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Economic evaluations of direct, indirect and hybrid coal liquefaction

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Abstract−The various geopolitical problems associated with oil have rekindled interest in coal, with many countries working on projects for its liquefaction. This study established the feasibility of coal liquefaction through a technical and economic examination of direct coal liquefaction (DCL), indirect coal liquefaction (ICL) and hybrid coal liquefaction (HCL) processes. An economic efficiency analysis was prepared involving costs of initial investment, annual operating and raw coal purchase and revenues from the sale of major products as key variables. For the raw materials, products and investments, analyses of net present value (NPV), internal rate of return (IRR) and sensitivity were carried out. The processes' IRRs were found to be 22.26% (DCL), 18.43% (ICL) and 20.90% (HCL). NPVs were $4.720 m (DCL), $3.811 m (ICL) and $4.254 m (HCL), and payback periods were DCL 3.3 years, ICL 4.2 years, and HCL 3.6 years. As a result of the sensitivity analysis, factors greatly affecting the earning potential of coal liquefaction included product prices, raw coal prices, and construction costs, which showed similar effects in each process.

Key words: Coal to Liquid, Direct Coal Liquefaction, Indirect Coal Liquefaction, Hybrid Coal Liquefaction, Sensitivity Analysis, Economic Evaluation

INTRODUCTION

Petroleum has potentially catastrophic drawbacks arising from its finite supply and politically sensitive distribution. With unstable oil prices, many countries with high dependencies on overseas energy are in need of energy development. Therefore, studies of alternative resources are actively in progress. Coal is relatively abundant, more equally distributed and has more stable supply and prices than oil. Therefore, countries without petroleum resources are studying coal liquefaction to convert coal to artificial crude oil.

Coal liquefaction originated in Germany, where there are no petroleum resources, in the 1920s, with coal liquefaction plants supplying fuel for WWII. Coal liquefaction supplied 98% of German aviation gasoline and 47% of that country's entire hydrocarbon products; however, the outbreak of peace led to most research and production being discontinued. Coal liquefaction was developed rapidly by advanced countries, such as the U.S. and Japan, after the oil shock. SAR Sasol built its first plant in the 1950s and succeeded in commercialization of coal liquefaction in the 1980s. Many countries have developed coal liquefaction processes appropriate for their energy security and carried out trial operations of pilot plants. Recently, mainly China and the U.S. have accelerated the development of coal liquefaction and the construction of commercial plants. India, New Zealand, Australia and the Philippines are also preparing or executing various projects related to coal liquefaction [1-5].

This study collected and considered economic data for 50,000 BPD scale production, including initial investment costs, raw material consumption and product output by DCL, ICL and HCL processes. This allowed the assessment of economic efficiency through calculation of NPV and IRR of coal liquefaction. Capital costs and raw material cost sensitivities were also analyzed.

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PROCESS AND ANALYSIS METHOD

1. Hybrid Coal Liquefaction Process

HCL means that DCL, ICL processes are integrated, and was proposed by Headwater Company in the U.S. DCL consists of coal slurry preparation, liquefaction, liquefied oil distillation, solvent hydrogenation, and liquefied oil up-grading (Fig. 1) [6,7]. ICL involves coal gasification, gas purification, indirect liquefaction and power production (Fig. 2) [8,9].

HCL process has advantages of both DCL and ICL, with each process sharing utilities and facilities and possibly reducing operating costs (Fig. 3). Also, the considerable amount of hydrogen necessary for the DCL can be supplied by the ICL. In addition, controlling diesel and naphtha as major products of coal liquefaction process output is easy, so outputs can be tailored to meet fluctuating demand [10].

HCL plants have been built in coastal areas. Diesel oil, naphtha and fuel oil are produced from Illinois #6 bituminous coal as crude coal (Table 1) [6]. Aspects of DCL and ICL are both included with the omission of duplicated unit processes.

2. Economic Efficiency Analysis

2-1. Net Present Value

NPV is a capital budgeting technique used to assess certain businesses. If the required investment capital is less than the net cash flow (NPV>0), the business may be judged worth the investment.

