهرت النتائج المبدئية ربحية كلا الوضعين ، إلا أن مشروع المجمع يعتبر أكثر واقعية ، نظرًا للمتطلبات الكثيرة المتعلقة بالاستثمار والتخطيط لإنشاء وحدة تفحيم داخل مصفاة نפט عاملة . وقد أظهرت دراسة الحساسية المبدئية أن ربحية المشروع تتأثر كثيرًا بأسعار بيع المنتجات الهيدروكربونية المصاحبة لإنتاج الفحم .