Comparison of Byproduct and Heat-Recovery Cokemaking Technologies

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This paper reviews the byproduct and heat-recovery cokemaking technologies, each of which offers opportunities to produce high-quality coke and to develop the energy balance while achieving the lowest possible operating cost.

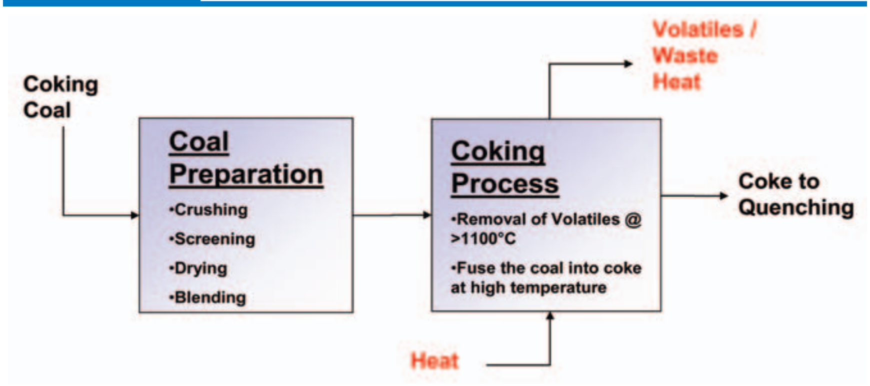
As part of pre-feasibility and feasibility studies performed by Hatch in recent years, several coke plant trade-off studies were completed to help clients recognize which cokemaking technology, byproduct or heat-recovery, would provide a competitive advantage. The work concluded that selection of the technology must be made on a case-by-case basis, as 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. 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 byproduct producing gas for use in the steelmaking process. Case study 1 favored the heat-recovery technology; the absence of natural gas and power from the grid favored its electrical power production and associated lower fuel oil consumption, resulting in a lower OPEX and better return on investment (ROI) over the project life. Case study 2 found that byproduct 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 gas prices presented a significant project risk. From an environmental standpoint, the two technologies were assessed using Hatch's 4QA sustainable development tool, considering the coke plant in an entire steel plant arrangement. This found in both cases that the heat-recovery option had a smaller environmental footprint.

Overview of Cokemaking Technologies

There are three proven processes for the manufacture of metallurgical coke: the byproduct 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 byproduct 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 while using the most cost-effective input coals. The blend is charged into the coke

Figure 1



Cokemaking flowsheet.



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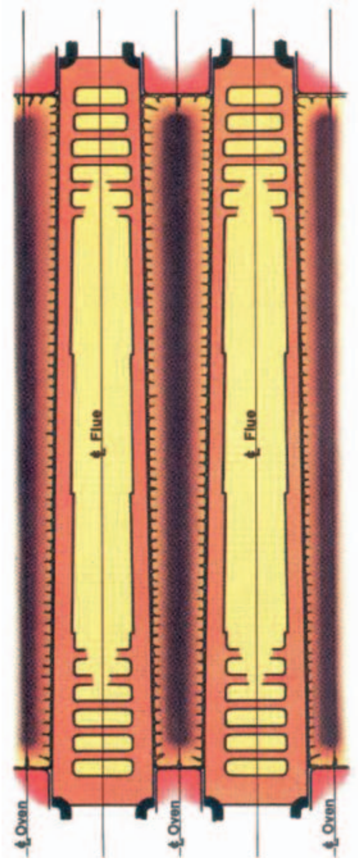
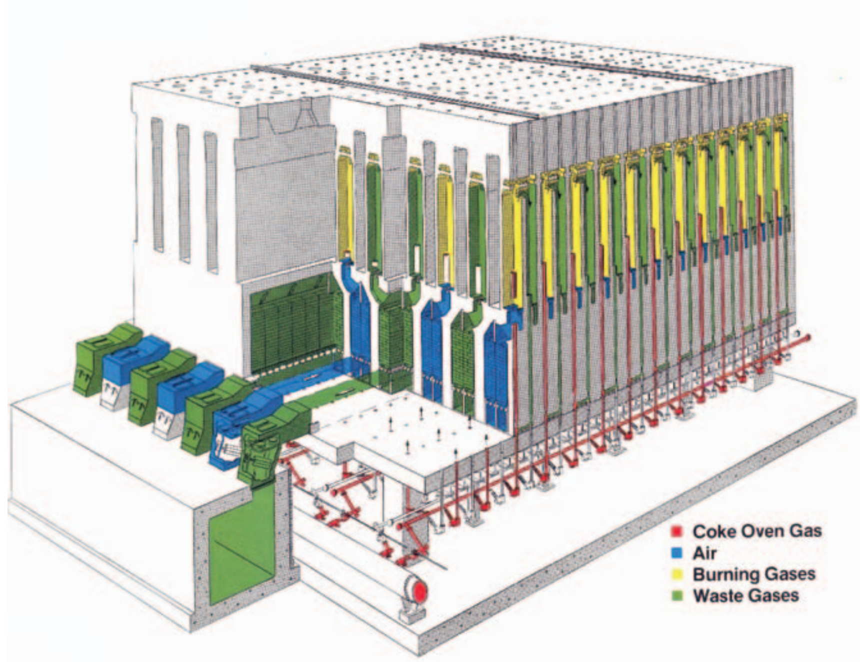
Figure 2