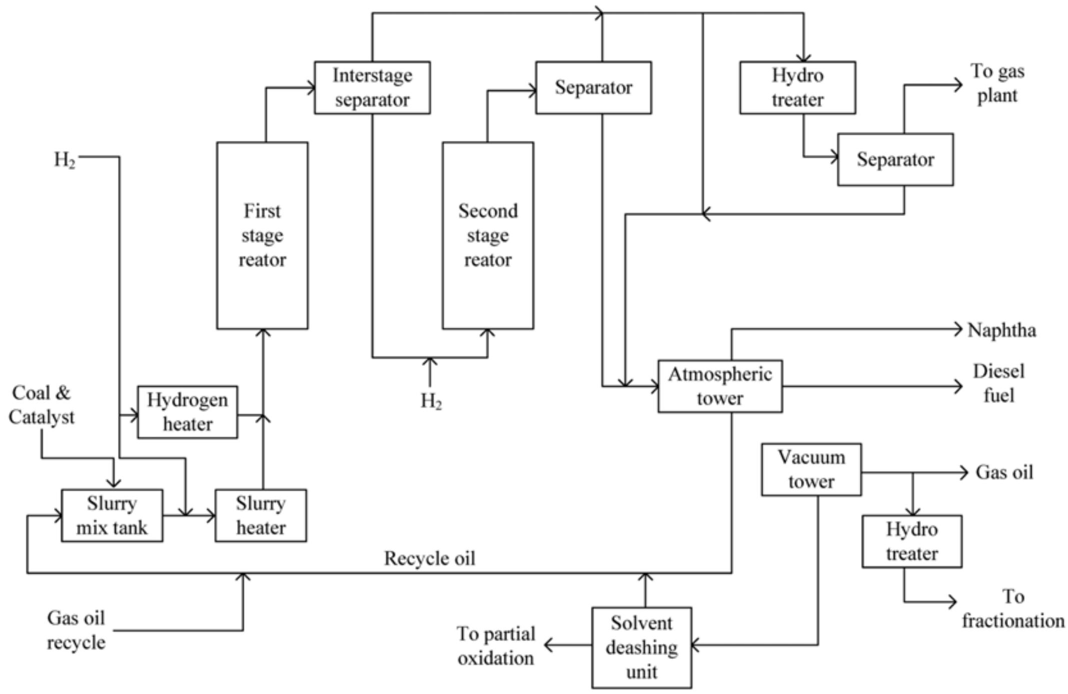

Fig. 1. DCL process flow chart [6,7].

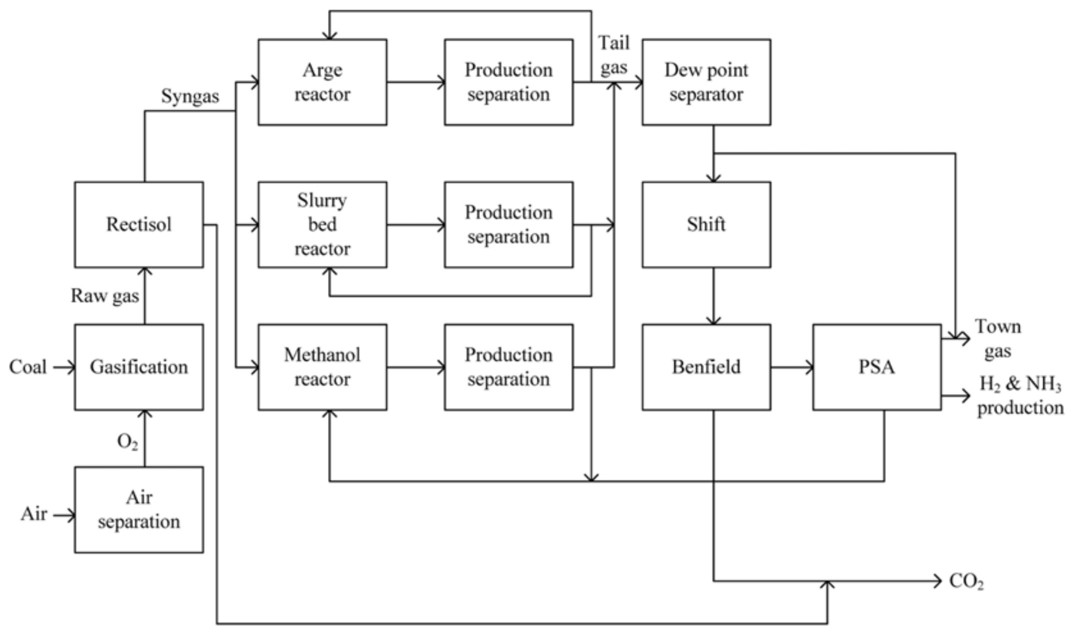

Fig. 2. Sasol process flow chart [8,9].

