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ARCHER HTR TECHNOLOGY IN SUPPORT OF A COAL TO LIQUID PROCESS – AN ECONOMIC FEASIBILITY VIEW

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Abstract – *The paper considers the economics of coupling a European developed HTR (as conceptualized by project ARCHER) to a Coal-to-Liquid (CTL) process as typically used by Sasol, the biggest Coal-to-Liquid (CTL) producer in the world.*
The approach followed was to create a techno-economic baseline for an existing CTL process using mass and energy balances determined with Aspen Plus chemical modelling software. The economic performance of a typical 80,000 barrels per day synthetic crude oil plant was determined from first principles. The techno-economic baseline model was validated with reference to published product output data and audited financial results of a Sasol CTL plant located at Secunda, South Africa, as reported for the 2011 financial year.
A number of schemes were identified to couple the European HTR plant to the CTL case study. Two schemes were studied in detail, while the remaining coupling schemes will be studied as part of the follow-on project NC2I-R (Nuclear Cogeneration Industrial Initiative – Research). Two Key Performance Indices were of interest, namely the Internal Rate of Return of a Nuclear supported CTL plant and the reduction of CO_2 emissions.
The case where nuclear co-generation replaced electrical power bought from the grid, and also replaced all the steam currently produced by the burning coal with nuclear steam, yielded interesting conclusions:
- *The case study plant would need a total of 16 HTRs, each with a capacity of 265 MWth.*
- *The coupling scheme would reduce CO_2 emissions by approximately 14.5 million ton/annum or 51 % of the current emissions of a 80,000 bbl/d plant.*
- *The economic feasibility challenge for large scale deployment of nuclear energy in a Coal-to-Liquid application - where steam and electricity are to be generated from Nuclear energy, is to construct such a facility at an all -inclusive overnight cost not exceeding $3400/kWe.*

I. INTRODUCTION

South Africa, through North-West University, is a non-EU partner in project ARCHER (Advanced Reactor for Cogeneration of Heat and Electricity Research and development, a FP7 European Commission (EC) project). ARCHER "focuses on generic and cross-cutting V/HTR-related R&D issues and supports European contributions towards international demonstration of HTR and VHTR technology".

The objective of South-Africa's participation in project ARCHER was: "To do a first order investigation into the integration of nuclear energy into a strategic South-African industrial process. The technical and economic merit of deploying a European developed HTR technology in support of a Coal-to-Liquid process will be determined" [Stoker PW, Fick JIJF, Conradie F 2013]

South Africa, being a signatory to the Kyoto protocol, is obliged to limit and eventually reduce its CO_2 emissions. Sasol's Coal-to-Liquid plant in Secunda is known to be the biggest point source CO_2 emitter in the world. Hence it offered an interesting case study for the application on nuclear co-generation. The contribution to the ARCHER Sub-project 1 work package by North-West University (NWU), the lead organization of South Africa's participation in ARCHER, comprised the following work.

- Task 1.1.2 Definition and application of key performance indicators (KPIs)
- Task 1.1.3 Elaboration of schematics and case studies
- Task 1.2.1 Technology gap and risk analysis
- Task 1.2.2 SWOT analysis

It was therefore opportune for NWU to propose a South African view on the utilization of European developed HTR technology in support of Sasol's coal-to-liquid process, as a contribution to project ARCHER. This work was well aligned with ARCHER's sub-project SP1 (System integration). The aim of SP1 was to "identify and solve issues that arise when a multitude of systems and components are combined with the objective of safe and economic operation whilst meeting end user needs". [Roelofs 2011]

This paper introduces the approach which the team followed to analyze the economic feasibility of a coupled nuclear co-generation/coal-to-liquids plant. It briefly discusses the simulation model that was used to determine a mass balance baseline for the CTL process, followed by an overview of the assumptions underpinning the analyses and the findings made by the research team.

