COMPARISON OF BY-PRODUCT AND HEAT-RECOVERY COKEMAKING TECHNOLOGIES[1]

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Abstract

As part of Pre-feasibility and Feasibility studies performed by Hatch in recent years, several coke plant trade-off studies were completed to help clients recognize which cokemaking technology, by-product or heat recovery would provide a competitive advantage. The work performed concluded that selection of the technology must be made on a case-by-case basis as many different factors can affect the decision. Two case studies show the distinct difference in the overall plant energy balance for each technology; the heat-recovery generating a large amount of electric power, and the by-product producing gas for use the steelmaking process. Case study 1 favoured the heat-recovery technology. Case study 2 found that by-product cokemaking resulted in a lower Capex and had no requirements for an alternative fuel source. This gave it an economic advantage over the heat-recovery coke plant, although sensitivity analyses showed that electricity and natural prices presented a significant financial risk. From an environmental standpoint, the two technologies were assessed using Hatch's 4QA sustainable development tool, showing the Heat-recovery as a cleaner technology

Key words: Heat-recovery; By-product; Cokemaking; Energy balance.

COMPARAÇÃO ENTRE AS TECNOLOGIAS DE PRODUÇÃO DE COQUE COM E SEM RECUPERAÇÃO DE SUB-PRODUTOS

Resumo

Como parte de estudos de pré viabilidade e viabilidade recentemente realizados pela Hatch, vários estudos comparativos de coqueria foram feitos para auxiliar clientes na avaliação de qual tecnologia, coqueria com recuperação de sub-produtos ou vertical (*By-products*) ou com recuperação de calor (*Heat-recovery*) fornece vantagem competitiva. Pelos trabalhos executados conclui-se que a seleção da tecnologia deve ser tratada caso a caso pois vários fatores podem afetar a decisão. Dois estudos de caso mostram diferença no balanço energético geral da usina para cada tecnologia: a coqueria *Heat-recovery* gera uma grande quantidade de energia elétrica e a coqueria vertical produz gás valioso para a usina. O estudo de caso 1 favoreceu a tecnologia *Heat-recovery*. No caso 2 foi verificado que a coqueria vertical resultou num custo menor de investimento sem demandar uma fonte de combustível alternativa. Isto proporcionou uma vantagem econômica sobre a tecnologia *Heat-recovery*, embora uma análise de sensibilidade mostrar que preços de eletricidade oriunda de gás natural apresenta um significativo risco financeiro. Do ponto de vista ambiental, as tecnologias foram avaliadas usando a ferramenta 4QA da Hatch mostrando que a tecnologia *Heat-recovery* é sempre mais limpa.

Palavras-chave: Coqueria com recuperação de calor; Coqueria com recuperação de sub-produtos; Balanço energético.

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1 INTRODUCTION

1.1 Background

The selection of the cokemaking technology is a key decision when designing a greenfield steelworks. By-product and heat-recovery cokemaking technologies each offer the steelmaker different opportunities to produce good quality coke and to develop the steelworks' energy balance with the aim of achieving the lowest possible operating cost.

As part of Pre-feasibility and Feasibility studies performed by Hatch in recent years, several coke plant trade-off studies were completed to help clients recognize which cokemaking technology will provide a competitive advantage considering the locally available energy sources and the steelworks configuration.

1.2 Objectives

The objective of each coke trade off study was as follows:

- Develop the overall plant energy balance for each option
- Determine the capital cost (Capex) for each option considered
- Develop the operating cost (Opex) for each option
- Determine by simple cash flow analysis, which option represents the greatest return on investment over the life of the project
- Calculate the expected environmental impact of each option considering energy intensity, SO_2 and other toxic emissions

The number of scenarios considered is project dependant but as a minimum each study considered a by-product coke oven battery and a heat recovery battery, sized to meet the requirement of the blast furnace. Other scenarios such as a coke plant located remote from the steel plant and a brown-field pad-up rebuild in place of a new battery have also been considered in the studies Hatch has performed.

2 COKEMAKING TECHNOLOGIES

There are three proven processes for the manufacture of metallurgical coke, the by-product process, the heat recovery process and the beehive process. The heat recovery process is a modification of the beehive process and as such, the beehive process has been largely phased out. This paper will focus on the by-product and heat recovery technologies.

Selected coals are screened, crushed to less than 3 mm and blended based on their petrography to produce a high quality coke whilst using the most cost effective input coals. The blend is charged into the coke oven and coke is formed by the destructive distillation of coal at temperatures of approximately 1100℃ and higher. At the end of the coking cycle, the hot coke is pushed from the oven into a quench car which transports it to the quench tower to cool and stabilize the coke. Quenching is performed with either water (wet quenching) or nitrogen (dry quenching), after which the product coke is transported to the blast furnace or stockpile. Figure 1 shows a simplified cokemaking flow sheet.