Cross-section through a slot oven.

Figure 3



Cross-section through byproduct coke oven battery.

oven, and coke is formed by the destructive distillation of coal at temperatures of approximately 1,100°C 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.

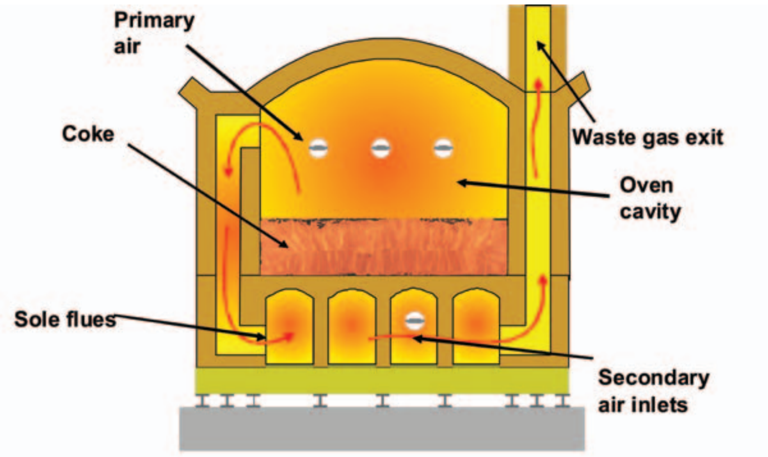
Byproduct Cokemaking — Byproduct cokemaking is so called because the volatile matter evolved during the coking process is collected and refined into byproduct chemicals. The coking process is performed in narrow, tall slot ovens which operate under a non-oxidizing atmosphere. A positive pressure within 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 byproduct 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.

Volatiles driven off during the coking process pass through a collector main to the byproduct 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 byproducts, including light oil, naphthalene, ammonium sulfate and sulfur, 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 steel plant as a heating fuel or reducing gas.

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, introduced though ports in the oven doors, 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 byproducts are incinerated within the oven. Hot gases pass in a waste gas tunnel to

Figure 4



Cross-section through a heat-recovery coke oven.

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 desulfurization plant prior to being discharged to the atmosphere.

Case Studies

Two different case studies are discussed in this paper. The case studies were selected to provide two different examples of trade-off studies performed with different steel plant configurations and raw material/fuel availability.

The objectives of each coke trade-off study were 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.