II. ECONOMIC FEASIBILITY MODELLING APPROACH

The economic feasibility study was done with reference to 3 scenarios:

- Scenario S0 - The existing Secunda West Plant (SWP) as a baseline case.
- Scenario S1a - The existing SWP with external ESKOM electricity replaced by nuclear electricity from high temperature gas cooled nuclear reactors.
- Scenario S1b - The existing SWP with internal coal fired cogeneration plant replaced by nuclear cogeneration plant, sized to replace all external and internal generated electricity and to supply all the required process steam, previously supplied by coal co-generation.

In each case the modelling approach was focused to investigate certain Key Performance Indices (KPIs). The latter were selected to reveal the business case for nuclear supported CTL rather than the technical performance of the system.

II.A. Key Performance Indices

Since the overall philosophy of the modelling approach was to develop insight and depth into the economic performance of this particular application of nuclear co-generation, it was decided to model only two KPIs, namely:

a) The internal rate of return (IRR) of a particular coupling scheme; and
b) The reduction in CO_2 emission that such a scheme offers that would attract serious interest from SASOL.

Although conceptually simple, these two key performance indicators present a global view of the economic merit of a solution, underpinned by a significant amount of plant related technical and cost detail in the case of the IRR metric. Internal rate of return (IRR) is a cash flow based investment performance metric which, if applied correctly, accounts for practically every dimension of a technology solution over its life cycle and sometimes even beyond. CO_2 emission is supported by detailed chemical reaction modelling that shows the reduction that would result from a coupling scheme when compared to the baseline case.

Operating values for the indicators in the present research, were derived through industry and academic judgment, and verified in informal discussion with senior ex-employees of SASOL. For the purpose of this research they were set at

- IRR =6% minimum in real monetary terms; and
- Reduction in overall CO_2 emission > 40%

In the ARCHER study the objective was to model the implementation of HTR technology with minimum disruption to existing operations and preferably with as little change as possible to the existing coal-to-liquid process.

II.B. Modelling Strategy

Maximum flexibility in the analysis approach was considered to be important, since it would enable "plug-and-play" analysis - not only of different nuclear coupling schemes, but also of process blocks of the CTL process itself. The latter is aimed at future work, which would seek to investigate the coupling of nuclear co-generation technology to futuristic CTL systems.

The modelling strategy called for a baseline to be created of the existing Secunda coal-to-liquid operation. This was done in the form of mass and energy balances of key process blocks. Each process block was represented as a discrete financial business unit in the model. Process streams from any one "business unit" were "sold" on to a next business unit, priced on the basis of achieving a set hurdle Internal Rate of Return. Where applicable, emission incentives, penalties or the "polluter pays" principle embedded in South Africa's environmental legislation were applied to the "seller".

III. PLANT SIMULATION APPROACH

III.A. Coal-to-liquid process

A plant with 40 fixed bed Lurgi gasifiers was simulated with the process simulator Aspen Plus. The process model included a coal preparation section, an air separation, steam and electricity generation as well as a steam methane reforming sections with most of the basic utilities included. The simulation also included gas clean-up (Rectisol) and Fischer-Tropsch hydrocarbon synthesis sections.

A typical Mpumalanga Highveld coal was chosen as feedstock, with an ash content of 30%. The Anderson-Schulz-Flory distribution was assumed to provide a sensible product spectrum for the Fischer-Tropsch reactors. The simulation results showed good correlation against process information that was available in published data.

IV. RESULTS AND DISCUSSION

IV.A. Key Assumptions and Inputs
IV.A.I. IRR Hurdle Rate, Risk and Levelized Cost

The IRR-hurdle rate (6% in this case) represents a risk appetite (defined as "the degree of uncertainty an entity is willing to take in anticipation of a reward" [PMBOK 2013]. The way the hurdle rate is applied in the modelling approach is that of a minimum reward for a perceived risk which the case study organization would be prepared to take when investing in the project.

What the actual risk would be for each of the modelling scenarios was outside the scope of the ARCHER study. The authors' experience of business in South Africa indicates that a 6% real internal rate of return is a modest reward, anticipating a low risk. This calls for a project employing mature technology, particularly in relation to licensing and operations safety; high confidence in capital cost estimate and construction lead time; and political and labour stability.