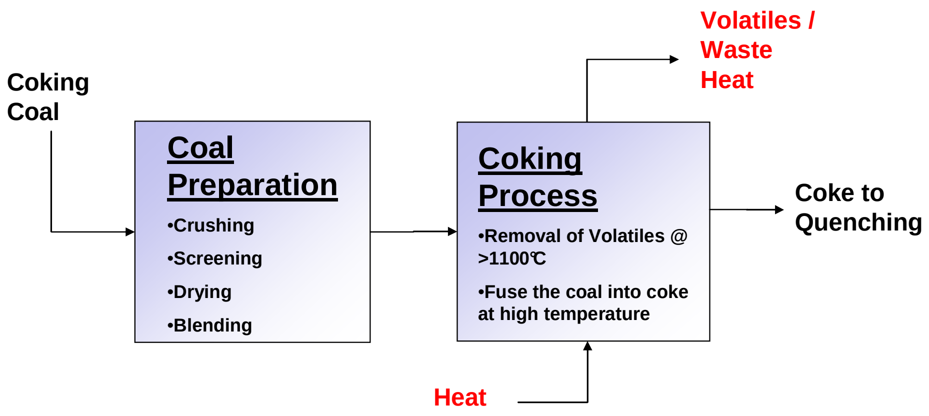


Figure 1: Cokemaking flowsheet

2.1 By-Product Cokemaking

By-product cokemaking is so called because the volatile matter evolved during the coking process is collected and refined into by-product chemicals. The coking process is performed in narrow, tall slot ovens which operate under a non-oxidizing atmosphere. A positive pressure within the oven cavity prevents air ingress and subsequent combustion of the volatile matter. Ovens typically range in height from 4 m up to 8 m in the latest plants. Figure 2 shows a cross section through a slot oven; in Figure 3 the complex twin flue by-product coke oven construction is illustrated that is essential to maintaining high and constant temperature profiles throughout the battery.

The main emission sources from the ovens occur during coke pushing, at which time the oven doors are opened and the coke is exposed to the atmosphere. Taller ovens allow greater amounts of coke to be produced per oven therefore minimizing the number of charges and pushes and related emissions to make the needed tonnage.

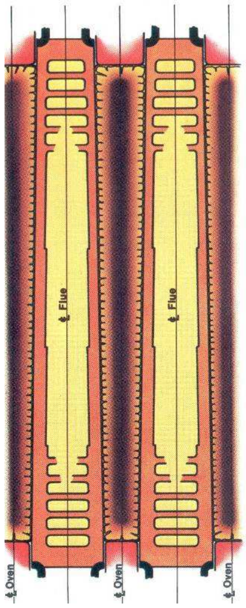


Figure 2: Cross section though a slot oven

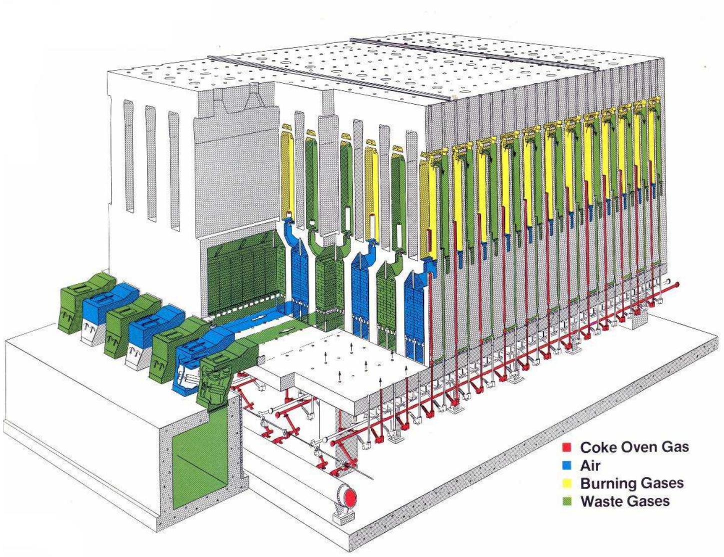


Figure 3: Cross section through by-product coke oven battery

Volatiles driven off during the coking process pass through a collector main to the by-product chemical plant. Tars are condensed by cooling the crude gas with flushing liquor and then in a primary cooler. An electrostatic precipitator removes the remaining tars. The gas is further treated, producing additional by-products including, light oil, naphthalene, ammonium sulphate and sulphur depending on market demand. The cleaned gas, known as coke oven gas (COG), is normally stored in a gas holder and boosted in pressure for use around the steelplant as a heating fuel or reducing gas.