If the required investment is greater than the net cash flow (NPV< 0), project financing will likely be rejected. This method is considered superior to other capital budgeting techniques since the cash flow is discounted at the discount rate of the company and it coincides with the value additivity principle and provides a unique solution. The NPV is estimated by the following equations [5]:

$$NPV = \sum_{t=1}^{N} \frac{C_t}{(1+r)^t} - C_0 \quad (1)$$

t=year of cash flow (yr)
C_t=cash flow at t year (M$)
C_0=investment (M$)
r=discounted rate
N=total year of business (yr)

2-2. Internal Rate of Return

IRR is the discount rate (r) at which the NPV of the negative cash flows is equal to the NPV (C_0) of the positive cash flows. Namely,

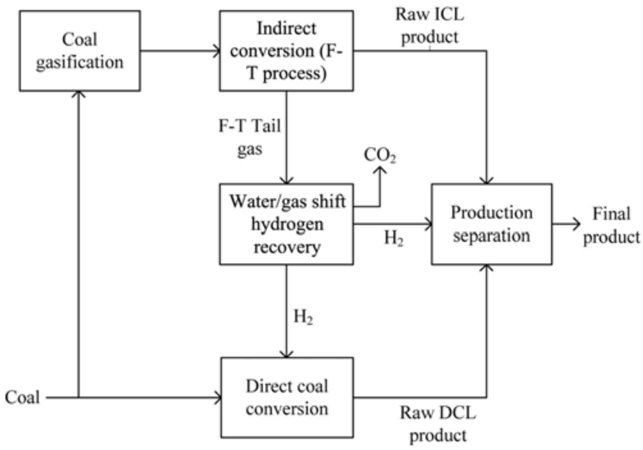

Fig. 3. HCL process flow chart [10].

Table 1. Proximate and chemical analyses of feed coal [6]

	Feed coal	
Seam	Illinois #6	
Source	Old Ben Mine	
Proximate analysis (wt%)		
	As Rec'd	Dry
Moisture	11.12	0
Ash	9.7	10.9
Volatility	34.99	39.37
Fixed carbon	44.19	49.72
HHV, Btu/lb	11,666	13,126
Chemical analysis (wt%)		
	As Rec'd	Dry
C	63.75	71.72
Moisture	11.12	0
H_2	4.5	5.06
N	1.25	1.41
Cl	0.29	0.33
S	2.51	2.82
Ash	9.7	10.91
O_2	6.88	7.75
Total	100	100

it is the equivalent compound interest rate that an investment in a project would yield, and is the discount rate at which the NPV of project financing becomes zero. If this internal earning rate is higher than the cost of capital, profits from the investment can be expected. The internal earning rate is estimated by the following equation [5].

$$\mathrm{NPV}=\sum_{t=0}^{N}\frac{C_t}{(1+\mathrm{IRR})^t}-0 \tag{2}$$

2-3. Payback Period Method

Analyzing payback period is used to assess value before investing capital. It assesses the investment by comparing the time to pay back the initial capital from the cash flows generated by the investment with a predetermined suitable payback period. If the payback period is found shorter than the limit set beforehand, the project will be financed. Such considerations can reduce uncertainty about future cash flows and improve the company's liquidity, but has drawbacks of ignoring future cash flows and the time value of money [11].

2-4. Sensitivity Analysis

Any capital budgeting method has to assume and analyze all variables that have uncertain future conditions and, as such, will invariably incur error. Sensitivity analysis involves analyzing how fluctuations of a given variable affect the NPV in order to anticipate the effects of future uncertainty. The larger the financing, the more serious the effects of fluctuations of NPV. Sensitivity analysis is a means of measuring relative risk associated with project financings [7].

3. Cost Estimation

3-1. Definition and Constituents of Initial Investment Costs

Costs used in analyzing a project's economic efficiency include the initial investment costs and the operating costs of annual maintenance and management. Costs can be distinguished as fixed costs, which are not proportional to output, and variable costs. The initial investment costs form the basis of the fixed costs. Operating costs can be divided into the fixed and variable costs.

Construction costs are all capital expenditure necessary for constructing facilities and commercial operation. It is assumed that all the facilities are constructed at once, the total construction cost includes overnight cost (or forecost), which is not considering the time value of money, EDC (escalation during construction) and IDC (interest during construction) as financial expense. The overnight costs are included with basic cost associated with the facilities, owner's cost as incidental expenses and emergency expenses etc. [12].

