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# Coupling a Nuclear Energy Source to a Coal to Liquid Process SASOL Secunda as a case

Authors : STOKER Piet (NWU) , Noordwes Universiteit

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EC Scientific Officer: Dr. Panagiotis Manolatos

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**Summary**

This report presents various technical scenarios and supporting techno-economic analysis whereby the merits are discussed of coupling a High Temperature Co-generation Reactor to a Coal-to-Liquid process in South Africa.

Approval

| Date | By |
|---|---|
| 29/01/2015 | Greg KELSALL |
| 29/01/2015 | Ferry ROELOFS |
| 29/01/2015 | Steven KNOL |

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# 1. *Executive Summary*

This document reports on the deliverables by the South African team on the ARCHER research project.

The objective of the research was to demonstrate the possible technical and economic viability of the concept of introducing nuclear energy into the SASOL Coal to Liquid process.

The concept was driven by the researchers' perceived need for SASOL to reduce the very heavy carbon footprint of their Coal To Liquid process.

This report describes various technical scenarios and supporting techno-economic models whereby the financial merits of each scenario were quantified.

The overall conclusion reached is that introducing nuclear energy into the SASOL Coal To Liquid process faces serious economic challenges regarding the capital cost of such a venture.

These challenges are compounded by the safety and licensing challenges of building and operating a nuclear plant in the close proximity of a petrochemical plant.

One of the most important outcomes of this work has been to independently benchmark the existing SASOL techno-economic model.

This will provide the research team the future opportunity to create and test the financial viability of various innovative process schematics. These will be the subject of further research under the follow up to the ARCHER project, the NC2I-R project.

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## 5. Nomenclature and definitions

| | |
|---|---|
| ARCHER project | Advanced Reactor for Cogeneration of heat and Electricity- R&O |
| Billion | $10^9$ |
| bbl/d | Barrel per day ( oil) |
| CTL | Coal-to-liquid |
| DST | Department of science and technology |
| EBITA | Earnings before interest tax and amortisation |
| EUROPAIRS project | End user requirements for industry process heat applications with innovative nuclear reactors for sustainable energy supply |
| EFM | Economic financial modelling |
| ESKOM | The South African state owned electricity utility |
| ESASTAP | European South African Science and Technology Advancement Programme |
| FT | Fischer Tropsch |
| GTL | Gas-to-Liquid (Fuel) |
| HTR | High temperature (gas cooled nuclear) reactor as defined for the ARCHER project. Westinghouse 530MWth |
| HyS | Hybrid Sulphur (thermochemical water splitting process) |
| IRR | Internal rate of return |
| KPI | Key performance indicator |
| Million | $10^6$ |
| NC2I-R project | Nuclear Cogeneration Industrial Initiative – Research |
| NIL | Nuclear installation license (obtained from the NNR) |
| NNR | National nuclear regulator (the regulating body in RSA) |
| NWU | North-West University (Republic of South Africa) |
| PBMR | Pebble Bed Modular Reactor (Pty) Ltd |
| RSA | Republic of South Africa |
| SSF | SASOL Synthetic Fuels (Comprising an East and West plant, situated at Secunda in the province of Mpumalanga South Africa) |
| SWP | Secunda West Plant (the case plant for this research) |
| R | South African Rand (ZAR) |

## 6. *Introduction to the Archer Project*

This document serves to report the work and deliverables which the RSA team contributed to the ARCHER project.

The objective of the South-African project 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".

The contribution by North-West University (NWU) to the ARCHER Sub-project 1 (SP1 System Integration) was contracted on the following tasks:

- 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

The case study project was modelled on the Sasol Secunda (West Plant), with a capacity of approximately 80,000 barrels synthetic crude per day.

South Africa, being a signatory of 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. In fact it was argued at the EUROPAIRS-I public information meeting that at the 60 million tonnes of $CO_2$ per annum, emitted by Secunda constitutes approximately 50% of the total $CO_2$ emission of the EU (30 countries) from burning natural gas.

The total NWU-Archer project value was determined at R2.5m (approximately 300,000 Euro). South Africa's Department of Science and Technology contributed 80% of project funding under the ESASTAP program and NWU the balance.

The project start date was January 2012 and end date December 2013.

## 7. *Background to the South African involvement in the ARCHER project*

South Africa's endeavours to develop a first-of-a-kind HTR (the PBMR) are well known. The project was abandoned at the time when the EUROPAIRS project was initiated. (EUROPAIRS: End-User Requirements industrial Process heat Applications with Innovative nuclear Reactors for Sustainable energy supply). PBMR consequently decided to withdraw from the project and requested NWU to take over its obligations.

It took some time for the NWU team to come on stream. As a result it was not feasible for the University to make a proposal to the ARCHER team for South Africa's participation. However this was done in 2011, when it became apparent that the South African team was in a position to make a valuable contribution to ARCHER's SP1.

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 the ARCHER 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".

## 8. *Task 1.1.2 Definition and application of key performance indicators*

As a starting point for this task NWU postulated that the two key performance indicators that were judged to be of cardinal importance in the roll-out of a nuclear supported coal-to-liquid process would be:

a) The internal rate of return (IRR) of such a project; and

b) The reduction in $CO_2$ emission that such a solution should result in to attract serious interest from SASOL.

Although conceptually simple, these two key performance indicators were the drivers of the coupling scenarios envisaged for this research. Consequently it was necessary to define a progressive set of coupling scenarios, building one upon the other, contributing stepwise to $CO_2$ reduction in a logical fashion, and always being subject to achieving the target internal rate of return.

Operating values for the abovementioned two postulated key performance indicators in the present research, were derived through industry and academic judgement, and verified in informal discussion with senior ex- employees of SASOL.

Thus 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%

These modelling scenarios are discussed in more detail in the following section 9.

The approach taken by NWU in the scenario definition and the subsequent research execution also took the following strategic issues into consideration:-

- License-ability
- Technical feasibility
- Time-to-market
- Social & environmental responsibility
- Efficiency
- Cost effectiveness
- Capex, risk and return on investment aspects
- Issues relating to business strategy

## 9. *Task 1.1.3 Elaboration of schematics and case studies*

The bulk of NWU's contribution to the ARCHER project lay in Task 1.1.3. This report documents the inputs made to the ARCHER team at the SP1 meeting in April 2013.

This document further reports the progress in respect of Task 1.1.3 that the RSA-team has made since April up to end November 2013.

### 9.1. Introduction to case study, links to key performance indicators and modelling scenarios

From a techno-economic feasibility point of view, two views were contemplated for this task:-

- The view for substituting nuclear heat and/or electricity in the existing coal-to-liquid process at Secunda and;
- The view for utilising nuclear heat and/or electricity in a greenfield coal-to-liquid project.

In the first case 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. These process gains were traded off against the economic feasibility to gauge the viability of the modelled changes.

In the second case it was appropriate to take a "fresh look" at the existing process, to conceptualize innovative ways to couple nuclear energy to the coal-to-liquid process in an endeavour to drastically increase the overall carbon efficiency, if retrofitting the solution to the existing SASOL plant was considered impractical. The possible outcome of this view, could result in the concept for a future greenfield project.

Striving to achieve maximum flexibility in the analysis approach, the South African team implemented a modelling strategy whereby a baseline for the existing Secunda coal-to liquid operation was created 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 a "business unit" were "sold" on to the receiving business unit, priced on the basis of achieving the minimum hurdle internal rate of return discussed in section 9.3.1. Where applicable, emission incentives, penalties or the "polluter pays" principle embedded in South Africa's environmental legislation were applied to the "seller".

The following "plug-in" building blocks were defined for development:

- HTR optimised for electricity production*
- HTR optimised for steam and electricity production*
- HTR optimised for electrochemical water splitting*
- Electrochemical water splitting model[#]
- Lean gasification model*

- Plasma arch reforming (PAR) model#
  * Completed under the ARCHER project
  # Ongoing for completion under the NC2I-R project

This strategy was adopted to allow ongoing “plug and play” modelling scenarios by arranging the “plug-in” building blocks in the various conceptualised process configurations as envisioned in the planned modelling scenarios.

The modelling results for the following coupling scenarios are reported on in this document:-

- Scenario S0 - The existing Secunda west plant (SWP) as a baseline case.
- Scenario S1a - The existing Secunda west plant with external ESKOM electricity replaced by nuclear electricity from high temperature gas cooled nuclear reactors.
- Scenario S1b - The existing Secunda west plant 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.

These scenarios are illustrated in simplified flow diagrams in appendix 2.

A number of advanced coupling scenarios were further identified for future investigation and were developed in a logical progression with the addition of plasma arc reforming and thermo-chemical water splitting and exploring the application of $CO_2$ lean gasification.

The main ambit of the advanced scenarios is described section 9.4 and further illustrated in simplified process diagrams in appendix 2

## 9.2. Process Modelling Approach

### 9.2.1. High temperature gas cooled nuclear process heat and power plant simulation model

The Nuclear team of the South African ARCHER group was tasked to develop a model for a combined Process Heat and Power Plant (PHPP) to integrate with a typical Fischer-Tropsch coal-to-liquid plant. This plant is based on the Sasol Synfuel operation in Secunda.

The PHPP layouts were based on combined gas cycle (Brayton cycle) and steam cycle (Rankine cycle). The layouts included circulators, steam generators, pumps, turbines and heat exchangers. The choice of the best PHPP layout for the scenario was based on the requirement of the coal-to-liquid plant as well as sound engineering judgment and principles. This plant was then modelled in Engineering Equation Solver (EES) using the network simulation approach.

The network simulation approach makes use of a collection of one-dimensional elements connecting nodes in any unstructured manner. The elements can be any type of thermal-fluid component such as a pipe, pump, circulators, turbine etc. The various elements are based on four fundamental types of equations in order to be properly formulated. These are:

- Conservation laws: Mass, momentum (and angular momentum) and energy.

- Component characteristics: Heat transfer rates, pressure drops, compressor and turbine pressure ratios, etc.

- Fluid properties: Thermodynamic property tables, gas laws, etc.

- Boundary values: Temperatures, pressures, mass flows of the ARCHER nuclear reactor and coal-to-liquid plant requirements as defined by the NWU-ARCHER group.

The next phase of the project, included in the NC2I scope, will be to develop a Flownex model of the PHPP. The Flownex models will then be extended to include transients from the coal-to-liquid plant. These transient conditions will all include the complete loss of turbine load and typical ESKOM load-following transient.