The ARCHER economic feasibility modelling was carried out in an assumed inflation free environment. Consequently only real rates and increases were included - and only so if good reasons could be stated in support of such real increases. This approach allowed the calculation of levelized cost of commodity and chemical process streams with a high level of confidence. Levelised cost is widely acknowledged as a sound way of comparing the economic merit of alternative candidate technologies. The requirement was to calculate levelized cost in current value of money, using current cost data as input.

IV.A.2. Identification of business units

A crucial step in the development of the economic feasibility model was the identification and demarcation of various business units which, when combined, would represent the operations of the plant as a whole. The approach followed was to identify the physical battery limits of plant units. Input streams to and output streams from these units were then determined. Engineering judgment was subsequently used to eliminate those input/output streams which were deemed to have minor cost implications for the study, when compared to main process streams. (For example instrument air).

Figure 1 [Murray, Fick and Stoker 2010] shows the main business units and key inputs/outputs.

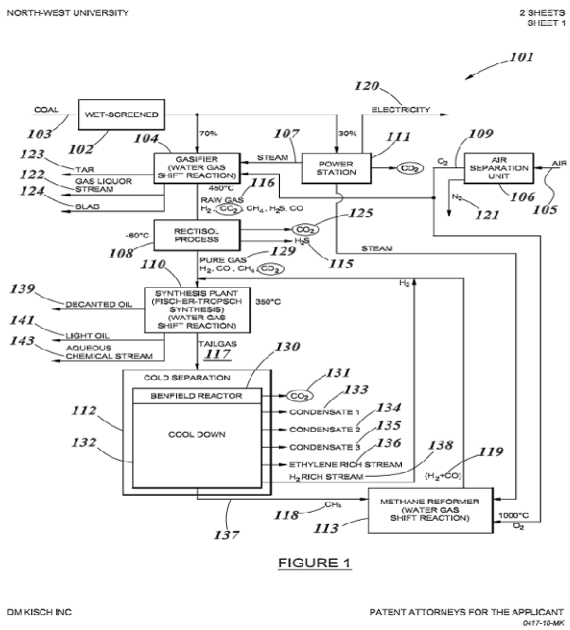

Fig. 1: CTL input/output relationships. Source: [Murray, Fick and Stoker 2010]

IV.A.3. Mass and Energy Balances

The nature of the coal-to-liquid plant is that of a continuous process (for example the supply of utilities such as steam, electricity, high temperature helium gas; or input commodities such as coal, natural gas; or intermediate process streams such as H_2, CO_2, etc.) The overall mass balance of these streams was calculated by ASPEN Plus as a mass flow rate balance in ton/hour. The annual input cost of a commodity stream was then calculated as (cost/ton)*(ton/h)*(h/year). Equally, the annual income associated with a process stream was calculated as price/ton)*(ton/h)*(h/year).

Table 1 shows CTL mass balances on business unit level, as calculated by the process model.

Table 1: Business Unit Mass Balance

Business Unit Mass Balance (all numbers in ton/hour)							
Lurgi Gasifier (LGG)				Rectisol (REC)			
Input		output		Input		output	
Coal	1442	Dry Raw Gas	2090	Dry Raw Gas	2090	Pure Gas	901
Steam	1739	Tar	35			CO2	1180
O2	486	Ash	434			H2S	9
Clarified Water	3700	Process water	4770				
		Gasification products	32				
	7367		7362		2090		2090
Sasol Advanced Synthesis (SAS)				Cold Separation Unit (CSU)			
Input		output		Input		output	
Pure Gas	901	Tail Gas	946	Tail Gas	946	Refined products	174
Reformed Gas	644	Alcohol & Ketones	32			Chemical feedstock	91
		Process water	565			Heating fuel	36
						CH4 to SMR	166
						CO2	479
	1544		1543		946		946
Steam Methane Reformer (SMR)				Steam Boiler (STB)			
Input		output		Input		output	
CH4	166	Reformed Gas	644	Coal	721	Steam	3068
Steam	356			Demin Water	3068	Ash	153
O2	121			Air	1923	CO2	1659
						Other	832
	644		644		5713		5713

The energy balance of the coal to liquid process was a challenge due to complexity and the lack of “inside” data. A top down allocation process was used in the case of electrical power. The energy balances of steam and process streams were not considered. These areas will require more detailed analysis in the future.