3-2. Assumptions of the Economic Analysis

In the analysis of economic efficiency, DCL was based on the two-stage process, ICL on the Fischer-Tropsch process. The HCL process was based on integrated DCL and ICL. Estimation of corresponding costs used figures supplied by Headwaters Company. Each plant was assumed to be built on green-field sites, and construction costs had overnight costs applied. License fees or royalties and expenses for domestic infrastructure were not considered. DCL's capacity (50,000 BPD) was assumed split between production of 3,803 barrel LPG and 46,197 barrel fuel oil per day through the consumption of 16,460 ton bituminous coal [6,13,14]. ICL's capacity (50,000 BPD) assumed the production of 124.3 MW dump power and 49,992 barrel fuel oil from 24,533 ton bituminous coal each day [8,15]. HCL's capacity assumed DCL in the first stage and ICL in the second by producing 50,000 barrel of fuel oil from 18,224 ton of bituminous coal per day [10].

DATA OF ECONOMIC EFFICIENCY

1. Estimation of Initial Investment Costs

The total initial investment cost of a DCL plant was estimated through the definition of initial investment costs and constituents mentioned above. The details of total working expenses are listed in Table 2. The total working expenses are split into capital costs and financing costs, with capital costs divided into the total plant cost, initial working capital and owner's cost, and the financing costs divided into the interest during construction and the financing fee. The total plant cost was divided into EPC (Engineering Procurement Construction, Design and Construction Batch Bids), owner's contingency, and process contingency [7].

Table 2. Total plant costs of DCL, ICL and HCL [7]

	DCL	ICL	HCL
1. Capital cost * M$	3,598	4,447	3,706
1) Total plant cost	3,158	3,923	3,252
(1) EPC	2,429	3,036	2,502
(2) Owner's contingency (26% of EPC costs)	632	789	651
(3) Process contingency (25% of Tech. uncertain EPC costs	97	97	100
2) Working capital (7% on 1st year revenues)	134	141	138
3) Start up (2% on total plant)	63	78	65
4) Owner's cost (10% of EPC costs)	243	304	250
2. Financing 11% capital cost	396	495	408
1) Interest (84%)	333	416	343
2) Fees (16%)	63	79	65
3. Total project cost	3,994	4,943	4,115
(% on EPC)	164.46	162.80	164.46
1) Equity (45%)	1,798	2,224	1,851
2) Debt (55%)	2,197	2,719	2,262

Table 3. Interest calculation and assumptions for economic evaluation of CTL processes

Source & Funds	
- Equity	45%
- Debt	55%
- Total	100%
Project debt terms	
- Interest rate, financing fee	10%
- Repayment terms	15 Year
- Plant economic life	30 Year
Tax	
- Tax holiday	-
- Income tax rate	20%
Operation	
- 1st Year	85%
- 2nd Year	85%

The total working expenses were configured by 45% capital and 55% loan. The interest on working expenses was 10% of the total loan. Taxes and dues were 0.5% of the total initial investment cost. Depreciation cost was calculated for 15 years of constant mortgage payments with the total initial investment costs as principle. The income tax of the coal liquefaction plant was set at 20% by applying domestic legislation. The total plant operation period was 30 years with an average operating rate of 85% considering the shutdown period (Table 3). In addition, we used real prices without inflation effects. The total construction period was four years, and the distribution of the initial investment costs during construction is listed in Table 4.

Table 4. Distribution of total project cost of DCL, ICL and HCL during construction

DCL	1st Year	2nd Year	3rd Year	4th Year	Total (M$)
EPC	364	729	729	607	2,429
Initial working cost	0	0	0	134	134
Contingency	255	255	219	0	729
Start up cost	0	19	44	0	63
Owner's cost	0	73	170	0	243
Interest during conct	0	100	233	0	333
Financing fee	0	19	44	0	63
Total	619	1,195	1,439	741	3,994

ICL	1st Year	2nd Year	3rd Year	4th Year	Total (M$)
EPC	455	911	911	759	3,036
Initial working cost	0	0	0	141	141
Contingency	311	311	265	0	887
Start up cost	0	24	55	0	79
Owner's cost	0	91	213	0	304
Interest during conct	0	125	291	0	416
Financing fee	0	24	56	0	80
Total	766	1,486	1,791	900	4,943

HCL	1st Year	2nd Year	3rd Year	4th Year	Total (M$)
EPC	375	751	751	625	2,502
Initial working cost	0	0	0	138	138
Contingency	263	263	225	0	751
Start up cost	0	20	45	0	65
Owner's cost	0	75	175	0	250
Interest during conct	0	103	240	0	343
Financing fee	0	20	46	0	66
Total	638	1,232	1,482	763	4,115

2. Sales and Raw Material Cost Estimation

The cost applied in this study was the raw material price announced by the Korea Energy Economics Institute and Energy Information Administration, and it was a mean value of data from January to June 2010. The annual sales of DCL, ICL and HCL were calculated by multiplying the annual output of naphtha diesel, LPG and dump power by their unit cost. In addition, the raw material cost was calculated by multiplying the annual total usage of coal by its unit purchase cost. Unit costs of each material are listed in Table 5. Sales and raw material cost are listed in Table 6.