### 9.2.2. Coal-to-liquid process simulation model

The Sasol Synfuels operations in Secunda, Mpumalanga was used as the basis for developing a base case scenario as this is the only industrial scale Fischer-Tropsch coal-to-liquid plant currently in operation. Although open literature on the Secunda operations is limited, appropriate assumptions were made in the simulation to ensure the results and operating conditions are logical and confirmable where possible. A plant with 40 fixed bed gasifiers was simulated. A typical coal to liquids processing plant was simulated with the help of a 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 section with most of the basic utilities included. The simulation also included a fixed bed coal gasification, Rectisol gas clean-up and Fischer-Tropsch hydrocarbon synthesis section. The Soave-Redlich-Kwong (SRK) equation of stage with Kabadi-Danner (KD) modifications for water-hydrocarbons systems was used as property package for the base case simulation. A typical Mpumalanga -highveld coal with an ash content of 30% was chosen as feedstock for the gasification and steam boiler simulation. In the Sasol plant fixed bed coal gasification was used and the gasification section was simulated to mimic this process. Anderson-Schulz-Flory distribution was assumed to provide a sensible product spectrum for the Fischer-Tropsch reactors. For the FT reactor the Anderson-Schulz-Flory α-value is usually limited to <0.71, with 0.67 a standard modelling value for HTFT with fused-Fe catalyst. The simulation results showed good correlation against process information that was available in published data.

#### 9.2.3. Low $CO_2$ gasification simulation model

In theory the Lurgi gasification could be run in a low $CO_2$ mode by reducing the steam input, but in practice, operating the moving-bed gasifier under the steam-lean regime may be difficult to implement without affecting overall gasifier operability. A steady-state simulation of a conventional syngas production facility based on Shell coal gasification technology was performed using Aspen Plus®. The simulation was used to generate mass balances, which will be used in subsequent economic feasibility modelling.

The input parameters needed to model the reference syngas plant performance were based on various baseline study reports and operational data of commercially operated Shell-gasifier based coal-fired IGCCs'. In order to predict the behaviour of the different components within the syngas plant, appropriate thermodynamic models were used. The Soave-Redlich-Kwong equation of state with Kabadi-Danner mixing rules (SRKKB) was the recommended thermodynamic model for conventional components. The heating values, enthalpies and densities of the nonconventional components (coal and ash) were determined in AspenPlus® using HCOALGEN and DCOALIGT models. The holistic approach entailed three steps: (1) decomposition of coal; (2) conversion of elements to gas-phase components; and (3) equilibration of the gas-phase components. This modelling approach of the gasification facility yielded results comparable to typical syngas composition values.

#### 9.2.4. Thermo-chemical water splitting simulation model

The chemical engineering team of the SA ARCHER group was tasked to develop a Hybrid Sulphur Cycle (HyS) process model that could be integrated with both the Fischer-Tropsch coal-to-liquid process and PHPP-process for different case studies. The HyS-process was simulated by using Aspen Plus. The Soave-Redlich-Kwong equation of stage and ELECTNRTL were used as property package for the base case simulation. The simulation included a sulphuric acid decomposition reactor unit, electrolyser unit, various separation units and power generation and heat source section.

### 9.3. Economic feasibility modelling approach.

The approach to economic feasibility modelling (EFM) was determined by the application of the key performance indicators identified in task 1.1.2. Consequently the internal rate of return (IRR) had to be calculated for the investments associated with the modelling scenarios listed in paragraph 9.1.

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.

In the case of this research, the following modelling approach was followed:-

### 9.3.1. Internal rate of return - hurdle rate, risk and levelized cost

Project overall risk is accounted for by the hurdle internal rate of return (6% in this case). It 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 a widely acknowledged as a sound way of comparing the economic merit of alternative candidate technologies.

In the ARCHER economic feasibility modelling approach the hurdle internal rate of return was set at 6% and then the levelized cost was calculated for the utility/process stream that would deliver a return to meet the hurdle internal rate of return. The levelised cost, thus calculated, was in effect the "selling" price of the utility/process stream to the next process "business unit". The requirement was to calculate levelized cost in current value of money, using current cost data as input.

It can be noted here that the internal return hurdle rate is a strong driver of levelized cost.

### 9.3.2. Mass and energy balances

Since 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, etc.) it was imperative that an overall mass balance be established as input to economic feasibility model. This was achieved in terms of a mass flow rate balance in tons/hour. The annual input cost of a commodity stream can then be calculated as (cost/ton)*(ton/h)*(h/year). Equally, the annual income associated with a process stream can be calculated as (price/ton)*(ton/h)*(h/year).

The methods that were used to calculate the overall mass balance for each of the modelling scenarios are discussed in section 9.4.

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.

### 9.3.3. Plant comprises 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 that was followed was to identify the physical battery limits of plant units. Input streams to and output streams from these units were then determined. Engineering judgement 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. An example of such a minor input/output stream was instrument air.

### 9.3.4. The approach for plant overnight cost estimates

The Secunda plant was constructed in the eighties. Overnight cost structures of that era were of no practical use for estimating plant overnight cost for this study in 2012 monetary value. Therefor methods had to be devised to estimate overnight cost of plant equipment (and construction) for both the coal-to-liquid plant and other "building blocks", such as the nuclear cogeneration plant.

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. This project was abandoned in 2011, but its target cost of R80 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 under-estimation of overnight cost by industry.

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 internal rate of return- 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.

#### 9.3.5. 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 judgement 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.

#### 9.3.6. Economic feasibility model validation

Model validation 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 endeavours to predict. This objective can be achieved to some extent in the case of the coal to liquid business, since it is actually in operation in South Africa. Limited data were available in public domain documents such as overviews of investment analysts and the Integrated Annual Report of the Sasol Group. Both these sources were used to achieve at least a measure of validation.

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.

The approach planned by the team in the case of the nuclear cogeneration plant, plasma arc reforming and thermo-chemical water splitting building blocks, will be to follow a next best approach. Here sensitivity analysis will be conducted on those inputs which are known to exhibit high sensitivity to levelized cost.

### 9.4. Modelling Scenarios

In this section a more detailed description is given of the modelling scenarios addressed in the reported research, as well as the future planned modelling scenarios which will be addressed in the follow up NC2I-R project, in which the RSA team has been included to participate, and continue this work.

#### 9.4.1. Scenario S0 - SASOL Secunda west plant-base case

The theme of this scenario was the existing SASOL coal-to-liquid process at Secunda.
A high level, simplified schematic of the existing SASOL – coal to liquid process may be seen in Appendix 2. This is supplemented with a diagram from a provisional patent by the authors, which exhibits the nomenclature for the various process streams.

#### 9.4.2. Scenario S1 - Introduction of nuclear cogenerated steam and electricity.

The theme of this model was the stage-wise introduction of nuclear cogenerated steam and electricity.

Scenario S1a - The external electricity supply from the utility ESKOM was eliminated by the application of nuclear generated electricity

Scenario S1b - This scenario built on S1a by also eliminating the coal fired cogeneration plant with nuclear cogeneration plant.

The above mentioned scenarios where studied in detail and a comprehensive financial feasibility model was constructed for each.

In the following sections a description is given for a number of scenarios that where visualised and documented in the course of the present reseach project, with the aim of completing the detail financial feasibility modelling for each in the follow up NC2I-R project.

#### 9.4.3. Scenario S2 - Plasma arc reforming to replace steam methane reforming

The main theme of this scenario is to replace steam methane reforming with plasma arc reforming of methane and $CO_2$. This would allow the introduction of nuclear derived energy into the process, the saving of valuable methane normally consumed to combustion in auto-catalytic steam methane reforming, and the recovery of $CO_2$ as a valuable feedstock in the form of CO and $H_2$ .

Two implementation stages are contemplated for modelling:-

Scenario S2a – Implemented plasma arc reforming on top of S1a with minimal changes to the rest of the plant.
This scenario sees the replacement of imported electricity from ESKOM with HTR co-generated electricity. This HTR co-generated electricity is used to co-reform methane in the stream from cold separation together with $CO_2$ recovered from Rectisol and Cold Separation. See appendix 2 for a simplified process diagram.

Scenario S2b – Will implemented plasma arc reforming with additional changes to the plant.
This scenario built on scenario S2a above by additionally replacing the coal fired steam boilers with nuclear co-generated steam and electricity.

### 9.4.4. Scenario S3 - Eliminate the air separation unit with thermo-chemical water splitting.

This scenario will build on scenario S2b with the addition of producing the $O_2$ for gasification by thermo-chemical water splitting driven by high temperature nuclear reactor (HTR) generated process heat and co-generated electricity.

### 9.4.5. Scenario S4 - $CO_2$ lean gasification

The main theme of this scenario is to limit the quantity of $CO_2$ produced during gasification, by limiting the introduction of steam in the gasifiers. The resultant lack of a sufficiently high H:CO ratio will be corrected with externally produced $H_2$ .

Three implementation stages are contemplated for modelling:-

Scenario S4a - In this scenario the Lurgi gasifiers are operated at conditions favouring the production of CO at the expense of $H_2$ production. The required $H_2$ is produced in the plasma-arc reforming of methane and $CO_2$ in place of steam methane reforming.

Scenario S4b - In this scenario the Lurgi gasifiers are replaced with Shell Slagging Gasifiers (SSG). The air separation unit (ASU) is replaced with thermo-chemical water splitting (TWS). The $H_2$ required to adjust the H:CO ratio is produced as a by-product of $O_2$ production in the thermo-chemical water splitting process. Plasma arc reforming recovers CO from $CO_2$ and produces additional $H_2$.

Scenario S4c - This scenario builds on the previous two by the elimination of the coal fired cogeneration plant with nuclear steam and electricity, and the gasification of all the coal feed in the Shell Slagging gasifiers.

## 10. Results for modelling scenarios : S0, S1a and S1b

This section reports the results obtained for the scenarios that were concluded during this phase of the project.

## 10.1. Scenario S0. Baseline - Existing Secunda West Plant

### 10.1.1. Plant level mass balance

Figure 1 shows the simulated plant level mass balance for the Secunda West Plant. Also shown is the actual reported production output of Sasol Synfuels, 2012. (Analyst Book 2012. www.sasol.com)

The simulation results show excellent correlation with actual production output as reported in the Analyst book.

| 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 | | |

**Table 1 Simulated plant level mass balance of the Secunda west plant**.

### 10.1.2. Mass balance and stream prices per business unit

Commodity input/output balances were calculated for the following business units, using the ASPEN simulation software:

- **Utilities:** Steam Boiler (STB), Power Station (GEN) and Air Separation Unit (ASU)
- **Process:** Gasification (LGG), Rectisol (REC), Sasol Advanced Syntheses (SAS), Cold Separation Unit (CSU) and Steam Methane Reforming (SMR)

**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 |

**Table 2 Simulated mass balances of the Secunda west plant business units**.

### 10.1.3. Capital and operational cost estimates

Overnight capital cost (in 2012 Rand value at R8/USD) for an 80,000 bbl/d plant was assumed to be R120 000 million. (See section 9.3.4 for method).