2.2 Heat-Recovery Cokemaking

In heat-recovery cokemaking, all of the volatiles in the coal are burned within the oven to provide the heat required for the cokemaking process. The oven is a horizontal design and operates under negative pressure. Primary combustion air is introduced though ports in the oven doors which partially combusts the volatiles in the oven chamber. Secondary air is introduced into the sole flues which run in a serpentine fashion under the coal bed. The design of the flues and the control of the air flow allow the coking rate at the top and bottom of the coal bed to be equalized. Figure 4 shows a cross section through a heat-recovery oven. Due to the temperatures generated, all of the toxic hydrocarbons and by-products are incinerated within the oven. Hot gases pass in a waste gas tunnel to heat recovery steam generators (HRSGs) where high pressure steam is produced for either heating purposes or power generation. The cool waste gas is cleaned in a flue gas desulphurization plant prior to being discharged to atmosphere.

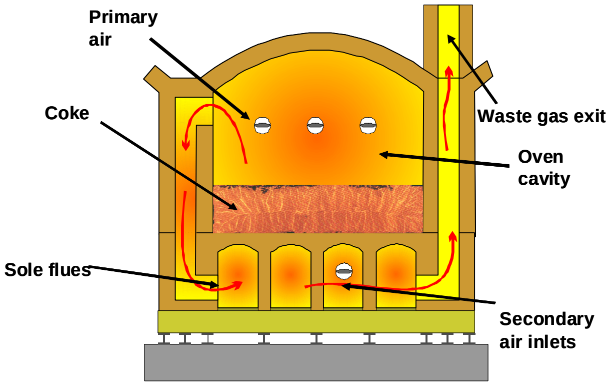


Figure 4: Cross section through a heat-recovery coke oven

3 CASE STUDY 1

3.1 Overview

Case 1 was a coke plant trade off study that Hatch performed for a greenfield pig iron plant planned for a remote site in South America. The facilities included a sinter plant, pellet plant, coke plant, blast furnace, and power plant. Figure 5 shows the overall material balance for the plant. The coke plant was required to produce 830,000 tpa of metallurgical coke (25-80mm) and nut coke (15-25mm) for the blast furnace. Coke Breeze (<15mm) was required as solid fuel in the sinter and pellet plants. Both pig iron and iron ore pellets were to be sold on the export markets with no further downstream processing.

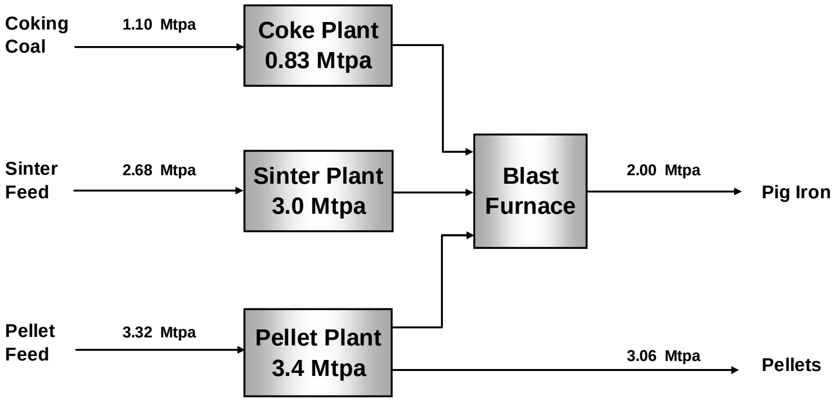


Figure 5: Case 1 flowsheet

3.2 Methodology

To perform the trade off study, the analysis focused on the development of a plant wide energy balance for each option, by-product or heat recovery coke plant. This allowed the energy requirements for each coke plant to be calculated and the interaction between other facilities to be assessed. To fully develop this, a number of assumptions were made as follows:

- The pig iron plant shall be capable of producing all the electrical power required as no import of power form the grid is allowed.
- All of the by-product gases produced by the blast furnace and by-product coke plant not used in the ironmaking process would be used to generate steam and power.

- Any excess power produced would be exported to the local power grid to provide extra revenue for the plant.
- Flaring of gases was assumed to be negligible and was not considered. Gas holders were included where needed to make this an acceptable assumption
- When a high heating value fuel was required to supplement blast furnace gas, heavy fuel oil would be used. Fuel oil would also be used to produce the balance of the electrical power requirement if not achievable with the by-product gases. Natural gas was not available at the plant site.

Three fuel sources were considered in the course of this study:

1) Blast Furnace Gas (BFG): From the blast furnace, this gas consists of approximately 20% CO, 20% CO_2, 5% H_2 and 55% N_2 and has a relatively low heating value of 3.5 MJ/Nm³ due to the high percentage of inerts. This gas is used at the blast furnace for hot stove heating with the balance exported to the other processes where possible. Due to its low heating value, BFG is not suitable for use at the sinter plant or pellet plant, and fuel oil must be used to supplement BFG at the power plant.
2) Coke Oven Gas (COG): is the primary by-product from the by-product cokemaking process. After cleaning, the main components include 50% H_2, 25% CO, 20% CH_4 and 5% CO_2. With a relatively high heating value of 18MJ/Nm³, COG can be used in all heating applications on a steel plant including heating of the coke oven battery itself.
3) Fuel Oil (FO) is the supplementary fuel used when other gases have been fully consumed or if a high heating value fuel is required and no COG is available such as in the heat recovery coke plant case. Fuel oil has a heating value of 40MJ/kg, and it has a relatively high sulphur content which produces SO_2 emissions when burned.