Table 2 summarizes the assumptions made and allocated electrical power baseline.

Table 2: Electrical Power Allocation

Electrical Distribution Systen			(EDS)		
Secunda West Plant total	650	MW			
% bought from Eskom	60%	or	390	MW	
Own generation	40%	or	260	MW	
Top-down allocation	**MW**	**%**	**alloc**	**MW**	
STB (Steam Boiler)			5.0%	15.9	2.4%
GEN (Power Station)			0.0%	0.0	0.0%
ASU (Air Separation Unit)	310	47.7%		0.0	47.7%
LGG (Lurgi Gasifier)	22	3.4%		0.0	3.4%
ASH (Ash Handling Sustem)			5.0%	15.9	2.4%
WDS (Water Distribution System)			10.0%	31.8	4.9%
REC (Rectisol Plant)			12.0%	38.2	5.9%
SAS (sasol Advanced Synthesis)			8.0%	25.4	3.9%
CSU (Cold Sepoaration unit)			25.0%	79.5	12.2%
SMR (Steam Methane Reforming)			8.0%	25.4	3.9%
PWS (Product Workup, Storage, Site & facilities)			27.0%	85.9	13.2%
	332	51.1%	100.0%	318	100%

IV.A.4. Plant overnight cost estimates

Testing and verification of the economic feasibility model showed a high sensitivity of levelized cost to the value input for overnight cost in the model. This sensitivity required particular accuracy in the allocation of overnight cost by the researchers.

Two methods were used to set overnight cost in the economic feasibility model:

i) The overnight cost of the coal-to-liquid plant was derived from published data for the planned construction on a 80,000 bbl/d green fields coal-to-liquid plant in the Waterberg area in South Africa. This project was abandoned in 2011, but its target cost of $10,000 million was revealed on several occasions by senior Sasol executives. These historic project target costs were used as basis and then projected to the economic feasibility model base-year of 2012. An additional 30% allowance was also made to compensate for the historic underestimation of overnight cost by industry. The overnight cost of the CTL facility was thus determined at $15,000 million.

Overall plant cost was subsequently allocated to business units, based on the authors’ insight into the relative complexities of the plant units. Table 3 shows the result

Table 3: Overnight Cost Allocation

Allocation of Project Overnight Cost			
			M$USD
Total project cost, 80,000bpd			15000
Project item	**%**	**%**	**M$**
Pre-project and project management	15%		2250
Construction, plant & equipment	85%		
STB (Steam Boiler)		14%	1785
GEN (Power Station)		3%	383
ASU (Air Separation Unit)		10%	1275
LGG (Lurgi Gasifier)		25%	3188
ASH (Ash Handling Sustem)		4%	510
WDS (Water Distribution System)		2%	255
REC (Rectisol Plant)		6%	765
SAS (sasol Advanced Synthesis)		7%	893
CSU (Cold Sepoaration unit)		6%	765
SMR (Steam Methane Reforming)		4%	510
PWS (Product Workup, Storage, Site & facilities)		19%	2423
		100%	15000

ii) In the case of the nuclear plant, a target range for overnight cost was deduced by parametric methods using a range of capital cost per electrical output equivalent, assuming that all thermal energy was used to generate electricity with an efficiency of 30%. For this approach the price of generated electricity was then determined with IRR-hurdle rate bounded between a minimum of 6% and a maximum of 10%.

The resulting upper bound and lower bound price of electricity was subsequently used in the economic feasibility model to determine the effect of the underlying overnight cost of the nuclear plant on the internal rate of return of the coal-to-liquid plant.

IV.A.5. Other assumptions and inputs

When data was available for commodity input prices (for example coal) this was used. In the absence of actual data, engineering judgment was used, based on the experience of team members. An example of such a "guestimate" is the maintenance cost of a gasifier unit. It is known to be high in relation to that of other units. Maintenance cost was thus attributed accordingly. Fortunately levelized cost showed low sensitivity to many of these operational costs when compared to cost drivers such as the price of input streams.