Table 3 shows how the total overnight cost was allocated to the above business units and other accounts. The allocation was made using engineering judgement after consultation with senior ex-employees of SASOL.

| Allocation of Project Overnight Cost | | | |
|---|---|---|---|
| | | | Rm |
| Total project cost, 80,000bpd | | | 120000 |
| **Project item** | **%** | **%** | **Rm** |
| Pre-project and project managemer | 15% | | 18000 |
| Construction, plant & equipment | 85% | | |
| site works and facilities | | 9% | 9180 |
| STB (Steam Boiler) | | 14% | 14280 |
| GEN (Power Station) | | 3% | 3060 |
| ASU (Air Separation Unit) | | 10% | 10200 |
| LGG (Lurgi Gasifier) | | 25% | 25500 |
| ASH (Ash Handling Sustem) | | 4% | 4080 |
| WDS (Water Distribution System) | | 2% | 2040 |
| REC (Rectisol Plant) | | 6% | 6120 |
| SAS (sasol Advanced Synthesis) | | 7% | 7140 |
| CSU (Cold Sepoaration unit) | | 6% | 6120 |
| SMR (Steam Methane Reforming) | | 4% | 4080 |
| Product Workup Systems (PWS) | | 10% | 10200 |
| | | 100% | 120000 |

**Table 3 Allocation of overnight cost to major business units and project accounts**

The economic feasibility model further required inputs relating to operating costs. A figure of R22,114 million as total operating cost for the whole Secunda plant was available from the Analyst Book. Therefor R11,057 million was allocated for Secunda west plant. A confidential analyst report set material cost at 39.1% of cash cost, (or R4 323 million for west plant). Cost of coal was derived from the Analyst Book at R211/ton. The balance of material cost was attributed to cost of Sasol Advanced Synthol catalyst.

Water usage by Synfuels is stated in the Sasol Integrated Annual Report reported at 88.4 $Mm^3$. At R4/m3 (approximate Rand Water bulk tariff, 2012), the water cost for West Plant was derived at R177 million.

Sasol Synthetic Fuels (SSF) employed an average of 5554 persons during 2012. An estimated average cost-to-company of R350 000 put salary cost at R1 944 million, so R972 million was allocated for West Plant in the model.

Average Eskom electricity import by Synfuels for the base year was estimated at 750 MW. Sasol imported part of its electricity from Eskom. At an assumed average cost of 45c/kWh the annual cost of electricity was estimated at R1 443 million for the West Plant.

Plant and equipment maintenance cost was assumed to be 1.5% of plant and equipment overnight cost.

A factory overheads provision was budgeted at R600 million. This provided for security services, fire services, administrative expenses and other expenses.

Finally the balance of operating cost was calculated, using Analyst Book data as the true operating cost. Thus the balance of R1 718 million was attributed as Synfuels' contribution to Sasol's corporate overhead expenses.

The above accounts were subsequently allocated to business units (BU's) either directly when a particular cost was uniquely attributable to a specific BU, or proportional to the estimated overnight capital cost of the BU as per table 3 above. Although most of the above allocations are based on the authors' engineering judgement, the total operating cost was an accurate figure. The results are shown in table 4 below

| Cost recon to Analyst Book and allocation to Business Units | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| vs. Analyst Book | Material | | Operating cost | | | | | | | | |
| | 4,323 | | 6734 | | | | | | | | |
| | Material | | Manpower | Electricity | Water | Maintenace | O/heads | other | sub-total | Balance to | Total |
| | Coal | Other | | 45 | | | | | | Corporate | |
| | | | | 390 | | 1.50% | | | | Overhead | |
| Estimate (MR/Y) | | | 972 | 1537 | 177 | 1530 | 600 | 200 | 5016 | 1718 | |
| **Allocation to BUs** | | | | | | | | | | | |
| STB (Steam Boiler) | 1,333 | | 136 | 38 | | 214 | 84 | 28 | | 241 | 2073 |
| GEN (Power Station) | | | 29 | 0 | | 46 | 18 | 6 | | 52 | 151 |
| ASU (Air Separation Unit) | | | 97 | 733 | | 153 | 60 | 20 | | 172 | 1235 |
| LGG (Lurgi Gasifier) | 2,666 | | 243 | 52 | | 383 | 150 | 50 | | 429 | 3973 |
| ASH (Ash Handling Sustem) | | | 39 | 38 | | 61 | 24 | 8 | | 69 | 238 |
| WDS (Water Distribution System) | | | 19 | 75 | 177 | 31 | 12 | 4 | | 34 | 352 |
| REC (Rectisol Plant) | | | 58 | 90 | | 92 | 36 | 12 | | 103 | 391 |
| SAS (sasol Advanced Synthesis) | | 325 | 68 | 60 | | 107 | 42 | 14 | | 120 | 736 |
| CSU (Cold Sepoaration unit) | | | 58 | 188 | | 92 | 36 | 12 | | 103 | 489 |
| SMR (Steam Methane Reforming) | | | 39 | 60 | | 61 | 24 | 8 | | 69 | 261 |
| Product Workup Systems (PWS) | | | 185 | 203 | | 291 | 114 | 38 | | 326 | 1157 |
| | 3998 | 325 | 972 | 1537 | 177 | 1530 | 600 | 200 | | 1718 | 11057 |
| | | | | | | | | | | Proof | 0 |

**Table 4. Cost allocation to business units and reconciliation with the SASOL analyst book.**

### 10.1.4. Electrical energy balance

There were insufficient data available in the public domain to estimate the electrical energy requirements of the business units from the ratings of equipment items.

The air separation unit (ASU) is known to use almost half of the plant's electricity. Kruger 2003, estimated the electrical energy requirements of cold separation plants. In his Masters dissertation the author uses Sasol Secunda plant as case study, reporting ASU specific energy between 0.66 and 0.74 KW-h/Nm3. The numbers used in this analysis yielded a specific energy of 0.73 KW-h/Nm3.

Table 5 shows how the total electrical energy usage of Secunda West Plant, estimated at 650 MW, was allocated to the different business units (BUs) using engineering judgement.

| | | | | | |
|---|---|---|---|---|---|
| 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) | | | 5.00% | 15.9 | 2.4% |
| GEN (Power Station) | | | 0.00% | 0.0 | 0.0% |
| ASU (Air Separation Unit) | 310 | 47.7% | | 0.0 | 47.7% |
| LGG (Lurgi Gasifier) | 22 | 3.38% | | 0.0 | 3.4% |
| ASH (Ash Handling Sustem) | | | 5.00% | 15.9 | 2.4% |
| WDS (Water Distribution System) | | | 10.00% | 31.8 | 4.9% |
| REC (Rectisol Plant) | | | 12.00% | 38.2 | 5.9% |
| SAS (sasol Advanced Synthesis) | | | 8.00% | 25.4 | 3.9% |
| CSU (Cold Sepoaration unit) | | | 25.00% | 79.5 | 12.2% |
| SMR (Steam Methane Reforming) | | | 8.00% | 25.4 | 3.9% |
| PWS (Product Workup, Storage, Site & facilities) | | | 27.00% | 85.9 | 13.2% |
| | 332 | 51.08% | 100.00% | 318 | 100% |

**Table 5. Allocation of the total electricity energy of Secunda West Plant to the various business units.**

### 10.1.5. Economic performance results

A simplified method was used to validate the levelized cost calculations presented in section 10.1.5.3 below as follows:

1. Cash generated in Financial Year 2012 from Secunda West Plant operations was obtained from data presented in the Analyst Book. This was assumed to be (cash) earnings before interest, tax and amortization (EBITA).
2. Table 1 (section 10.1.1) shows that the mass balance for Secunda West Plant was very close to the product mass sold in 2012.
3. The external selling prices of products were estimated 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.
4. Overnight Capital Cost was assumed to be R120 000 million expended over an optimistic three year construction period. (20%, 40%, 40%).
5. The EBITA for 2012 was assumed to be constant for the next 20 years, the latter being the time period for calculating project IRR. A zero end value was assumed. This approach was followed for all instances to calculate all IRR's.
6. The EBITA of all Business Units were subsequently consolidated. See 10.1.5.2. In a consistent economic model, consolidation has the effect of cancelling all internal sales i.e. sales between Business Units. Hence the aggregation of the EBITA of all BU's should reveal the EBITA of Secunda

West Plant as calculated in 10.1.5.1, and of course a consistent plant level IRR.

7. With the economic modelling algorithm validated, the levelized cost that yields the pre-determined IRR was calculated for of each of the utilities and process streams. See section 10.1.5.3.

#### 10.1.5.1. Secunda West Plant internal rate of return

The Analyst Book reports Synfuels turnover for FY 2012 as R48 791 million and cash operating cost as R 22 114.million. Cash operating margin calculates to R26 677 million thus R 13 339 million for Secunda West Plant.

The above assumptions and inputs yielded an IRR of 8.1%

#### 10.1.5.2. Internal rate of return of aggregated earnings before interest tax and amortisation of all the business units.

EBITAs of all simulated Business Units are shown in table 6. 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 using the pricing approach in 10.1.5, bullet 3. The IRR of the last production step was finally calculated at 15.8%.