Operating costs (Opex) were derived from unit consumptions calculated from plant mass and energy balances and information supplied by Chinese equipment suppliers. Unit costs were supplied by the client or were derived from other projects in the same region. Capital costs (Capex) for by-product and heat-recovery plants were derived from Chinese equipment supplier quotations combined with construction costs and indirect costs calculated by Hatch.

A simple financial analysis was performed for each scenario with results expressed in terms of the Net Present Value (NPV) over a period of 20 years with a 10% discount factor. To calculate revenue, a pig iron selling price of 300 US$/t and an iron ore pellet price of 115 US$/t were used. The project duration was estimated to be 3 years.

Environmental impact was calculated using Hatch's Sustainable Development tool, 4QA, which allows different environmental factors to be weighted and assessed quantitatively and qualitatively; these included:

- Energy Intensity – A measure of the net energy usage.
- Sulphur Dioxide (SO_2) Emissions – Calculated relative to the volume of fuel oil burned. SO_2 from burning of COG and SO_2 in the exhaust of the heat recovery power plant is considered to be small due to the desulphurization technologies employed.
- Other Pollutants – Namely benzene and other aromatic hydrocarbons, expressed qualitatively.
- Electricity Exported – Electricity sold to the local grid.

3.3 Results

Figure 6 shows the output results from the plant wide energy balance calculations, expressed in a Sankey diagram format, for the plant with a by-product coke facility.

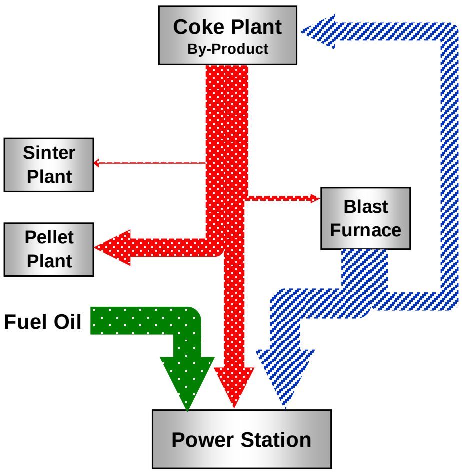


Figure 6: Sankey Diagram for the by-product coke oven plant configuration

Energy flows between the different processes are shown but for clarity, internal recycles, for example the use of BFG in the blast furnace stoves, have not been shown. Gas consumers included the sinter plant, pellet plant, coke plant and blast furnace. The power station was required to produce all of the electricity for the steel plant as well as steam required to drive the blast furnace air blowers. In this case there was no export of electricity to the grid.

Figure 7 shows the Sankey diagram for the plant configured with a heat-recovery coke plant. The major difference is that the COG has been replaced by a flow of waste heat from the heat recovery ovens that is ducted to heat recovery steam generators (HRSGs) for generating high pressure steam. Utilization of waste heat at the pellet plant is a possibility, but was not explored at the time. As heat-recovery coke ovens are self heating, all excess BFG was consumed at the power station. Interesting to note is that the total fuel oil consumption required in the sinter plant, pellet plant and power station was less than in the by-product case by approximately 400,000 GJ/y. The Sankey diagram illustrates that a significant amount of excess power will be exported to the local electricity grid.

The big differentiator between the two scenarios is the recovery of the sensible heat from the off-gases produced by the heat recovery ovens. This is not achieved in the by-product technology, which requires cooling of the gas in order to precipitate tars and light oils. The COG produced has a high heating value but is close to ambient temperature; present technologies do not consider the recovery of its sensible heat.

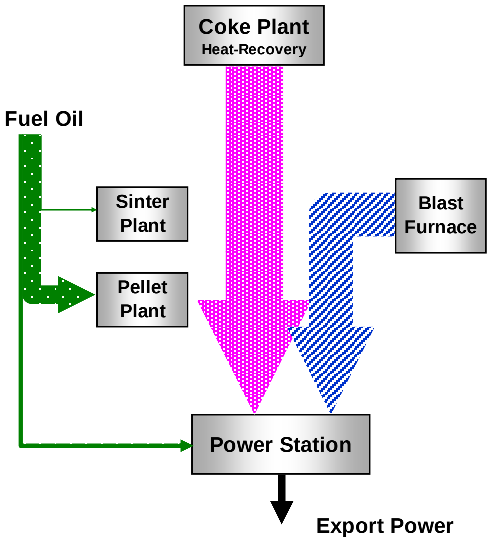


Figure 7: Sankey Diagram for the heat-recovery coke oven plant configuration.