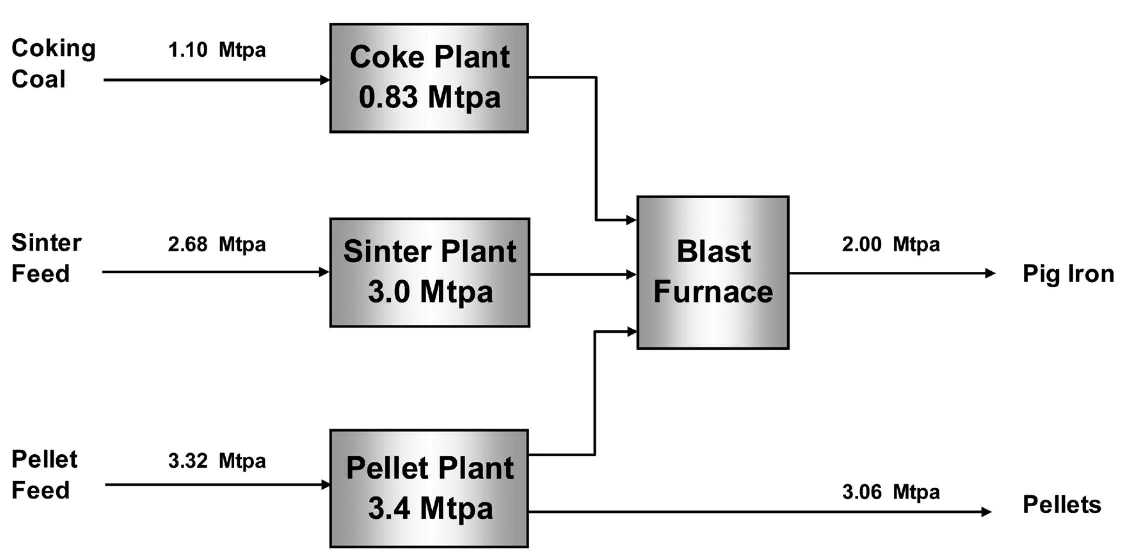
The number of scenarios considered was project-dependent, but as a minimum each study considered a byproduct coke oven battery and a heat-recovery battery, sized to meet the requirement of the blast furnace. Other scenarios, such as a coke plant located remote from the steel plant and a brownfield pad-up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

Case Study 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 (25–80 mm) and nut coke (15–25 mm) for the blast furnace. Coke breeze (<15 mm) 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.

Methodology — To perform the trade-off study, the analysis focused on the development of a plant-wide

Figure 5



Case 1 flowsheet.

energy balance for each option, byproduct 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:

- The pig iron plant shall be capable of producing all the electrical power required, as no import of power from the grid is allowed.
- All of the byproduct gases produced by the blast furnace and byproduct 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 byproduct gases. Natural gas was not available at the plant site.

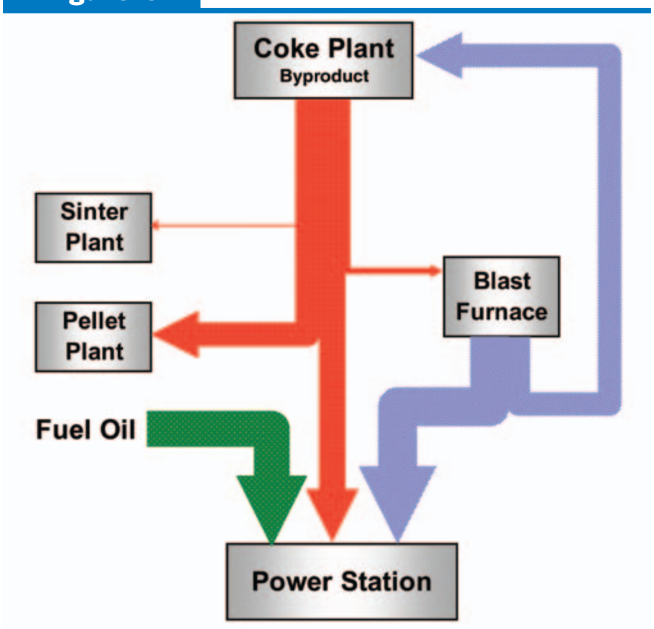
Three fuel sources were considered in the course of this study:

- *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/Nm^3 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.
- *Coke oven gas (COG)* is the primary byproduct from the byproduct 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 18 MJ/Nm^3, COG can be used in all heating applications on a steel plant, including heating of the coke oven battery itself.
- *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 40 MJ/kg, and it has a relatively high sulfur 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 byproduct and heat-recovery plants were derived from Chinese equipment supplier quotations combined with construction costs and indirect costs calculated by Hatch.

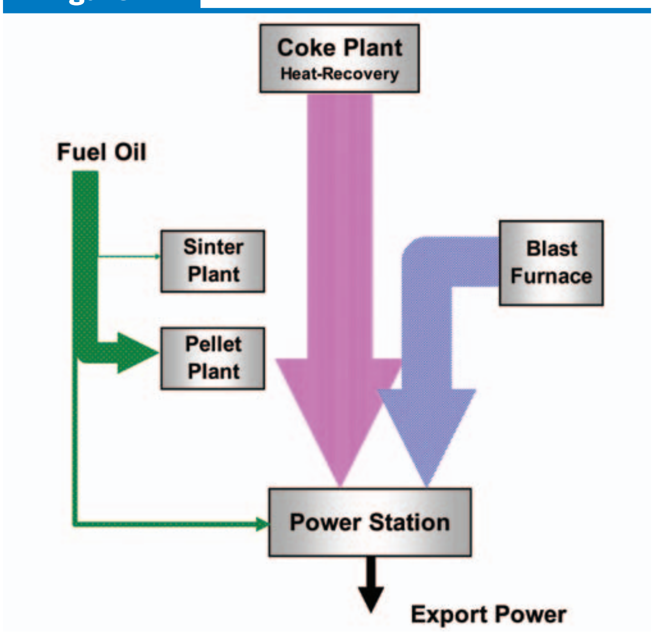
A simple financial analysis was performed for each scenario, with results expressed in terms of the Net Present Value (NPV) over a period of 20 years with a 10% discount factor. To calculate revenue, a pig iron

Figure 6



Sankey diagram for the byproduct coke oven plant configuration.

Figure 7



Sankey diagram for the heat-recovery coke oven plant configuration.

Table 1

Case 1: CAPEX Breakdown for Each Scenario

	Byproduct coke plant	Heat-recovery coke plant
	Million US$	Million US$
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
Subtotal	*263*	*322*
Balance of plant	*1,378*	*1,378*
Total	**1,641**	**1,700**

Table 2

Case 1: OPEX Breakdown for Each Scenario

	Byproduct coke plant	Heat-recovery coke plant
	Million US$/y	Million US$/y
Raw materials	149	148
Utilities	3	2
Byproducts	–8	0
Power (electrical) exported	0	–18
Fuel oil	46	40
Labor	10	7
Maintenance and repairs	1	1
Stockyard cost	4	4
Subtotal	*205*	*184*
Balance of plant	*460*	*460*
Total	**665**	**644**

Table 3

Case 1: Financial Analysis Results

	CAPEX	Project period	NPV (@10%)	IRR
	US$ '000,000	months	US$ '000,000	%
Byproduct option	1,641	36	370	13.6
Heat-recovery option	1,700	36	452	14.2

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.
- *Sulfur 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 desulfurization technologies employed.
- *Other pollutants,* namely benzene and other aromatic hydrocarbons, expressed qualitatively.
- *Electricity exported:* Electricity sold to the local grid.