Note that the IRR of the aggregated EBITAs is the same as reported in 10.1.5.1 (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 reported in section 10.1.5.3.

| | | | | | EBITA Consolidation | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 | 1533 | 1533 | 1533 | 1533 | 1533 | 1533 | 1533 | 1533 | 1533 | 1533 | 1533 | 1533 | 1533 | 1533 |
| ASU | 6.0% | -2400 | -4800 | -4800 | 1097 | 1097 | 1097 | 1097 | 1097 | 1097 | 1097 | 1097 | 1097 | 1097 | 1097 | 1097 | 1097 | 1097 |
| WDS -Clarified | 5.9% | -120 | -240 | -240 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 |
| WDS -Demin | 6.1% | -120 | -240 | -240 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 | 55 |
| WDS -RO | 6.0% | -144 | -288 | -288 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 | 65 |
| WDS -Proc. Cooling | 6.1% | -96 | -192 | -192 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 | 44 |
| GEN | 6.0% | -720 | -1440 | -1440 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 | 330 |
| 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 | 2745 | 2745 | 2745 | 2745 | 2745 | 2745 | 2745 | 2745 | 2745 | 2745 | 2745 | 2745 | 2745 | 2745 |
| REC | 6.1% | -1440 | -2880 | -2880 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 |
| SAS | 6.0% | -1680 | -3360 | -3360 | 766 | 766 | 766 | 766 | 766 | 766 | 766 | 766 | 766 | 766 | 766 | 766 | 766 | 766 |
| CSU | 6.0% | -1440 | -2880 | -2880 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 | 659 |
| SMR | 6.1% | -960 | -1920 | -1920 | 445 | 445 | 445 | 445 | 445 | 445 | 445 | 445 | 445 | 445 | 445 | 445 | 445 | 445 |
| PWS | 15.8% | -4560 | -9120 | -9120 | 4309 | 4309 | 4309 | 4309 | 4309 | 4309 | 4309 | 4309 | 4309 | 4309 | 4309 | 4309 | 4309 | 4309 |
| Total of BU EBITAs | 8.1% | -24000 | -48000 | -48000 | 13144 | 13144 | 13144 | 13144 | 13144 | 13144 | 13144 | 13144 | 13144 | 13144 | 13144 | 13144 | 13144 | 13144 |

**Table 6. Earnings before interest, tax and amortisation for all business units.**

#### 10.1.5.3. Levelized cost of commodity and process streams

Table 7 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 7 should be interpreted as applicable to a 80,000 bbl/d coal-to-liquid plant, with an overnight cost structure of R120,000 million and a cash operating margin exactly that reported for Secunda West Plant for Fiscal Year 2012.

| | | | | | | |
|---|---|---|---|---|---|---|
| | Key assumptions and EFA output report | | | | | |
| **Key assumptions** | | | | | | |
| % CO2 taxed | 0% | | | | | |
| IRR hurle rate | 6% | | | | | |
| Overnight Capital cost | 120000 | MR | | | | |
| Cost of Coal | 211 | R/ton | 26.4 | $/ton | | |
| Corporate tax rate | 0% | | | | | |
| | | | | | | |
| **CTL plant IRR:** | 8.1% | | | | | |
| | | | | | | |
| | | | LC | | | |
| **Utilities:** | 40 bar steam | supplied by STB at | 150 | R/ton | | |
| | Sasol electricity | supplied by GEN at | 77 | c/KW-h | | |
| | O2 | supplied by ASU at | 597 | R/ton | | |
| | | | | | | |
| **Process:** | Dry Raw Gas | supplied by LGG at | 551 | R/ton | 52.3 | R/GJ |
| | Pure Gas | supplied by REC at | 1346 | R/ton | 55.6 | R/GJ |
| | Reformed CH4 | supplied by SMR at | 1652 | R/ton | 110.1 | R/GJ |
| | Tail Gas | supplied by SAS at | 2356 | R/ton | 81.2 | R/GJ |
| | Saleable product | supplied by CSU at | 5109 | R/ton | 118.8 | R/GJ |

**Table 7 Levelized cost of process streams stated in R/ton and R/GJ**

#### 10.1.5.4. Sensitivity analysis for $CO_2$ taxation and coal price

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 Government's proposal in this regard, namely R120/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 8 shows the effect of various levels of taxation on the internal rate of return.

| Sensitivity to CO2 taxation | |
|---|---|
| Taxation level | IRR |
| 0% | 8.1% |
| 20% | 7.3% |
| 40% | 6.5% |

Table 8. The effect of various levels of $CO_2$ taxation on the internal rate of return of Secunda West plant.

Although not negligible, the impact of $CO_2$ taxation on economic performance is not the controlling factor.

Table 9 shows investment performance as a function of coal price. A coal price set at 80% of the FOB export price resulted an in an internal rate of return well below the hurdle rate.

*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.*

| Sensitivity to Coal price | |
|---|---|
| Coal price % FOB | IRR |
| 33% (R211/ton) | 8.1% |
| 40% (R256/ton) | 7.3% |
| 80% (R512/ton) | 1.9% |

**Table 9. Secunda coal-to-liquid internal rate of return as a function of coal price**

*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.*

These more advanced process options in particular scenarios S3 and S4 and their nuclear coupling schemes will be studied as part of the NC2I-R project.

Although not an objective of the current study, it is evident from the above analysis that carbon sequestration is NOT the answer, since it adds more costs while not improving the process's carbon efficiency.

### 10.2. ScenarioS1a Electricity from Eskom replaced by nuclear

Scenario S1a is identical to S0 except for the price of electricity, which was calculated for the nuclear generation option based on the following assumptions:

- Two Nuclear Steam Supply Systems (NSSS) (4 reactors) configured to produce 175 MW per NSSS, as per Westinghouse 2013 (350 MWe in total)

- 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

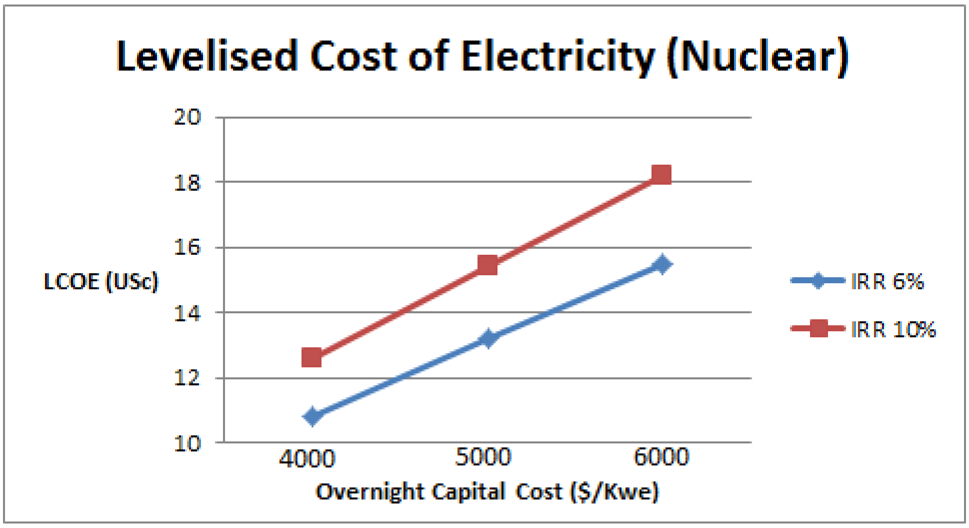


**Figure 1 Levelized cost of electricity in scenario 1a for a range of overnight capital cost.**

With the range of LCOE(Nuclear) defined, the question 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)

| Power scenario | | Cost of O2 | CTL Plant IRR |
|---|---|---|---|
| From | (c/KWe) | (R/ton) | % |
| Eskom | 45 | 580 | 8.1% |
| Nuclear low | 87 | 727 | 6.8% |
| Nuclear high | 145 | 908 | 4.8% |

**Table 10. Coal-to-liquid sensitivity to electrical energy cost.**

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 (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), 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 80,00 bbl/d coal-to-liquid process would require approximately 650 MWe, assuming no change to the baseline process.

*Westinghouse Work Package 11 / Task 1.1.3. Westinghouse Contribution - Description of Nuclear Heat Source. Report number. GBRA 154 219. February 2013.

### 10.3. Scenario S1b. Electricity from Eskom replaced by nuclear plus cogeneration of 40 bar steam supply

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 and 3600 ton/hour steam at 40 bar and 450$^o$C.
- 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 175MWe. For example: 3000 $/kWe yields a nuclear plant 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 utilised 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 (R14 280 million). Associated operational cost was set to zero in the model.

Table 11 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.

| Equivalent $/KWe | Selling price which yields N-IRR=6% | |
|---|---|---|
| | Steam (R/ton) | Electricity (c/KW-h) |
| 3000 | 191 | 62 |
| 4000 | 243 | 79 |
| 5000 | 295 | 96 |

**Table 11. Nuclear steam and electricity selling prices.**

The above utility prices were subsequently used to calculate the IRR of the investment in the CTL plant. (Note: selling prices of utilities such that the nuclear plant IRR=6%). It is clear from Figure 2 that if the overnight cost of the nuclear plant exceeds 3500$/KWe, it would jeopardise the return on the investment made in the CTL plant.

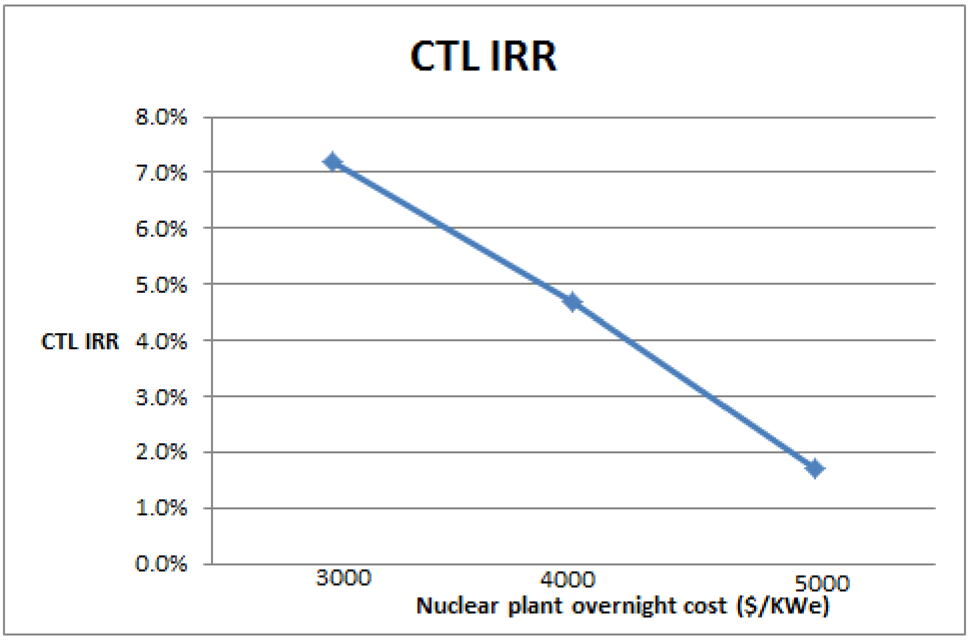


**Figure 2 Internal rate of return of the coal-to-liqud plant as a function of the nuclear plant overnight cost.**

*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 $3000/kWe.*

## 10.4. Siting and licensing of the nuclear plant.

A preliminary high level study was conducted to obtain a first order estimation of the time and cost implications of obtaining a nuclear site license in the proximity of the SECUNDA plant. In the following sections reference is made to a Masters Dissertation by Ravelot (2013), which was completed under the supervision of one of the authors of this report.