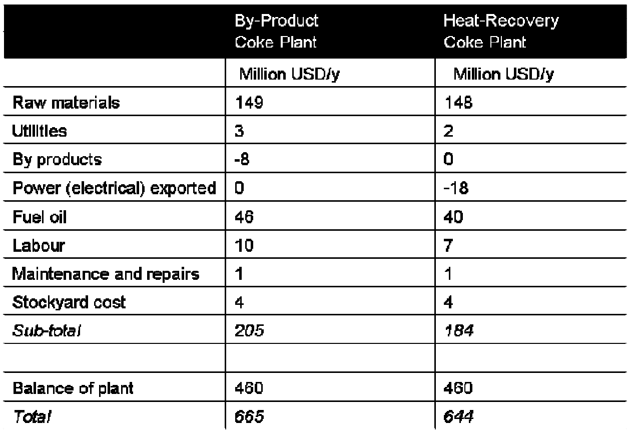
A comparison of the estimated capital costs for the whole pig iron facility is given in Table 1. The Capex for the coke plant has been broken down to show the differences between the two technologies. One of the reasons for the higher investment cost of the heat recovery coke plant was that the coke plant cost included the waste heat power plant and flue gas desulphurization equipment. The power plant line item included the by-product gas/fuel oil co-generation plant which provided steam to the blast furnace blowers as well as producing power. Integration of the two power plants could potentially reduce the heat-recovery coke plant Capex, but was not considered at that phase of the project.

Table 1: CAPEX breakdown for each scenario

	By-Product Coke Plant	Heat-Recovery Coke Plant
	Million USD	Million USD
Coke plant	125	212
Power plant (excl. HRCP PP)	59	31
Fuel oil storage and distribution	0.6	1.4
COG gas holder	5.5	0
Construction	72	77
Sub-total	*263*	*322*
Balance of plant	1,378	1,378
Total	*1,641*	*1,700*

A comparison of the operating costs is shown in Table 2. Key differences are the sale of by-products, the sale of electricity and the cost of fuel oil. Labour for operations and maintenance was less with the heat-recovery technology primarily because there was no chemical plant required to produce the by-products.

Table 2: OPEX breakdown for each scenario



	By-Product Coke Plant	Heat-Recovery Coke Plant
	Million USD/y	Million USD/y
Raw materials	149	148
Utilities	3	2
By products	-8	0
Power (electrical) exported	0	-18
Fuel oil	46	40
Labour	10	7
Maintenance and repairs	1	1
Stockyard cost	4	4
Sub-total	*205*	*184*
Balance of plant	460	460
Total	*665*	*644*

A financial analysis evaluating the 2 options on a cash flow basis over the project life was used to select the preferred technology. Table 3 shows that over a 20 year project life, including a 3 year construction and start-up period, the heat recovery coke plant option had a more favourable Net Present Value (NPV) and Internal Rate of Return (IRR). Even though the heat recovery plant had a higher Capex, it represented the best return on investment over a 20 year period due to a lower running cost.

Table 3: Financial Analysis Results

	Capex	Project Period	NPV (@10%)	IRR
	USD '000,000	months	USD '000,000	%
By-Product Coke Plant Option	1,641	36	370	13.6
Heat-Recovery Coke Plant Option	1,700	36	452	14.2

A sensitivity analysis was performed to determine which parameters significantly affected the project NPV. Figures 8 and 9 show the sensitivity to changes in the project Capex and the electricity selling price, and show that almost all of the time, the heat-recovery coke plant option had the greatest NPV.