IV.A.6. Economic feasibility model validation

Model validation is vitally important, but it is a difficult problem. In the final analysis an economic feasibility model can only be validated against the actual financial performance of the plant which the model endeavors to predict. This objective was partly achieved in the case of the Secunda West Plant. Limited data is available in public domain documents such as overviews by investment analysts [Comer 2012] and the Integrated Annual Report of the Sasol Group (Sasol, Ltd. 2011). Both these sources were used to achieve at least a measure of validation.

Table 4 shows a comparison of simulation data with data obtained from the above sources.

Table 4: Plant Level Mass Balance

Plant level mass balance			
Inputs	**ton/h simulation**	**mton/Y simulation**	**mton/Y Analyst book/2**
Coal	2163	18.95	18.95
O2	2578		
Water	5795		
Total	10536		
Outputs		**kton/Y**	**kton/Y**
Refined product	209	1831	1790
Heating fuels	36	313	340
Gasification products	32	281	280
Alcohols and ketones	32	285	280
Chemical feedstocks	91	795	820
Other	9	79	80
Total saleable products	409	3583	3590
CO2	3306		
Ash	587		
Process waste water	5336		
Other	891		
Total waste streams	10121		
Proof	6		

The Analyst Book reports Synfuels turnover for FY 2012 as R48,791 million ($6,099 million) and cash operating cost as R22,114 million ($2,764 million). Cash operating margin calculates to R26,677 million ($3,335 million) thus R13,339 million ($1,667 million) for Secunda West Plant.

The above assumptions and inputs yielded an IRR of 8.1%

In a consistent model one would expect Earnings Before Interest, Taxation and Amortization (EBITA) of the respective business units, when consolidated, to yield the same IRR as reported in the above calculation, based on the Analyst Book.

EBITAs of all simulated business units are shown in table 5, included here for completeness. Note that the IRR of each BU (except Ash Handling System, ASH) satisfies the hurdle criterion (6%). All product refinement after cold separation was included in a single BU, called Product Work-up and Storage", PWS). This unit sells product over the "plant boundary" at an estimated price using price equivalence of petrol and diesel as reference. Proceeds from external sales where then scaled to yield 2012 turnover reported in the Analyst Book. The IRR of the last production step was finally calculated at 15.8%.

Note that the IRR of the consolidated EBITAs is the same as calculated using high level data as illustrated above (8.1%). Hence it may be concluded that the model delivers a consistent outcome, resulting in high confidence in the levelized cost of commodity and process streams.

Table 5: EBITA Consolidation

					EBITA Consolidation (RM). (Devide by 8 to get in M$)													
Business Unit	**IRR**	**Construction**			STB	ASU	WDS-Clfd	WDS-dem	WDS-RO	WDS-PC	GEN	ASH	LGG	REC	SAS	CSU	SMR	PWS
STB	6.0%	-3360	-6720	-6720	1537	1537	1537	1537	1537	1537	1537	1537	1537	1537	1537	1537	1537	1537
ASU	6.0%	-2400	-4800	-4800	1097	1097	1097	1097	1097	1097	1097	1097	1097	1097	1097	1097	1097	1097
WDS -Clarified	6.0%	-120	-240	-240	55	55	55	55	55	55	55	55	55	55	55	55	55	55
WDS -Demin	5.9%	-120	-240	-240	55	55	55	55	55	55	55	55	55	55	55	55	55	55
WDS -RO	6.0%	-144	-288	-288	66	66	66	66	66	66	66	66	66	66	66	66	66	66
WDS -Proc. Cooling	6.0%	-96	-192	-192	43	43	43	43	43	43	43	43	43	43	43	43	43	43
GEN	6.0%	-720	-1440	-1440	329	329	329	329	329	329	329	329	329	329	329	329	329	329
ASH	4.5%	-960	-1920	-1920	382	382	382	382	382	382	382	382	382	382	382	382	382	382
LGG	6.0%	-6000	-12000	-12000	2746	2746	2746	2746	2746	2746	2746	2746	2746	2746	2746	2746	2746	2746
REC	6.0%	-1440	-2880	-2880	654	654	654	654	654	654	654	654	654	654	654	654	654	654
SAS	5.9%	-1680	-3360	-3360	767	767	767	767	767	767	767	767	767	767	767	767	767	767
CSU	6.0%	-1440	-2880	-2880	660	660	660	660	660	660	660	660	660	660	660	660	660	660
SMR	6.1%	-960	-1920	-1920	438	438	438	438	438	438	438	438	438	438	438	438	438	438
PWS	15.8%	-4560	-9120	-9120	4291	4291	4291	4291	4291	4291	4291	4291	4291	4291	4291	4291	4291	4291
Total of BU EBITAs	8.1%	-24000	-48000	-48000	13120	13120	13120	13120	13120	13120	13120	13120	13120	13120	13120	13120	13120	13120