### 10.4.1. Discussion of the assumptions and limitations.

"For the purpose of this study the following assumptions were made:-

- At the time of applying for a license in RSA, the HTR plant would have already been licensed in the country of origin.
- The first of a kind NPP, would have been built and commissioned.
- The study did not assess the feasibility of applying for a site license in the vicinity of the SSF plant in SECUNDA, which is heavily undermined and of unknown geological stability." (Ravelot 2013)

### 10.4.2. Discussion of the results of the licensing study

#### 10.4.2.1. Lessons learned from the PBMR project

"Although it is acknowledged as an ARCHER project assumption that the envisioned HTR technology for the NCTL coupling to the SECUNDA plant would be fully licensed in the country of origin, a review of the PBMR licensing process was deemed valuable in seeking to identify commonalities and risks.

In mid-2000 a nuclear installation license (NIL) application was submitted by Eskom to the NNR for its demonstration HTR plant for electricity generation (IAEA, 2012,). The basis of the licensing requirements was primarily formulated from the safety standards and regulatory practices and regulations in terms of section 36 and 47 of the National Nuclear Regulatory Act (NNRA).

A multi-staged licensing approach was adopted by Eskom due to the developmental nature and complexity of the PBMR project. The envisaged program to license the PBMR followed five (5) licensing stages, (IAEA, 2012, pp. 4-6):

I. Site preparation, construction and manufacturing were covered under stages 1 and 2.

II. Nuclear fuel on site/commissioning and start-up was covered in stage 3;

III. Commercial operation was covered in stage 4; and

IV. Decommissioning was covered in stage 5.

As the licensing process developed, the NNR was confronted with major challenges for licensing the first of a kind reactor technology in South Africa (IAEA, 2012), in particular:

- Acquiring the technical services from international companies to formulate requirements, guidance and reviews;
- Developing in-house expertise of NNR staff in graphite/gas reactor technology;
- Developing a process to license the "first of a kind" reactor in South Africa; and
- Reviewing licensing submissions made by PBMR (Pty) Ltd. on behalf of ESKOM who would be the owner operator.
- During stage 1 (application), the authorisation to design had to entail the assessment of the applicant's management, organisational, design development and control processes;
- In stage 2, the design assessment had to contain the assessment of the reference design against supporting information;
- Key safety issues had to be agreed upon, when identified including its proposed technical resolution;
- The requirements of the NNR's had to be defined and understood prior to engagement by the applicant;
- Nuclear safety had to be demonstrated and not assumed;
- All roles had to be understood by the NNR, designer and applicant;
- Safety concept considering safety principles had to be agreed upon (i.e. Defence-in-depth (DiD), safety and quality classification, etc.);
- The design had to be adequately developed and be stable;
- The design had to survive a postulated transient and accident condition; and
- The engagement framework had to be such that the architect/designer engineer can be directly engaged with." (Ravelot 2013)

#### 10.4.2.2. Regulatory Framework in SA

"Nuclear related activities in South Africa are legislated in the Nuclear Energy Act (No 46 of 1999) (NEA) while the National Nuclear Regulator Act (No 47 of 1999) (NNRA), exclusively deals with regulating the nuclear sector. Thus, the licensing process for nuclear installations is covered in sections 2I, 23 and 24 of the NNRA.

The Nuclear Energy Policy presents a framework for the utilisation of nuclear energy sources for peaceful intentions.
Legislation is supported by three relevant regulations in the hierarchy:

- R388 Safety standards and regulatory practices,

- R927 Licensing sites for new nuclear installations,
- R479 Format for the application for a nuclear installation license.(NIL)

The legislative and regulatory framework is further supported by detail requirement documents:-

- PP-0009 Authorisations for nuclear installations
- RD-0034 Quality and safety management requirements for nuclear installations.
- RD-013 Requirements on public safety information documents to be produced by applicants for new authorisations.
- LG-1041 (Licensing Guide on Safety Assessments of Nuclear Power Reactor Sites." (Ravelot 2013)

#### 10.4.2.3. Licensing Risk Plan

The following actions are presented as a preliminary identification of actions required to lessen the project risks envisioned at this early stage for coupling an HTR to an existing CTL plant such as SASOL Secunda plant.

- "It is suggested to engage early with the safety authority to determine the data requirements needed for the safety evaluations, agreement on scope and schedule when the license application is made for the NCTL.
- It is suggested to formulate a site safety report (SSR) as part of the licensing application to address seismic qualification, radiological safety and emergency planning as it is a regulatory/legal requirement.
- The responsibility for nuclear waste disposal has been discharged by Necsa to date (Necsa, 2012). It is suggested that the nuclear waste be managed by the National Radioactive Waste Disposal Institute in South Africa (RSA, 2009)
- It is foreseen that the construction of multiple module nuclear reactors and the sharing of a central control room and other support systems may pose licensing challenges. It is suggested that the control room design be a priority project component, to define the requirements imposed by multi-unit monitoring and concurrent plant construction including the control of all resources (O'Hara, 2012)" (Ravelot 2013)

#### 10.4.2.4. Estimated licensing cost and duration

The preliminary study by Lavelot (2013) indicated that the overall timelines of the licensing plan for coupling a nuclear energy source to a chemical process plant is estimated at 8 years, and compares well to international best practise. The first order funding requirement for the overall licensing of the NCTL Production Plant estimated by Lavelot was R920 million in 2013 value.

The study recommends that the safety authority, the NNR, be involved in the licensing plan, from as early a stage in the project planning as practical, to amongst others, address the following issues:-

"a) To provide transparency in the process for all parties involved;
b) To gain clarity on the requirements for the site safety report (as required by the Regulations R 927) on the licensing of sites for new nuclear installations;
c) To agree on how to apply for multiple NILs for construction on a common site after being granted multiple NISLs and completion of the public participation process;
d) To agree communication channels in order to be timeously informed of major changes to Regulations, Regulatory Requirements and Regulatory Position;
e) In order to gain clarity on how to demonstrate safety of the NCTL production plant in South Africa, to support the safety case;
f) Risks analysis of applying the existing codes and standards applicable to licensing of PWR power plants, to the licensing of NCTL production plants;
g) Vendor bidding and procurement process for integration into the licensing plan." (Ravelot 2013)

#### 10.4.2.5. Discussion of the licensing gaps identified.

Some of the gaps identified during the research into a licensing plan for coupling a nuclear energy source to a chemical process plant where enumerated as suggestions for further research by Lavelot.

- Determine the effects of tritium migration beyond the nuclear heat system of the NCTL production plant through system modelling.
- Safety of the nuclear energy source due to the effect of the proximity of chemical process plant.
- Risks analysis of applying the existing codes and standards applicable to licensing of PWR power plants, to the licensing of NCTL production plants.
- Capability of the NNR to accommodate multiple NIL's applications for the NCTL production plant.
- Identification of unique hazards relating to external events and chemical corrosion emanating from the NCTL production plant.
- Capability of the NNR to accommodate multiple NIL's applications for the NCTL production plant.
- Development of a project and risk management plan to complement the existing licensing plan for the NCTL production plant.
- The requirements of a safety plan for constructing a nuclear plant in the vicinity of an existing industrial site." (Ravelot 2013)

## 11. *Task 1.2.1 Technology Gap and Risk Analysis*

This section reports on the gaps in HTR technology as seen from the RSA perspective for application to the SASOL Secunda case study.
The approach taken to identify technology gaps and risks pertaining to the envisioned application of HTR co-generation technology to the SASOL process was performed in a combined NWU project team meeting.
A formal risk analysis was beyond the scope of this project, but where sound judgement indicated risks that exceeded the risk tolerance allowed by the traditional SASOL discount rate for capital projects - these were flagged as gaps to be addressed at an appropriate future time.

### *11.1. Technology Gaps*

The technology gaps relating to coupling a nuclear energy source to the SASOL CTL process,that have become apparent during this research, are briefly summarised below.

- Overall nuclear steam and electricity was found to be expensive relative to coal, therefore future work will aim to explore ways to minimise reliance on Nuclear energy
- Methods to store nuclear energy in the coupled system, is seen as a technology gap and needs to be explored.
- The maximum design outlet temperature of the HTR may be too low to provide sufficient efficiency in the HyS water splitting process.
- The above may indicate the need for a “temperature pumping” technology.
- Uncertainty as to which water splitting technology to pursue. HyS and Cu-Cl models to be constructed.
- Plasma Arc Reforming technology and economic feasibility to be completed
- Fine coal gasification is a required technology, to gasify the remaining coal fines if the coal fired boilers are replace with nuclear steam.
- The above requirement may be achieved with the $CO_2$ lean gasification with the Shell Slagging Gasifier (SSG).

### *11.2. Risk Analysis*

Risks involved in the licensing process

- Licensing issues have been dealt with in detail in paragraph 10.2.3.5 and include the capacity of the NNR to license a HTR and the cost of licensing.
- A total life cycle spent fuel management plan is required to convince a “non-nuclear” client such as SASOL.

## 12. *Task 1.2.2 SWOT Analysis*

A Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis was carried out by the combined NWU team at the end of the current project phase. The process was in the form of a “brain storm” and the results are presented in a bulleted “brain-storm” format.

## 12.1. **Strengths** (Internal issues)

The team identified the following strengths as seen from an internal perspective to South Africa.

**Strengths of the European HTR in South Africa:-**

- Will have a higher credibility with industry than a locally developed HTR (as was the PBMR)
- Inherently safe design features of the HTR have the following strengths:
  - Sales advantage to RSA stakeholders
  - Should regulatory and licensing advantages
  - Design, manufacturing and project benefits resulting in cost effectiveness.

- The modular design of the HTR has the following strengths:-
  - Aggregated high availability
  - Lower investment hurdle
  - Phased implementation
  - Lower unit manufacturing cost due to serial production
  - Lower construction cost
- South Africa has a positive international “nuclear” image because it exited its enrichment technology and concentrated on peaceful nuclear application.
- SASOL has built a strong international presence with large projects in North America.

**Strengths of the RSA ARCHER team:**

- NWU have now got a verified economic feasibility model for the existing SASOL coal-to-liquid process on which it can build various business cases for the application of HTR energy in an industrial process.
- NWU were able to field a strong multi-disciplinary research team providing the following skills and attitudes:-
  - Chemical process simulation
  - Thermal-fluid system simulation
  - Nuclear process integration
  - Economic Feasibility Modelling
  - Can- do attitude (mentality)
- The team took a realistic and objective approach. They asked if a scenario can work economically. Then tried to find ways to make it work through research and creative thinking.
- The focus was primarily on economic feasibility and not process efficiency as a first approach.

- South Africa research community has a positive legacy from PBMR.