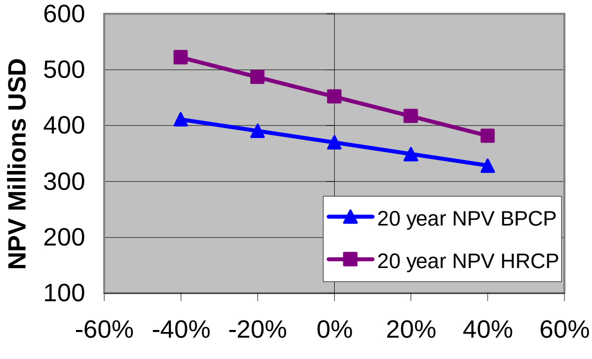


Figure 9: Capex Sensitivity

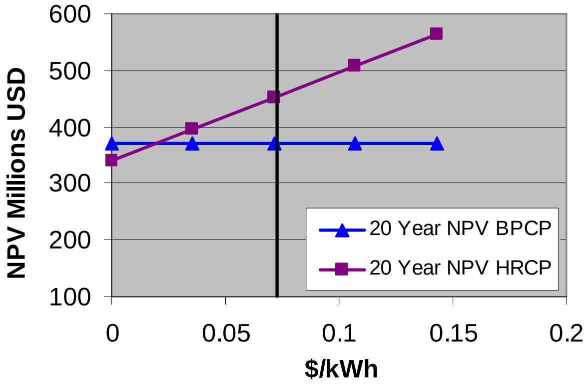


Figure 8: Electricity Price Sensitivity

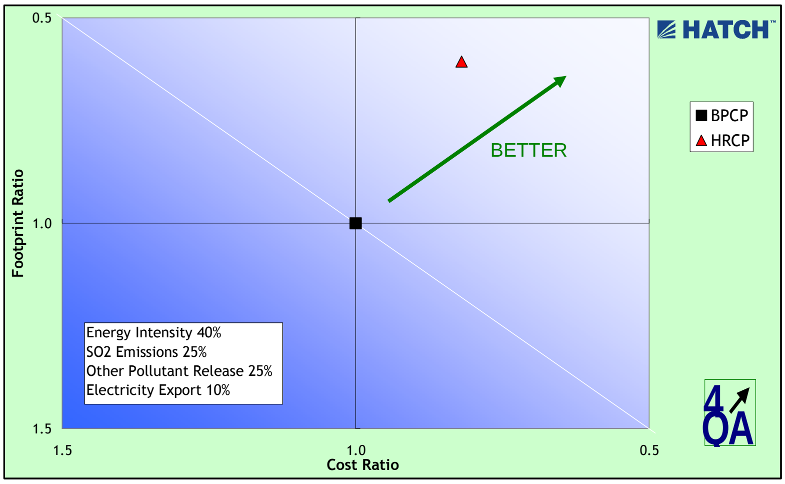


Figure 10: 4QA Environmental Comparison

An environmental comparison was performed utilizing Hatch's 4QA method, the results of which are shown in Figure 10. The graph shows environmental footprint and net present cost (NPC), as ratio of the base case, plotted on inverse scales. In both cases smaller is better therefore anything above the white line is better with the top right quadrant indicating the smallest environmental footprint and lowest cost scenario. For Case 1, the by-product coke plant was considered to be the base case and the heat-recovery coke plant was shown to have a smaller environmental footprint and lower cost.

4 CASE STUDY 2

4.1 Overview

This coke trade off study was performed for a greenfield steel plant also to be constructed in South America in a more developed area. The main facilities included a sinter plant, coke plant, blast furnace, BOF, thin slab caster, hot strip mill and power plant. In this case study, electricity was available from the local grid, and natural gas was available.

Figure 11 shows the overall material balance for the plant. A coke plant was required to produce 410,000 tpa coke for the blast furnace and coke breeze (<15mm) was used as solid fuel in the sinter plant. The plant was sized to produce 1.0 Mtpa Hot Rolled Coil (HRC).

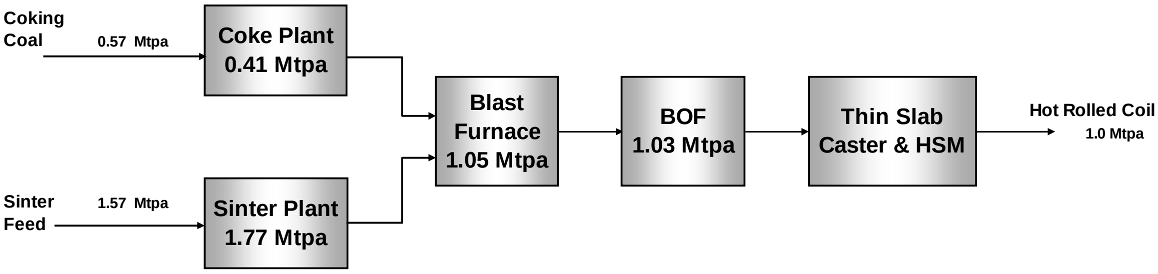


Figure 11: Case 2 Flowsheet

4.2 Methodology

A similar methodology to that described in section 0 was used to complete this case study. Assumptions made were as follows:

- All of the by-product gases produced by the blast furnace and by-product coke plant that were not used in the steelmaking process would be used to generate steam and power.
- Any excess power produced would be exported to the local power grid to provide extra revenue.
- Any electrical power requirement that was over and above that generated "on-site", would be imported from the local grid.
- Flaring of gases was assumed to be negligible and was not considered. Gas holders were included where needed to make this an acceptable assumption
- Where a high heating value fuel was required to supplement blast furnace gas, natural gas would be used.

As in case study 1, Opex and Capex figures were based on information provided by Chinese equipment suppliers for both the by-product and heat-recovery coke plants. Construction and indirect costs were calculated by Hatch.