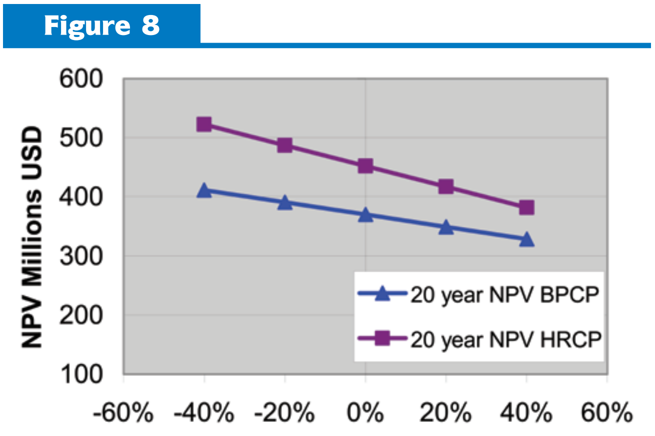
Results — Figure 6 shows the output results from the plant-wide energy balance calculations, expressed in a Sankey diagram format, for the plant with a byproduct coke facility.

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 the steam required to drive the blast furnace air blowers. In this case, there was no export of electricity to the grid.

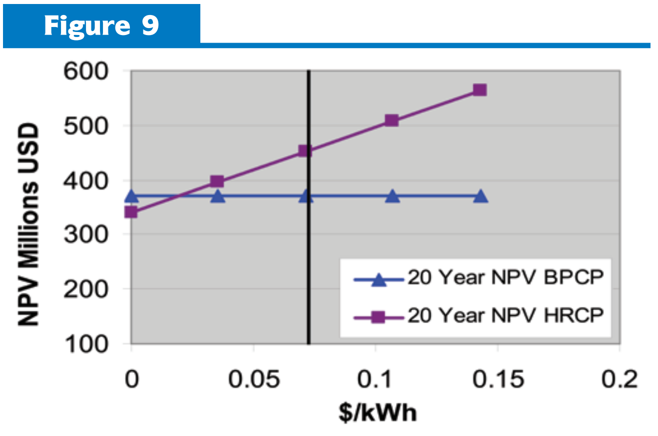
Figure 7 shows the Sankey diagram for the plant configured with a heat-recovery coke plant. The major difference is that the COG has been replaced by a flow of waste heat from the heat-recovery ovens that is ducted to heat-recovery steam generators (HRSGs) for generating high-pressure steam. Utilization 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 byproduct case by approximately 400,000 GJ/year. 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 was the recovery of the sensible heat from the offgases produced by the heat-recovery ovens. This is not achieved in the byproduct technology, which requires cooling of the gas in order to precipitate tars, naphthalene 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.

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 desulfurization equipment. The power plant line item included the



CAPEX sensitivity.



Electricity price sensitivity.

byproduct 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.

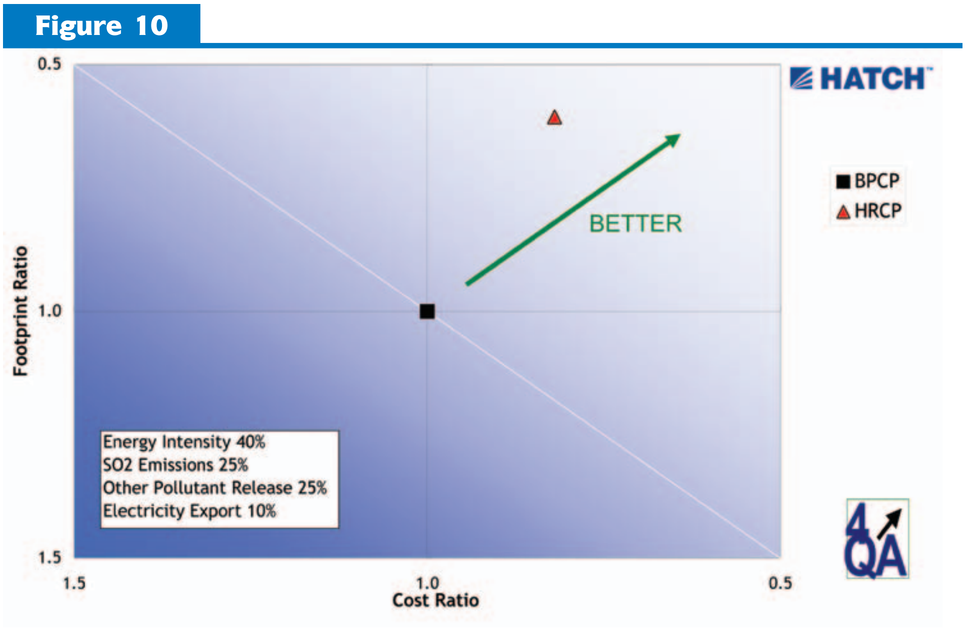
A comparison of the operating costs is shown in Table 2. Key differences are the sale of byproducts, the sale of electricity and the cost of fuel oil. Labor for operations and maintenance was less with the heat-recovery technology, primarily because there was no chemical plant required to produce the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