## 12.2. **Opportunities** (External Issues)

**Opportunities for the European HTR in South Africa:-**

- A first opportunity to decrease the $CO_2$ emission of the CTL process by as much as 50% lies in the replacement of the coal fired steam and electricity with nuclear co-generated steam and electricity.
- The team view is that the biggest opportunity for coupling an HTR to the SASOL process lies in the introduction of Nuclear Hydrogen with Thermo-chemical Water Splitting ($O_2$ will be a valuable by product)
  - The model for a Hybrid Sulphur process is in construction for application in the NC2I research phase.
  - The threat of $CO_2$ Tax is an opportunity for the technology, but the sensitivity is not high.

- The rising costs of ESKOM electricity could in future favour alternative sources such as nuclear cogeneration, by effectively raising the hurdle capital cost that could be invested in the HTR plant
- The growing feed-in of wind and solar to the grid will result in major instability due to the low inertia of these technologies. An independent power producer running an HTR cogeneration facility (with high load-inertia) could be used as a grid stabilizer; and could sell "stability" to the grid in addition to excess capacity.
- $O_2$ production could be cut back during peak electricity demand periods and then exported to the grid at a premium when required. The CTL plant's $O_2$ requirements could be stored during off peak periods. (Intermittency vs stability)
- The SASOL steam system could be used to store energy- to be investigated.
- SASOL could have an offtake agreement with IPP with extra nuclear capacity to sell to grid.
- The SECUNDA coal reserves could be extended by coupling nuclear energy to the SASOL process, extending the useful plant life beyond the present 2050 horizon.
- Assume that the CTL plant is already amortized. Model an NPP retrofit and calculate a new IRR on this scenario. Flag for NC2I project.
- Application of HTR - CHP to a GTL plant is seen as a logical next step.
- Opportunities may exist to convince environmental activists that on balance there will be a reduction in negative environmental impacts. Principally reduction of $CO_2$ release and environmental damage due to reduced coal mining.

**Opportunities for the RSA research team.**

- This project provides the opportunity for RSA research team to remain part of the international nuclear research community.
- Nuclear coal-to-liquid could be portrayed as a "green" alternative.
- Many of the major risks have been identified and flagged for action.

- Strategic gaps have been identified and flagged for further analysis.

### 12.3. **Weakness** (Internal issues)

**Weakness of the European HTR in South Africa:-**

- The actual risk tolerance and appetite of SASOL for such a venture is unknown, as well as the internal return hurdle rate it would apply to embracing such a new technology.

**Weakness of the RSA research team**

- Opposed to the strength of having a “can-do” attitude, RSA researchers and technology developers also unfortunately have a tradition of over optimism as was illustrated in the aborted PBMR project.

### 12.4. **Threats** (External Issues)

**Threats to the European HTR in South Africa:-**

- SASOL is perceived to have an anti-PBMR legacy.
- SASOL is perceived not to have Nuclear on its public radar.
- SASOL may have a shorter term view on project payback than required for a Nuclear –coal-to-liquid project.
- An Independent Power Producer license may have political requirements which could be unacceptable for SASOL or its IPP partner.
- Pricing of Nuclear – can we realistically expect to meet the design to cost target of $3000/kWh installed?
- Environmental activist action against nuclear deployment is a threat.
- Approval and licensing is spread over a number of organs of the government, with little experience of licensing the coupling of a nuclear plant to a chemical plant.
- The licensing process is expected to be onerous and expensive, and may prove to be a project hurdle.

**Threats to the European RSA research team:-**

Opportunities for the RSA reaserch team to continue its research in this field would be under threat if continued funding were not available in future.

## 13. *Conclusion and further work*

The project team has reached the following conclusions:

### *13.1. In respect of the modelling approach it is concluded that:*

The approach to model the coal-to-liquid production system as a sequence of Business Units delivered consistent results, from both mass balance and economic performance points of view. Simulation results correlated well with real life parameters reported in trustworthy sources such as Sasol’s Integrated Annual Report and Analyst Book.

### *13.2. In respect of scenario S0 - Secunda as is; 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 (assuming that reserves have acceptable quality) than to try to add value to it by converting it to fuel and chemicals.

For future coal-to-liquid processes to be viable from an economic point of view, their carbon to product conversion will have to be drastically improved. Nuclear heat, combined with a number of alternative coal-to-liquid process options may show the way.

### *13.3. In respect of scenario S1a - Eskom power replaced by nuclear power*; it is concluded that:

- The coal-to-liquid plant IRR shows remarkably high sensitivity to the cost of electrical energy. The primary mechanism for this is the electrical energy intensity of oxygen produced by the ASU.
- 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 CTL process would require approximately 650 MWe (assuming no change to the baseline CTL process).

### *13.4. In respect of scenario S1b - S1a plus nuclear steam;*

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 $3000/kWe.

### *13.5. In respect of plant safety and licensing.*

The preliminary work published by Lavelot in his masters dissertation indicates that further work is needed to:-

- Determine the effects of tritium migration beyond the nuclear heat system of the NCTL production plant through system modelling.
- Quantify the safety of the nuclear energy source due to the effect of the proximity of chemical process plant.
- Perform a risk analysis of applying the existing codes and standards applicable to licensing of PWR power plants, to the licensing of NCTL production plants.
- Gauge the capability of the NNR to accommodate multiple NIL's applications for the NCTL production plant.
- Identify unique hazards relating to external events and chemical corrosion emanating from the NCTL production plant.
- Develop a project and risk management plan to complement the existing licensing plan for the NCTL production plant.

- Determine the requirements of a safety plan for constructing a nuclear plant in the vicinity of an existing industrial site.

### *13.6.* In respect of future work;

It is recommended that:
Modelling scenarios S1-S4 be completed under project NC2I-R, with the objectives to:

- improve the carbon efficiency of the CTL process, and
- minimise the nuclear component of an integrated future NCTL process.

**References**

Lavelot (2013) Masters dissertation "A licensing plan for coupling a nuclear energy source to a chemical process plant. SASOL Secunda as a case study"

IAEA. (2012, October 22-26). Course on High temperature Gas Cooled Reactor Technology, Regulatory perspectives: PBMR Licensing experience - Lessons learned.

O'Hara, P. &. (2012). *Human-Performance Issues Related to the Design and Operation of Small Modular Reactors.* New York: Brookhaven National Laboratory.

Stoker and Fick (2013) A systems engineering approach to level the playing field. Electricity from coal versus nuclear. 7th Annual INCOSE SA Conference Pretoria, South Africa

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Mr. F Conradie
Mr. W Kaiser
Mr. S Chuita

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**Appendix 1- Definition of acronyms and abbreviations used in the following scenario diagrams**

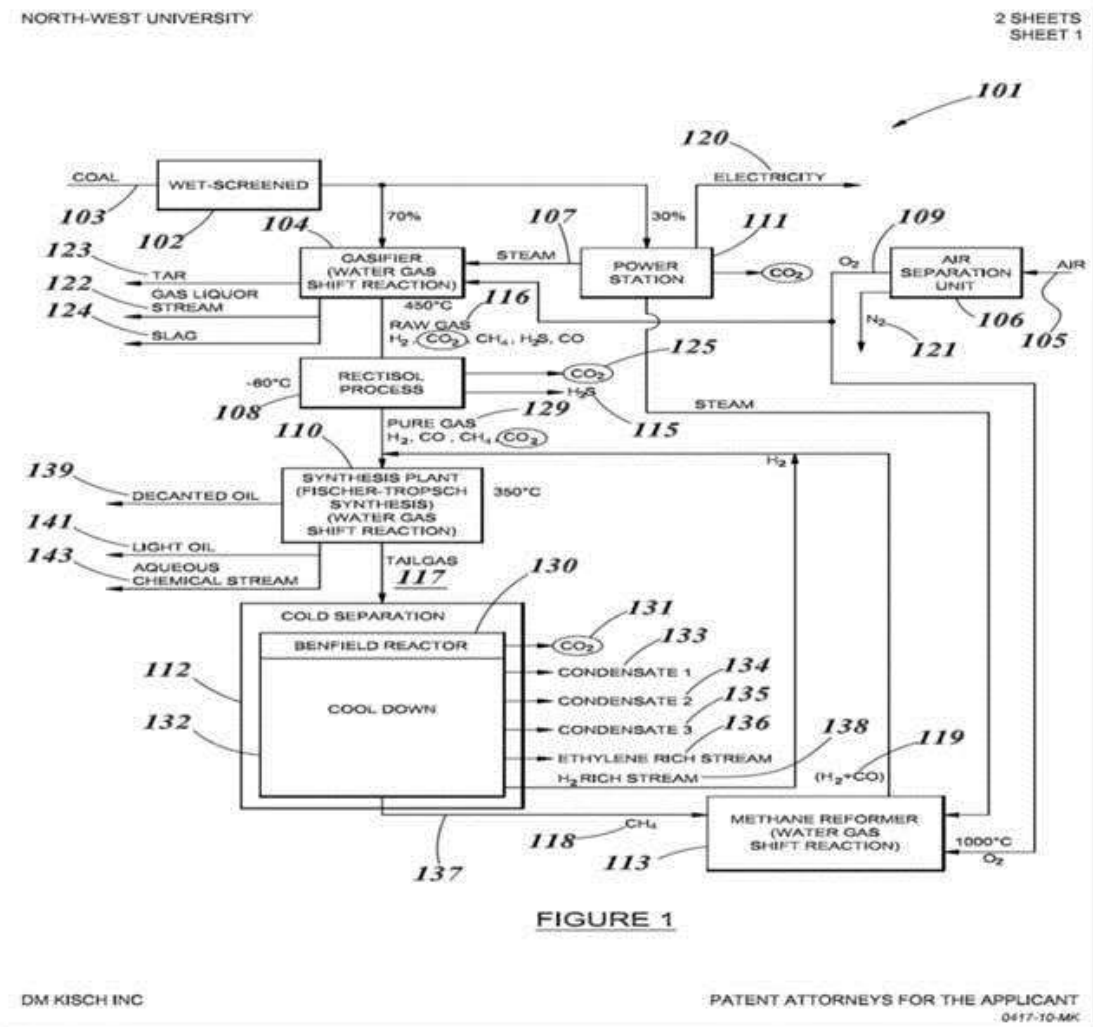
| **Abbreviation** | **Definition** |
|---|---|
| ASH | Ash handling systems |
| ASU | Air separation unit (cryogenic separation) |
| CDS | Coal distribution system |
| CPS | Coal preparation system |
| CSP | Cold separation system ( |
| EDS | Electricity distribution system |
| GEN | Generators in the steam station |
| LGG | Lurgi gasifier |
| PAR | Plasma-arc reforming |
| PWS | Product workup and storage |
| REC | Rectisol (Raw gas clean up) |
| SDS | Steam distribution system |
| SMR | Steam methane reforming |
| SSG | Shell slagging gasifier |
| SYN | Fischer-Tropsch Synthol Reactor |
| TWS | Thermochemical water splitting |
| WDS | Water distribution system |