4.3 Results

Figure 12 shows the plant wide energy balance for the by-product coke plant option. The power station used off-gases only but the steel plant needed a significant import of power from the local grid. No natural gas was required in this plant configuration.

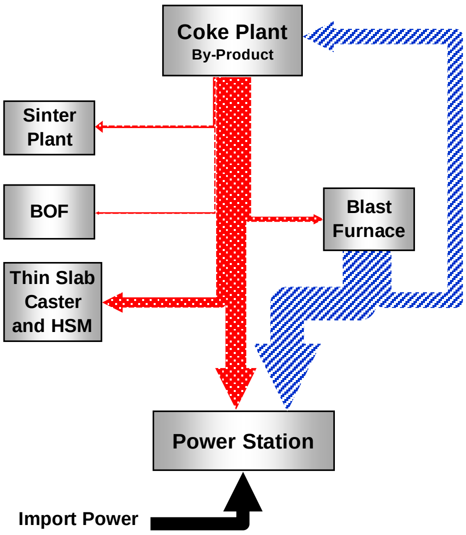


Figure 12: Sankey Diagram for the Case 2 by-product coke oven plant configuration

Figure 13 shows the equivalent energy balance for the heat-recovery coke plant option. With the heat recovery coke plant option, natural gas was used as the high calorific fuel in the sinter plant, BOF, blast furnace and equalizing furnace. The major difference between the 2 coke plant options was that the heat-recovery plant needed no power from the grid but did need significant quantities of natural gas, compared with no natural gas and an imported power requirement.

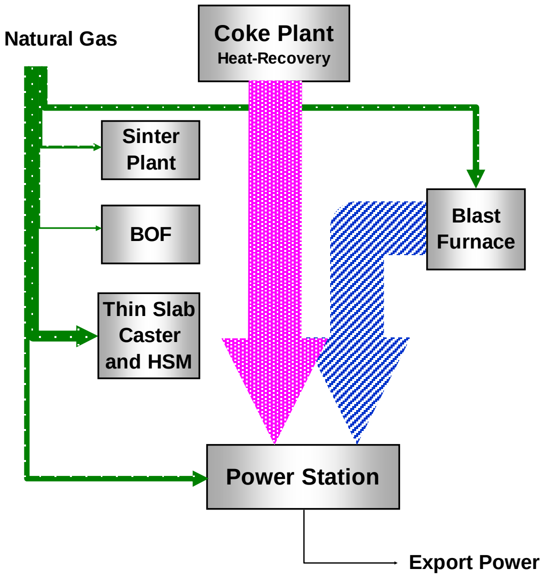


Figure 13: Sankey Diagram for the Case 2 heat-recovery coke oven plant configuration

The Capex breakdown for each scenario is shown in Table 4. Again the heat recovery plant featured a higher Capex mainly due to the scale of the power generation required with the heat-recovery coke plant technology.

Table 4: Capex breakdown for each scenario

	By-Product Coke Plant	**Heat-Recovery Coke Plant**
	Million USD	Million USD
Coke plant	83.1	141.3
Power plant	15.8	23.9
COG gas Holder	5.5	0.0
Construction	35.0	51.0
Subtotal	***139.4***	***216.2***
Balance of Plant	1,284.6	1,284.6
Total	***1,424.0***	***1,500.8***

As shown in Table 5 the main difference in operating costs were the requirements for imported electricity vs. imported natural gas. This led to a $7,000,000 per year advantage in favour of the of the heat-recovery option, however this was not significant enough to provide a greater return on investment over the life of the project as shown in Table 6**.** The results indicate that there was little to choose between the two options and as expected the sensitivity to electricity and natural gas prices play a big factor, as shown in Figure 14 and Figure 15.

Table 5: Opex breakdown for each scenario

	By-Product Coke Plant	**Heat-Recovery Coke Plant**
	Million USD/y	Million USD/y
Raw Materials	$74	$78
Utilities	$2	$1
By Products	-$4	$0
Power (electrical)	$21	-$2
Natural Gas	$0	$10
Labour	$5	$4
Maintenance and repairs	$0.4	$0.3
Stockyard cost	$2	$2
Subtotal	***$100***	***$93***
Balance of Plant	$213	$213
Total	***$313***	***$306***

Table 6: Case 2 financial analysis results

	Capex	**Project Period**	**NPV (@10%)**	**IRR**
	USD '000,000	months	USD '000,000	%
By-Product Coke Plant Option	1,424	36	250	12.8
Heat-Recovery Coke Plant Option	1,501	36	224	12.4