Where financial performance data were not available from real life plants or approximately similar real life plants, it was not possible to validate the output of the economic feasibility model.

IV.B. Results and Discussion

IV.B.1. Base-line scenario. SecundaWest Plant as is

Table 6 shows the levelized cost (LC) of commodity and process streams as calculated by the model. In this case corporate tax rate was taken as zero, resulting in pre-tax levelized costs. Note further that CO_2 taxation was taken as zero. The output reported in table 6 should be interpreted as applicable to a 80,000 bbl/d coal-to-liquid plant, with an overnight cost structure of $15,000 million and a cash operating margin exactly that reported for Secunda West Plant for Fiscal Year 2012.

Table 6: Levelized cost of process streams stated in $/ton and $/GJ

Key assumptions and EFA output report						
Key assumptions						
% CO2 taxed	0%					
IRR hurle rate	6%					
Overnight Capital cost	15000	M$				
Cost of Coal	26.375	$/ton				
Corporate tax rate	0%					
			LC			
Utilities:	40 bar steam	supplied by STB at	18.7	$/ton		
	Sasol electricity	supplied by GEN at	9.7	c/kW-h		
	O2	supplied by ASU at	74.6	$/ton		
Process:	Dry Raw Gas	supplied by LGG at	68.9	$/ton	52.3	$/GJ
	Pure Gas	supplied by REC at	168.2	$/ton	55.6	$/GJ
	Reformed CH4	supplied by SMR at	206.3	$/ton	110.0	$/GJ
	Tail Gas	supplied by SAS at	294.5	$/ton	81.3	$/GJ

It was considered informative to study the effect of cost of coal and CO_2 taxation on the economic performance of the Secunda West Plant.

CO_2 taxation was included in the model in accordance with the South African Government's proposal in this regard, namely R120/ton (15$/ton), escalating at 10% (nominal) for the next 6 years and taxed at 40% of emission level. The CO_2 emission of the Secunda West Plant was calculated at 29 million ton/annum, which is very significant. Table 7 shows the effect of various levels of taxation on the internal rate of return.

Table 7: The effect of various levels of CO_2 taxation on the internal rate of return of Secunda West plant.

Sensisitivity to CO2 taxation	
Taxation level	IRR
0%	8.1%
20%	7.3%
40%	6.5%

Although not negligible, the impact of CO_2 taxation on economic performance is not the controlling factor. Table 8 shows investment performance as a function of coal price. A coal price set at 80% of the Free on Board (FOB) export price resulted an in an internal rate of return well below the hurdle rate.

Table 8: Secunda coal-to-liquid internal rate of return as a function of coal price

Sensitivity to coal price	
Coal price %FOB	IRR
33% ($26.4/ton)	8.1%
40% ($32/ton)	7.3%
80% ($64/ton)	1.9%

It is concluded that at the current market price of coal, and given the high cost of capital, it would be more economical for Sasol to export its coal reserves (pending quality) than to try to add value to it by converting it to fuel and chemicals. This finding is perhaps not a surprise, since approximately 66% of the carbon content of coal is converted to CO_2 in the current coal-to-liquid process.