3. Variable Cost and Fixed Cost Estimation

DCL uses much hydrogen and catalyst, and so had higher estimated variable costs than ICL. ICL had a higher estimated total plant cost than DCL due to the gasification process etc. But the amounts of chemicals used for the process are small, resulting in small variable costs. HCL uses catalyst and chemical products of DCL and ICL, and so has lower estimated variable costs than DCL but higher than

Table 5. Unit costs of raw meterials and products

	Unit	$/Unit	References
Coal	Ton	93.60	Korea Energy Economics Institute (2009.1-6)
Diesel	Bbl	189.30	
Naphtha	Bbl	78.5	
LPG	Bbl	92.89	
Electricity	MW	55.0	Domestic "A" oil refining company average purchase price
Sulfur	Ton	400.0	Domestic "A" oil refining company average sale price
CO_2	Ton	43	
Water	Ton	0.4	Domestic "A" oil refining company average purchase price

ICL. The details of variable costs, chemical and water treatment costs, including the raw water and the catalyst, hydrogen, and estimations by scale are shown in Table 7.

The fixed costs are largely divided into personnel expenses, maintenance and repair, interest, taxes and dues and depreciation. The personnel expenses were estimated at $62,000/yr using the unit wage cost standard of "A" domestic refineries. Staffs consisted of four groups and three shifts in a standard plant (Table 8, 9), provided that DCL was based on three plants while ICL was four.

Table 9. Fixed costs of DCL, ICL and HCL

(M$)	DCL	ICL	HCL
Operating & maintenance labor	94	121	94
Annual operating labor cost	27	36	27
Maintenance labor cost	25	25	25
Administrative & support	9	93	9
Maintenance material cost	33	52	33

ANALYSIS OF ECONOMIC EFFICIENCY AND SENSITIVITY

1. Analysis of Economic Efficiency of DCL, ICL and HCL

In addition to initial investment, factors with significant effects on the economic efficiency of coal liquefaction are the selling prices

Table 6. Total sales and raw materials cost of DCL, ICL and HCL

DCL			ICL			HCL		
Product	Amt	Total price (M$)	Product	Amt	Total price (M$)	Product	Amt	Total price (M$)
DCL naphtha (BPD)	13,474	328	FT-naphtha (BPD)	22,173	540	Naphtha (BPD)	14,708	358
DCL diesel (BPD)	32,723	2,261	FT-diesel (BPD)	27,819	1,922	Diesel (BPD)	33,392	2,307
LPG (BPD)	3,083	95	Electricity (MWH)	124	2			
			Sulfur (TPD)	612	76			
Total		2,684	Total		2,540	Total		2,665
Feed coal (TPD)	16,460	478	Feed coal (TPD)	24,533	712	Feed coal (TPD)	18,224	529

Table 7. Variable costs of DCL, ICL and HCL

DCL			ICL			HCL		
Product	Amt	Total price (M$)	Product	Amt	Total price (M$)	Product	Amt	Total price (M$)
Water (TPD)	64,800	8	Water (TPD)	81,000	10	Water (TPD)	63,700	6
Catalysts (TPD)	210	283	Chemicals (TPD)	33,380	3	DCL catalyst (TPD)	70	94
Chemicals (TPD)	4,476	122	Water disposal (TPD)	2,862	15	ICL catalyst (TPD)	11,130	302
						Water disposal (TPD)	477	2
Total		413	Total		28	Total		404

Table 8. Operating and maintenance labor of DCL, ICL and HCL

Operating labor requirement	DCL		ICL		HCL	
Operating labor requirement	1 Unit/mod	Total plant	1 Unit/mod	Total plant	1 Unit/mod	Total plant
Skilled operator	4	12	4	16	4	12
Operator	20	60	20	80	20	60
Foreman	4	12	4	16	4	12
Lab Tech's etc.	8	24	8	32	8	24
Total	36	108*4=432	36	144*4=576	36	108*4=432