A financial analysis evaluating the two 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 favorable 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.

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 the time, the heat-recovery coke plant option had the greatest NPV.

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 a 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 byproduct 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.



4QA environmental comparison.

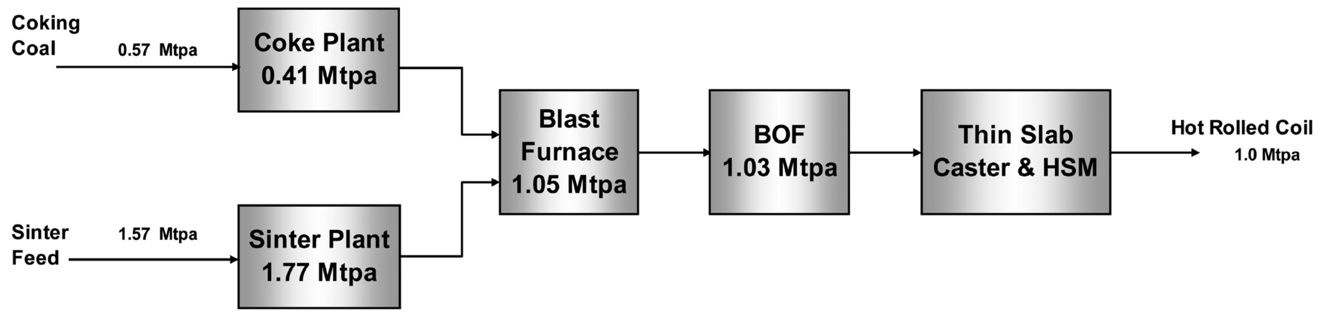
Case Study 2

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 (<15 mm) was used as solid fuel in the sinter plant. The plant was sized to produce 1.0 Mtpa hot rolled coil (HRC).

Methodology — A similar methodology to that described above was used to complete this case study. Assumptions made were as follows:

Figure 11



Case 2 flowsheet.

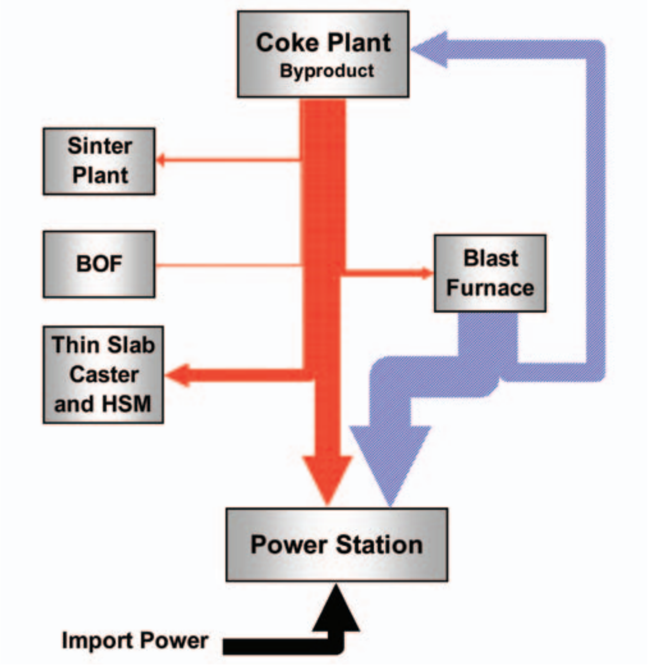
- All of the byproduct gases produced by the blast furnace and byproduct coke plant that were not used in the steelmaking process would be used to generate steam and power.
- Any excess power produced would be exported to the local power grid to provide extra revenue.
- Any electrical power requirement 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 necessary 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 byproduct and heat-recovery coke plants. Construction and indirect costs were calculated by Hatch.