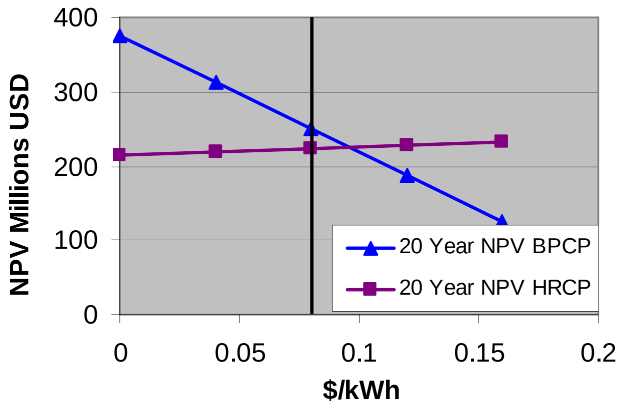


Figure 14: Electricity Price Sensitivity

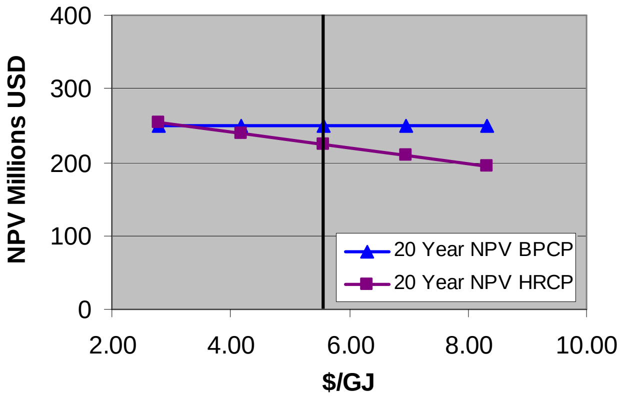


Figure 15: Natural Gas Price Sensitivity

The environmental comparison for Case 2 is shown in Figure 16. As before the heat recovery coke plant had a smaller environmental footprint and when compared together with the cost ratio, the heat recovery coke plant fell just above the white line indicating that the smaller return on investment represented a more sustainable plant.

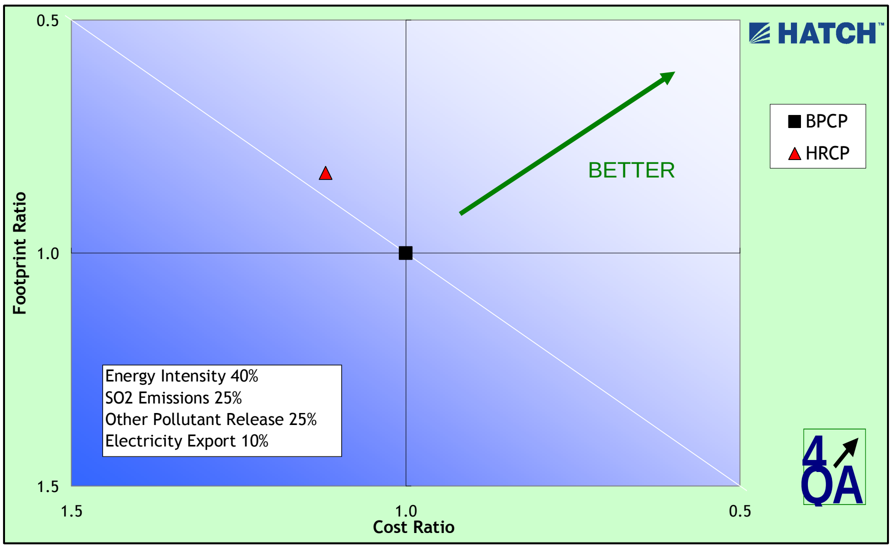


Figure 16: Environmental comparison.

5 CONCLUSIONS

Both by-product and heat-recovery coke plants technologies are capable to produce high quality coke suitable for high productivity blast furnaces. The decision as to which type of plant to build looked at from a return on investment viewpoint comes down to how the coke plant is integrated into the overall steel plant and what external energy sources are available to the plant.

In Case 1 due to the lack of available of electricity from the grid, and reliance on an expensive alternative fuel source, fuel oil required to generate the electricity, the heat-recovery coke plant was preferred. In Case 2, when both electricity and natural gas were available at a low cost, the by-product plant was shown to be the preferred option, although the sensitivity analysis showed that increases in electricity and gas prices could change this outcome.

From an environmental viewpoint the heat-recovery technology had a smaller footprint than the by-product technology. Due its negative pressure operation and incineration of all the volatile matter in the coal, the heat recovery process is less susceptible to toxic gas releases. The coal bed configuration also means particulate emissions are reduced. The US Environmental Protection Agency (EPA) recognizes the heat recovery process as meeting the Maximum Achievable Control technology (MACT). The by-product process has some technologies that can improve upon the standard design such as individual oven pressure control and Coke Stabilisation Quenching (CSQ), which can minimize particulate and toxic emissions.

The selection of the coke making technology must be made on a case-by-case basis. Many different factors can affect the decision including for example, available land and energy sources, steel plant configuration and energy consumers, environmental issues and the capital cost of equipment.