Table 10. Comparison of economic evaluation of CTL processes

Plant type	DCL	ICL	HCL
Economics (base)			
Relative capital cost	1.00	1.24	1.03
Net present value (M$)	4,720	3,811	4,254
Internal rate of return (%)	22.26	18.43	20.90
Payback period (years)	3.3	4.2	3.6

of liquefaction fuel oil, LPG and surplus electric power, and the purchasing costs of crude coal, catalysts and chemicals. In addition, the various coal liquefaction processes have varying strengths and weakness, and each process has many different forms or operating systems. Accordingly, the economic efficiency of DCL, ICL and HCL was assessed by scale. DCL is a pure consumption process in terms of power, while ICL produces dump power, so it generates income from power sales. A small amount of power is produced by HCL but it is sufficiently small to be ignored. Considering the above, the analysis of economic efficiency of 50,000 BPD DCL, ICL HCL was carried out, with IRR, NPV and payback period calculated as shown in Table 10. According to Table 10, the relative capital cost ratio of DCL : ICL : HCL was 1.0 : 1.24 : 1.03 (DCL: $3,994 m, ICL: $4,943 m, HCL: $4,115 m).

Furthermore, DCl had an IRR of 22.26%, NPV of $4.720 m and payback period of 3.3 years. It showed high earning rate relative to the standard of the first half of 2009 (IRR: 13.27%, NPV: $1.131 m, payback period: 6.6 years) due to increases of the sales [9]. In addition, through the development of DCL catalyst and association of DCL and ICL for the smooth supply of hydrogen, initial investment costs and variable costs are expected to be saved.

ICL had an IRR of 18.48%, NPV of $3.811 m and payback period of 4.2 years. IRR and NPV decreased compared with DCL, and payback period increased. Also, ICL needs more initial investment and crude coal; thus, ICL has higher initial investment costs compared with DCL. Initial investment costs are expected to be saved through linking with IGCC and HCL. Economic efficiency will be increased through the development of a process using the gasification of other materials and low rank coals.

HCL had an IRR of 20.90%, NPV of $4.254 m and payback period of 3.6 years. HCL used utilities and facilities simultaneously for both DCL and ICL, so reducing operating costs resulting in the short payback period. In addition, controlling the output control of diesel and naphtha as major products of coal liquefaction is easy so that output can respond to demand and prices.

Table 11. Basic data of sensitivity analyses

			Base	+25%	−25%
Oil price		Naphtha $/bbl	78.50	98.13	58.88
		Diesel $/bbl	189.30	236.63	141.98
LPG price		$/bbl	92.80	116.00	69.60
Net electricity		$/MW	57.20	71.50	42.90
Coal price		$/ton	93.60	117.00	70.20
Catalyst & chemicals	DCL	$1,000	283	353	212
	HCL	$1,000	397	496	298
Capital cost	DCL	M$	3,994	4,993	2,996
	ICL	M$	4,942	6,179	3,707
	HCL	M$	4,114	5,143	3,086

Table 12. Sensitivity analyses of DCL

		IRR (%)	NPV (M$)	Payback period
Base		22.26	4,720	3.3
Oil price	+25%	29.20	7,937	2.2
	−25%	14.30	1,501	5.9
LPG price	+25%	24.58	5,766	2.5
	−25%	19.81	3.673	3.8
Feed coal price	+25%	20.82	4,098	3.6
	−25%	23.65	5,340	3.0
Catalyst & chemicals cost	+25%	21.00	4,176	3.6
	−25%	23.48	5,262	3.0
Capital cost	+25%	18.42	3,828	4.2
	−25%	27.97	5,611	2.4

2. Sensitivity Analyses of DCL, ICL and HCL

IRR, NPV and payback period were calculated after varying costs ±25% from current prices for the sensitivity analysis. Table 11 shows the unit cost of each item with ±25% applied to the current price.

As shown in Table 12, DCL had IRR, NPV and payback period of 29.20%, $7.937 m and 2.2 years, respectively, when the selling prices of liquefaction fuel oil increased 25%. Also, sensitivity analyses to LPG, feed coal, catalyst and chemicals and capital were shown in Table 12. However, in the case of LPG as another product, fluctuations of IRR and payback period were smaller and were less sensitive to the price compared with the price of liquefaction fuel oil. Greatest price sensitivity was found to liquefaction fuel oil, then initial investment costs, followed by crude coal, and finally catalyst and chemicals. Therefore, stable raw materials' prices, stability of exchange rates and maintaining the cost of liquefaction are judged as conditions that can maximize the payability of this plant.