**Appendix 2 Scenario Diagrams**

**0Index**

| Scenario Ref. | Description |
|---|---|
| Scenario 0 | Process reference diagram - provisional patent document |
| Scenario 0 | Existing Secunda process - base case |
| Scenario 1a - | Eliminate electricity feed from ESKOM with HTR generation |
| Scenario 1b | Scenario 1a + eliminate the steam boilers with HTR co-generation |
| Scenario 2a | Scenario 1a + implement plasma arc reforming with minimal changes to the rest of the CTL plant |
| Scenario 2b | Scenario 1b + plasma arc reforming of $CO_2$ streams 131 and 121 |
| Scenario 3a | Eliminate the air separation unit (ASU) with thermo-chemical water splitting (TWS) |
| Scenario 4a | $CO_2$ lean gasification with Lurgi Gasifier (LGG) with plasma arc reforming |
| Scenario 4b | $CO_2$ leaner gasification with Shell Slagging Gasifier (SGG) HTR optimised for TWS plus plasma arc reforming |
| Scenario 4c | $CO_2$ leanest gasification with Shell Slagging Gasifier (SGG), HTR for cogeneration and TWS plus plasma arc reforming |

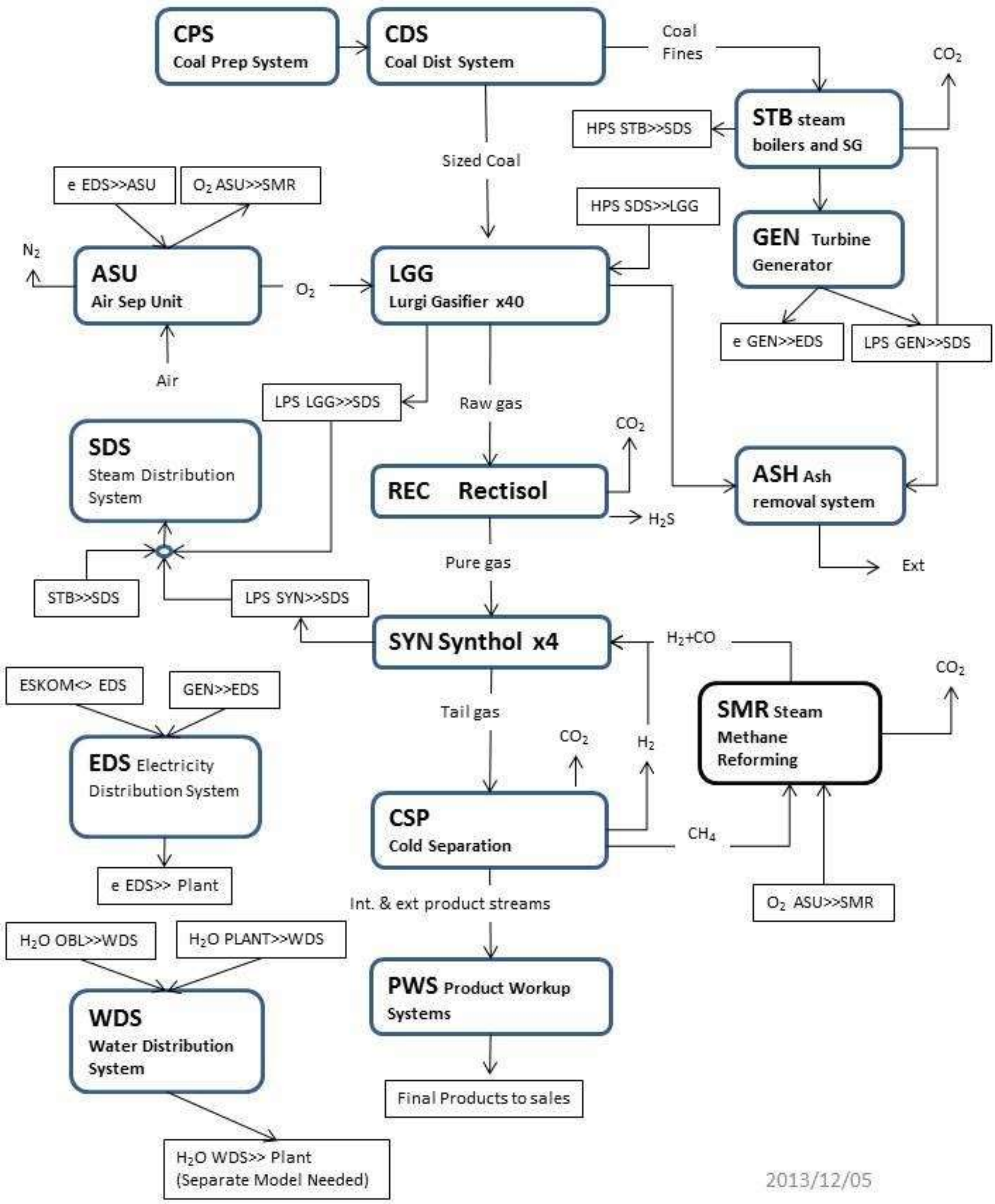
Scenario 0
Process Reference Diagram
Patent document



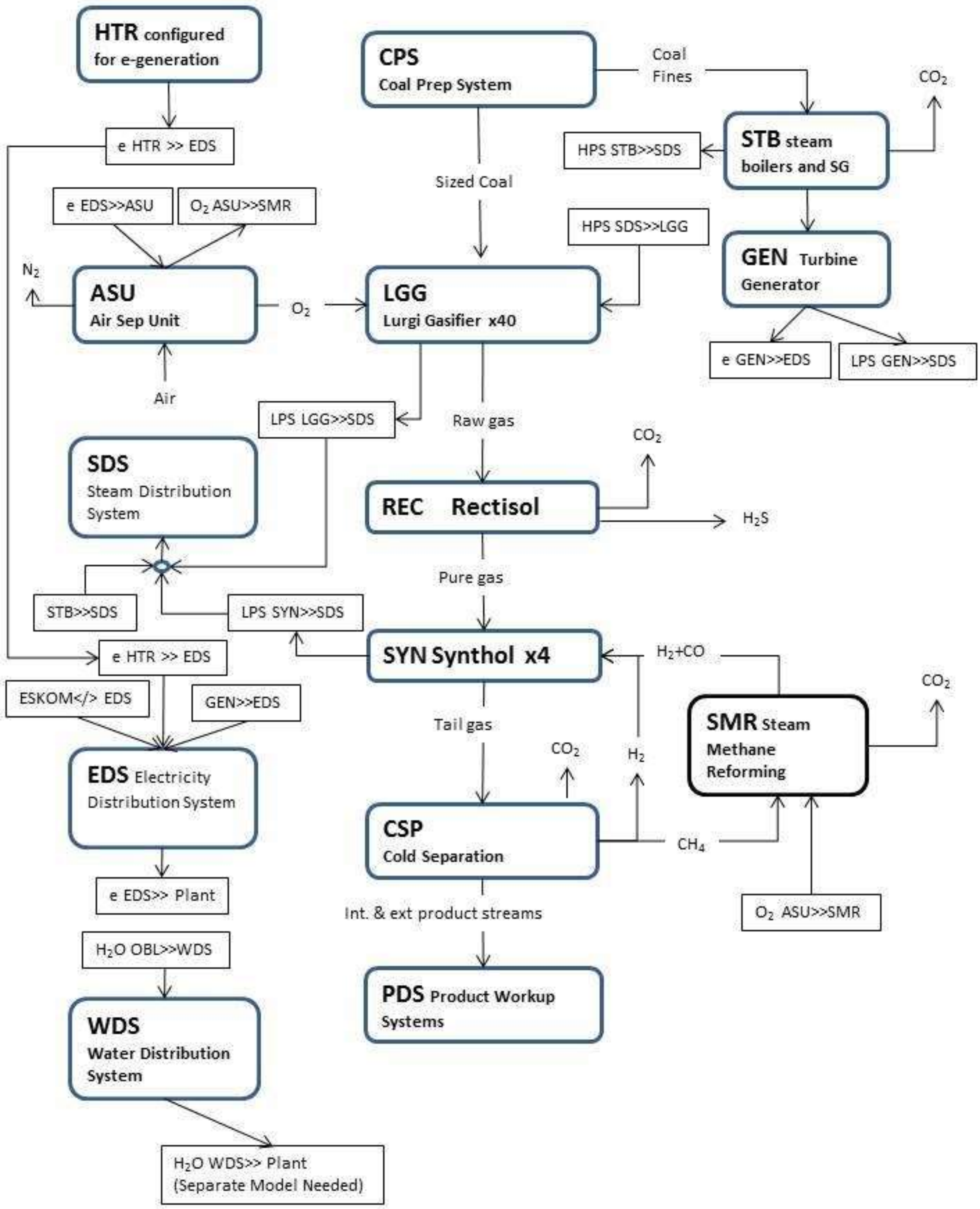

- Modeling Philosophy
- Steams 139,141,143 and 117 to be kept constant for all scenarios
- Processes to be modeled: 102, 104, 111, 106, 108, 110, 112, 130, 132, 113 (ideal)
- Processes excluded from model to be agreed with PWS
- Mass and energy balance of all steams 1** (ideal) PLUS ash and H2O-feed
- Streams excluded from model to be agreed with project leader