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

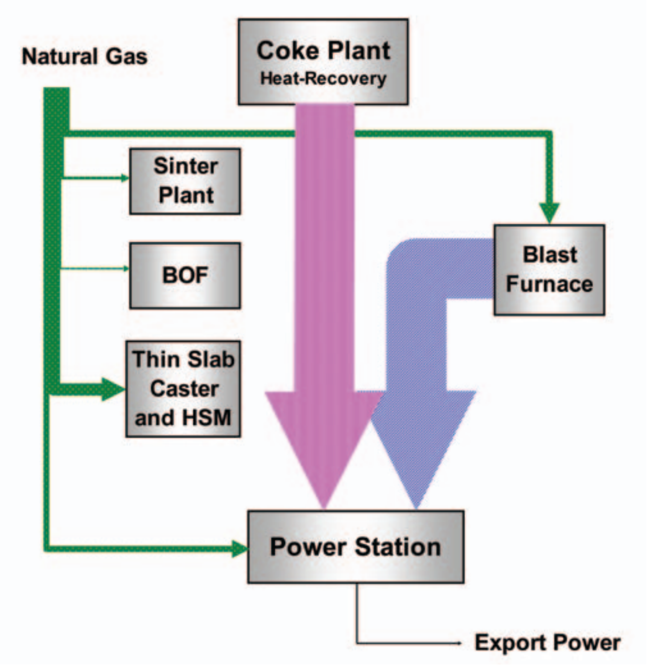
Figure 13 shows the equivalent energy balance for the heat-recovery coke plant option. With the heat-recovery coke plant option, natural gas was used as the high-calorific fuel in the sinter plant, BOF, blast furnace and equalizing furnace. The major difference between the two coke plant options was 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 12



Sankey diagram for the case 2 byproduct coke oven plant configuration.

Figure 13



Sankey diagram for the case 2 heat-recovery coke oven plant configuration.

Table 4

Case 2: CAPEX Breakdown for Each Scenario

	Byproduct coke plant	Heat-recovery coke plant
	Million US$	Million US$
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**

Table 5

Case 2: OPEX Breakdown for Each Scenario

	Byproduct coke plant	Heat-recovery coke plant
	Million US$/y	Million US$/y
Raw materials	74	78
Utilities	2	1
Byproducts	–4	0
Power (electrical)	21	–2
Natural gas	0	10
Labor	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

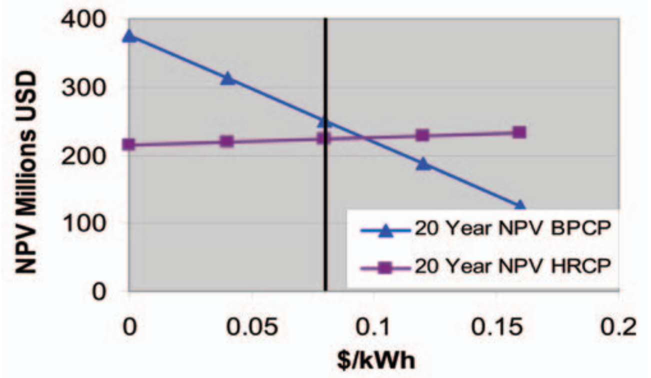
	CAPEX	Project period	NPV (@10%)	IRR
	US$ ’000,000	months	US$ ’000,000	%
Byproduct option	1,424	36	250	12.8
Heat-recovery option	1,501	36	224	12.4

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.