Similar to DCL, ICL (Table 13) had greatest sensitivity to the selling price of liquefaction fuel oil (25% fuel oil price increase gave: IRR 24.38%, NPV $7.055 m, payback period 2.9 years). Also, sensitivity analyses to electricity, feed coal and capital are shown in Table 13. Effects of surplus electric power price on sensitivities were low, similar to the LPG price on sensitivity of DCL.

Table 13. Sensitivity analyses of ICL

		IRR (%)	NPV (M$)	Payback period
Base		18.43	3,811	4.2
Oil price	+25%	24.38	7,055	2.9
	−25%	11.40	566	7.4
Electricity price	+25%	19.56	4,513	3.9
	−25%	17.10	3,049	4.5
Feed coal price	+25%	16.60	2,902	4.8
	−25%	20.19	4,720	3.8
Capital cost	+25%	14.89	2,621	5.5
	−25%	23.71	5,001	3.0

Table 14. Sensitivity analyses of HCL

		IRR (%)	NPV (M$)	Payback period
Base		20.90	4,254	3.6
Oil price	+25%	28.23	7,740	2.3
	−25%	12.21	767	7.3
Feed coal price	+25%	19.31	3,561	4.0
	−25%	22.45	4,947	3.2
Catalyst & chemicals cost	+25%	19.69	3,724	3.9
	−25%	22.09	4,784	3.3
Capital cost	+25%	16.85	3,177	4.8
	−25%	26.97	5,330	2.5

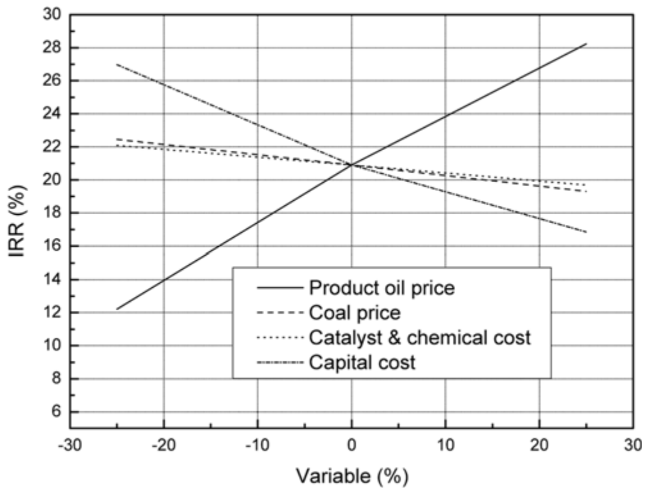

Fig. 6. Sensitivity analyses of HCL.

HCL (Table 14) also had greatest sensitivity to the price of liquefaction fuel (25% fuel oil price increase gave: IRR 28.23%, NPV $7.740 m, payback period 2.3 years). Also, sensitivity analyses of feed coal, catalyst and chemicals and capital are shown in Table 14. In addition, the total initial investment costs were found to be relatively unstable compared with DCL and ICL.

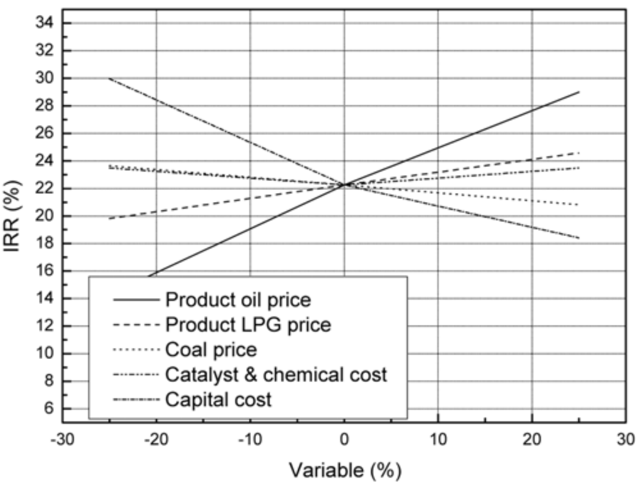

Fig. 4. Sensitivity analyses of DCL.