It is further concluded that, for a future coal-to-liquid project to be viable from an economic point of view, the carbon to product conversion will have to be drastically improved. Nuclear energy, combined with a number of alternative process options may show the way. Studies on advanced process options and their nuclear coupling schemes will be studied as part of the NC2I-R project. (Nuclear Co-generation Industrial Initiative)

IV.B.2. HTR "plug-and-play" building block

The HTR plug-and-plug building block used in the economic feasibility model, is based on the following assumptions:

- Two Nuclear Steam Supply Systems (NSSS) (4 reactors) configured to produce 175 MW per NSSS, 350 MWe in total [Freis 2013]
- Three overnight capital cost cases were calculated, namely 4000 $/kWe, 5000 $/kWe and 6000 $/kWe
- Fuel cost was taken as 1$/GJ
- Alternative internal return hurdle rates for the project were taken as 6% and 10%
- All-in operating cost excluding fuel cost was taken at 10% of overnight cost

An upper and lower bound of the nuclear electricity supply to a CTL plant was thus established. Figure 2 shows the results.

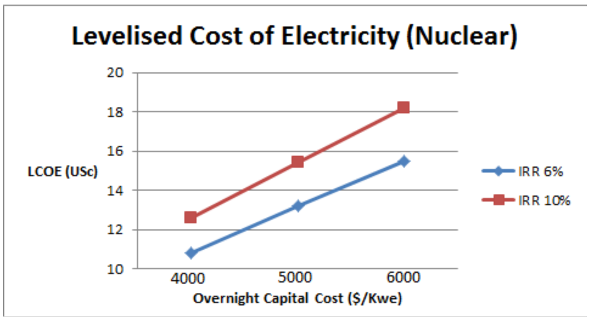

Fig.2: Levelised Cost of Electricity (Nuclear)

IV.B.3. Scenario S1a. Substitute grid electricity with HTR-electricity

With the range of LCOE(Nuclear) defined, the question to be answered is how will this affect the internal rate of return of the coal-to liquid plant?

Table 10 shows the results of the following three calculations:-

- Baseline case, Eskom power at 45c/kW-h (5.6 USc/kW-h)
- Lower value of nuclear electricity at 87c/kW-h (10.9 USc/kW-h)
- Higher value of nuclear electricity at 145c/kW-h (18.1 USc/kWh)

Table 9: Electricity Price Sensitivity

Power scenario		Cost of O2	CTL plant IRR
From	c/kW-h	$/ton	%
Eskom	5.6	72.5	8.1%
Nuclear low	10.9	90.9	6.8%
Nuclear high	18.1	113.5	4.8%

The internal rate of return of the coal-to-liquid plant showed remarkably high sensitivity to the cost of electrical energy. The primary mechanism for this was the energy intensity of oxygen produced by the air separation unit (ASU) which is stated to use approximately 50% of the plant's electrical energy.

It is noted here that the Eskom price is not cost reflective. Consequently NERSA (National Energy Regulator of South Africa) has allowed Eskom to escalate its prices in real terms for the foreseeable future. It is stated in the Sasol Integrated Annual Report that the company has launched a drive to produce its own electricity from natural gas. Considering the high sensitivity of internal rate of return to electrical energy costs, shown in table 10, this initiative appears to be well founded.

Scenario S0 calculated Sasol's cost to produce its own electricity by burning coal fines at 77c/kWh (9.6USc/kWh), excluding CO_2 taxation. This relatively high value is mainly due to low efficiency associated with small unit size and old generation generators currently employed by Sasol. When compared to Eskom's 45c/kWh [2012] (5.6USc/kWh), it must be born in mind that Eskom's selling price was not fully cost reflective.

It is unlikely that Sasol will opt to generate its own electricity from burning coal fines in a future scenario where nuclear could possibly be employed. It is therefore likely that a nuclear supported 80,000 bbl/d coal-to-liquid process would require approximately 650 MWe, assuming no change to the baseline process.