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 favor 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 Figures 14 and 15.

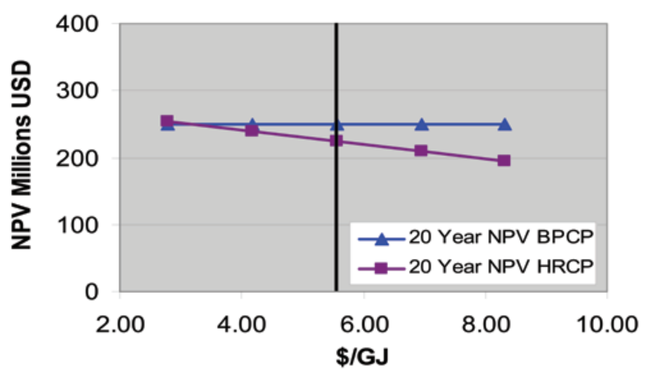
The environmental comparison for Case 2 is shown in Figure 16. As before, the heat-recovery coke plant had a smaller environmental footprint. When compared together with the cost ratio, the heat-recovery coke plant fell just above the white line, indicating that the lower return on investment represented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

Figure 14



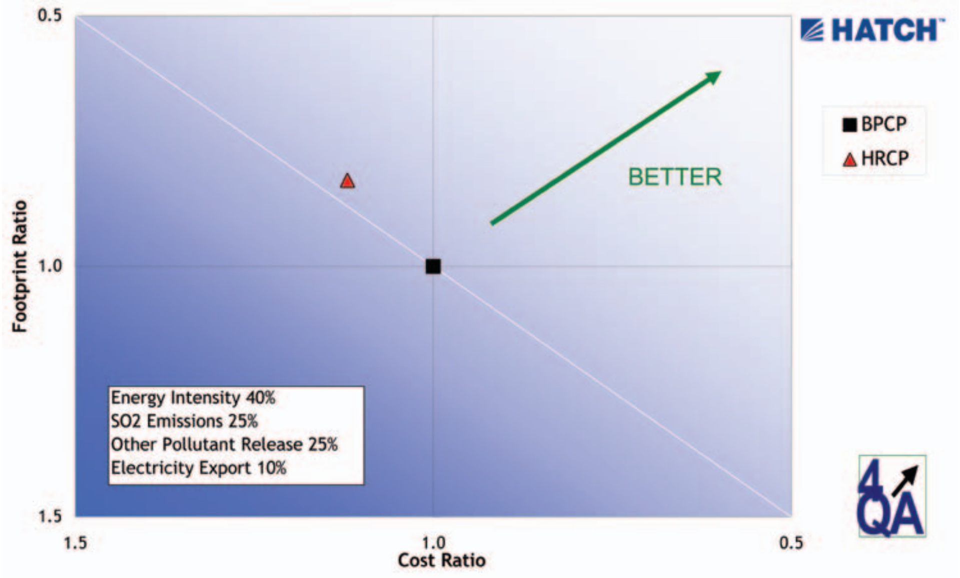
Electricity price sensitivity.

Figure 15



Natural gas price sensitivity.

Figure 16



4QA environmental comparison.

Conclusions

Both byproduct and heat-recovery coke plant technologies are capable of producing high-quality coke suitable for high-productivity blast furnaces. The decision as to which type of plant to build, considered from the viewpoint of return on investment, 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 byproduct 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 byproduct technology. Due to 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 U.S. Environmental Protection Agency recognizes the heat-recovery process as meeting the Maximum Achievable Control Technology (MACT). The byproduct process has some technologies that can improve upon the standard design, such as individual oven pressure control and Coke Stabilization Quenching (CSQ), which can minimize particulate and toxic emissions.

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

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