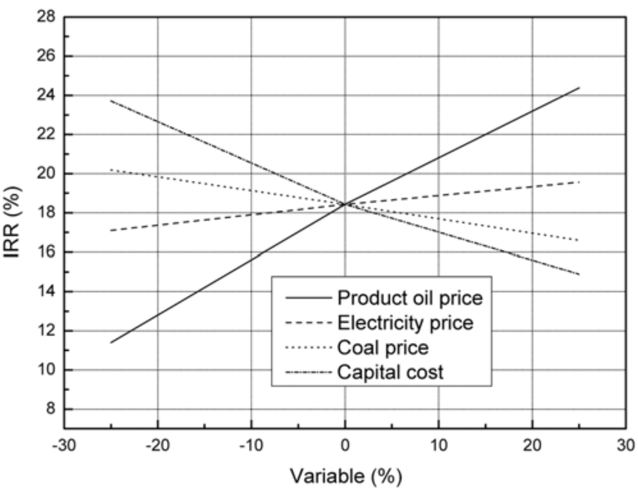

Fig. 5. Sensitivity analyses of ICL.

To compare the sensitivity to each item, the fluctuation of IRR by each process is shown in Figs. 4, 5 and 6. In order of decreasing price sensitivity, factors were ranked liquefaction fuel oil price, initial investment costs, crude coal price, catalyst and chemical's purchasing fee. Therefore, stable raw materials' prices, exchange rate stability and maintaining costs can maximize the payability of plant. Also, the sensitivity of NPV was similar to that of IRR because they are interrelated as shown in Eq. (2).

3. Comparison of Economic Efficiency of DCL, ICL and HCL

Cost analysis of CTL processes planned in China and the U.S assessed that ICL has about 22-29% higher initial investment costs than DCL. As shown in Table 15, the initial investment cost ratio of DCL : ICL : HCL was 1.0 : 1.24 : 1.03, similar to results from other internal/external CTL processes. The total initial investment

Table 15. Comparison of CTL processes

	DCL	ICL	HCL
Coal consumption TPD			
Coal to DCL	11,120	0	5,560
Coal to gasifier	5,340	24,533	12,640
Total	16,460 (1.0)	24,533 (1.49)	18,224 (1.11)
Liquid BPD			
Diesel	32,723	22,179	33,392
Naphtha	13,474	27,819	14,708
LPG	3,083	0	0
Total	49,208	49,992	50,000
Electric power (MWH)			
Gross	0	651.953	518
Parasitic	201	527.699	486
Net export	0	124.360	32
Net import	201	0	0
Relative coal cost	1.0	1.24	1.03
Investment (M$)	3,995	4,943	4,115

cost of the HCL was close to the initial investment cost of DCL, but the HCL showed much greater sensitivity to fluctuations of total initial investment costs than DCL. ICL had greater total initial investment costs through the addition of gasification and power facilities compared with DCL. Due to this increase of initial investment costs, ICL had a longer payback period than DCL.

DCL used *ca.* 32% of the feed coal for production of H_2. Feed coal consumption of the three processes (DCL : ICL : HCL) was by the ratio of 1.0 : 1.5 : 1.1. The thermal efficiencies of the processes were 60%, 33-36% and 56%, respectively, with DCL having the highest. In the production of liquefaction fuel oil, DCL and HCL show high outputs of diesel, ICL shows a similar rate of diesel and naphtha production. DCL and ICL produce high quality diesel with sulfur, N and aromatic materials removed. The quality of naphtha from ICL is lower than that from DCL. HCL can produce premium fuel oil by mixing naphtha and diesel from each DCL and ICL.

CONCLUSIONS

The economic efficiencies of DCL and ICL were compared with that of an HCL that combines aspects of both. Economic efficiency was assessed through the analysis of major products from comparable 50,000 BPD plants. Costs and revenues of each process were also estimated to allow the analysis of economic efficiency and price sensitivity.

Relative to DCL, the initial investment cost of ICL was 25% higher, while that of the HCL was 3% higher. NPV was positive for all three processes (DCL, ICL and HCL having respective NPVs of $4.720 m, $3.811 m and $4.254 m), implying their economic efficiency. IRR for DCL, ICL and HCL were, respectively, 22.26%, 18.43% and 20.90%. Their respective payback periods were 3.3 years, 4.2 years and 3.6 years. Sensitivity analysis found similar responses to significant factors affecting the earning rate of coal liquefaction across the processes. The most influential factor was product price, then crude coal price, followed by construction costs. The crude coal necessary for coal liquefaction is traded in a volatile market, as is the cash required for its international trade, which weakens the economic efficiency of coal liquefaction. But when viewed in the long term, coal liquefaction appears likely to be essential in terms of self-sufficiency and energy security. If coal liquefaction can use domestic coal supplies, then its development will be all the more valuable.

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