IV.B.4. Scenario S1b. Scenario S1a + Substitute coal steam with HTR-steam

In S1b the Steam Boiler Plant (STB) was eliminated. 40 bar steam was purchased from a nuclear cogeneration facility. The following assumptions were applied:

- Eight Nuclear Steam Supply Systems (NSSS) (16 reactors) configured to produce 350 MW electrical power (scenario S1a) and 3600 ton/hour steam at 40 bar and 450C.

- Three overnight capital cost cases were calculated, namely 3000 $/kWe, 4000 $/kWe and 5000 $/kWe. For the purpose of calculating overnight cost, it was assumed that a pair of reactors produces the equivalent of 175MWe. For example: 3000 $/kWe yielded a nuclear plant (16 reactors) overnight cost of $4200 million.
- Fuel cost was taken as 1$/GJ.
- IRR hurdle rate for the nuclear project was taken as 6%.
- All-in operating cost excluding fuel cost was taken at 8% of overnight cost, taking advantage of the economy of scale of this scenario compared to S1a.
- Coal fines not utilized in the steam boilers, were sold in the market by the coal-to-liquid plant at 80% of FOB price. The price was set to take account of the lower grade of the coal produced by SASOL Mining.
- The coal-to-liquid overnight cost was reduced by the overnight cost of the Steam Boiler ($1,785 million). Associated operational cost was set to zero in the model.

Table 10 shows the relationship between nuclear plant overnight cost and the prices which the nuclear plant owner would charge to obtain an internal rate of return of 6% on the investment made into the plant.

Table 10: Steam and Electricity pricing scenarios

Equivalent $/kWe	Selling price which yields N-IRR=6%	
	Steam ($/ton)	Electricity (c/kW-h)
3000	23.9	7.8
4000	30.4	9.9
5000	36.9	12.0

The above utility prices were subsequently used to calculate the IRR of the investment in the CTL plant. (Note: selling prices of N-steam and N-electricity such that the nuclear plant's IRR=6%). It is clear from Figure 3 that if the overnight cost of the nuclear plant exceeds 3400$/KWe, it would jeopardize the return on the investment made in the CTL plant.

CO_2 emission of this configuration was calculated at 14.2 million ton/Y, while the emission of the baseline case was 29 million ton/Y. This represents a saving in CO_2 emission of 51% compared to the baseline case.

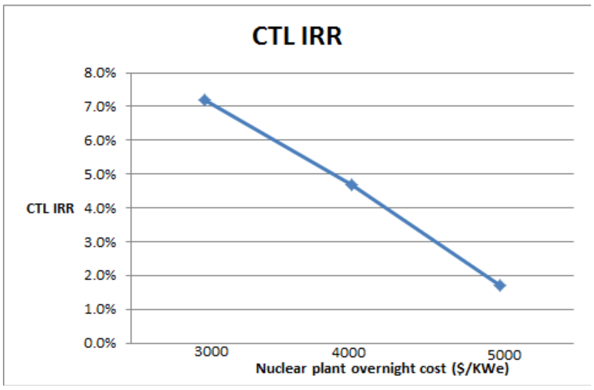

Fig.3: Coal-to-liquid IRR Sensitivity

V. CONCLUSION

The study has reached the following conclusions:

In respect of CTL:

It is concluded that at the current market price of coal, and given the high cost of capital, it would be more economical for Sasol to export its coal reserves (pending quality) than to try to add value to it by converting it to fuel and chemicals.

It is further concluded that, for a future coal-to-liquid project to be viable from an economic point of view, the carbon to product conversion will have to be drastically improved. Nuclear energy, combined with a number of alternative process options may show the way.

In respect of Nuclear CTL

It is concluded that the economic feasibility challenge for large scale deployment of nuclear energy in a Coal-to-Liquid application - where steam and electricity are to be generated from nuclear energy, is to construct such a facility at an all -inclusive overnight cost not exceeding $3400/kWe.

When steam and electricity from coal is replaced by nuclear steam and electricity, the CO_2 footprint of the conventional CTL plant is reduced by 51%

VI. REFERENCES

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