2013/12/04

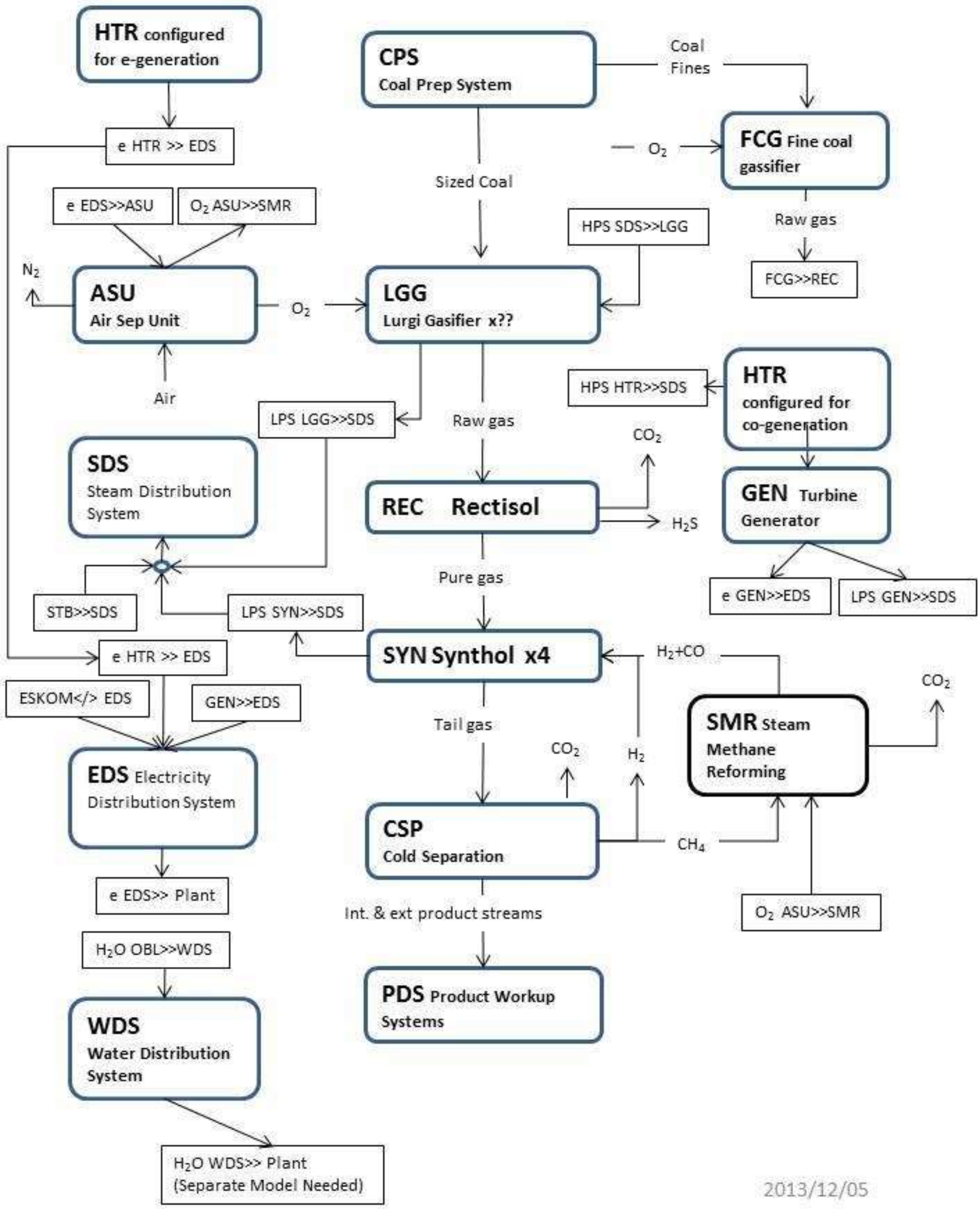
# Scenario 0
## (Secunda as is)



# Scenario 1a
## (Eliminate feed from ESKOM)

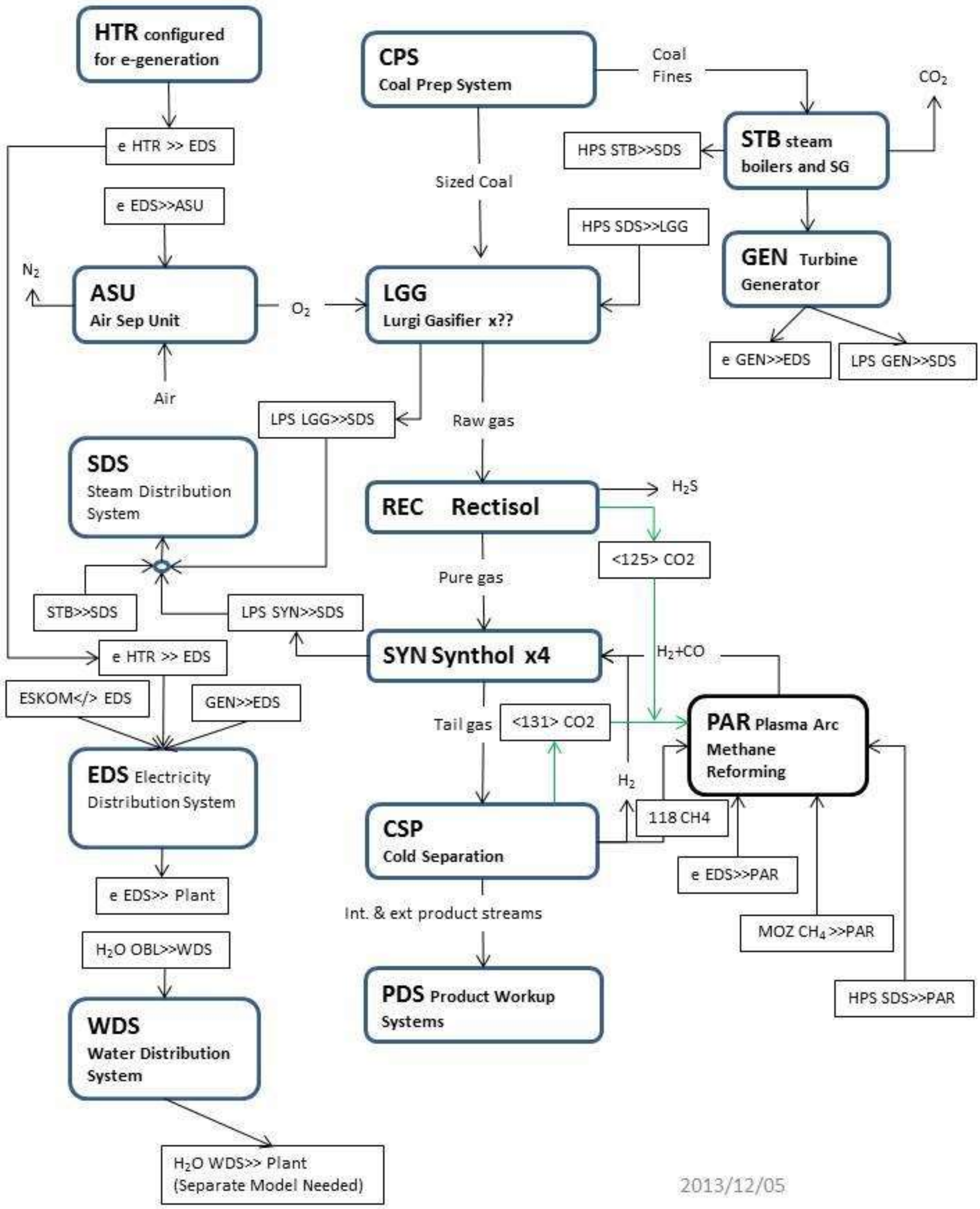


# Scenario 1b
## (1a+ Eliminate STB)



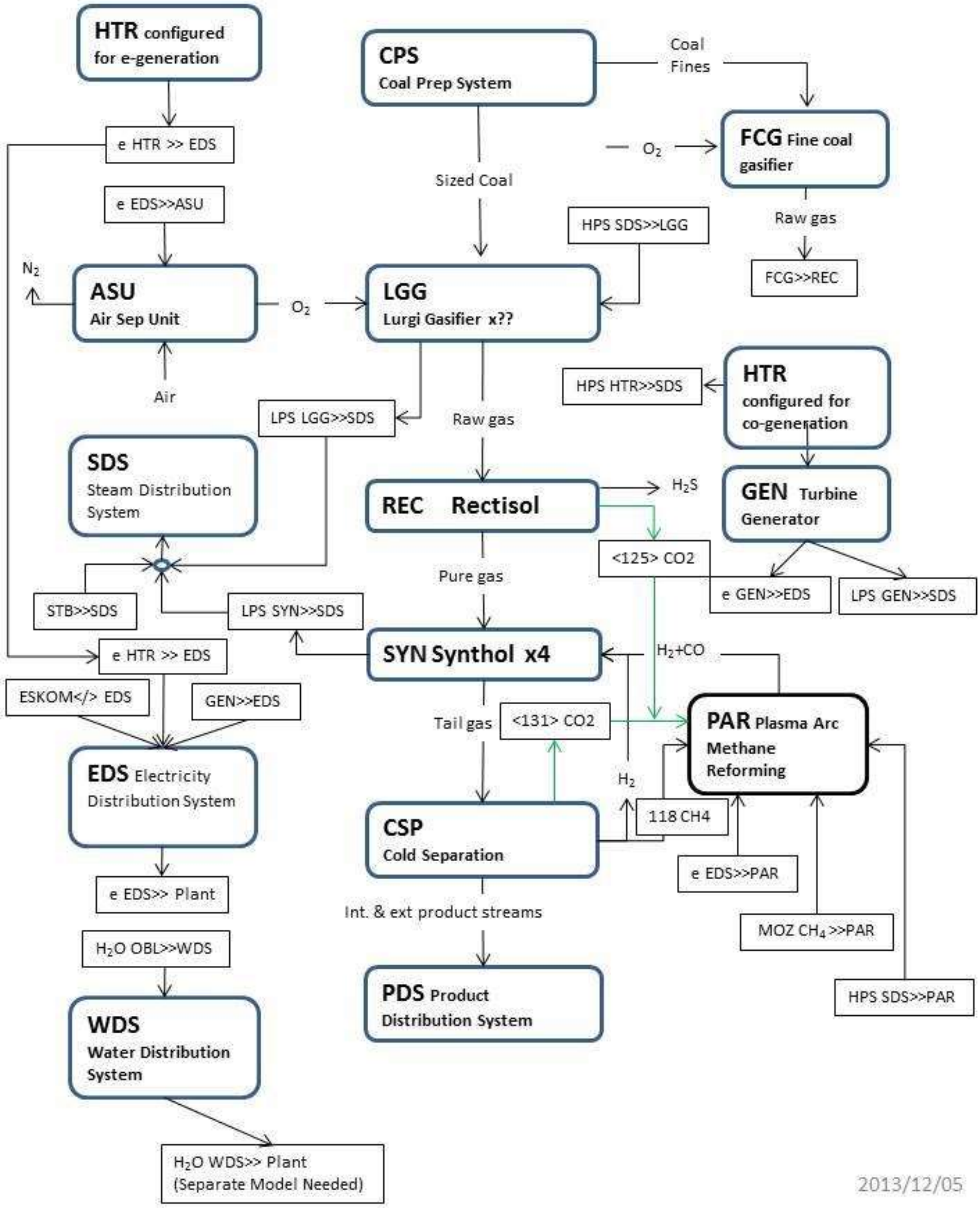
# Scenario 2a =S1a + PAR

(Implement PAR with minimal changes to the rest of the plant
PAR reformation of $CO_2$ streams 125 and 118 )



# Scenario 2b

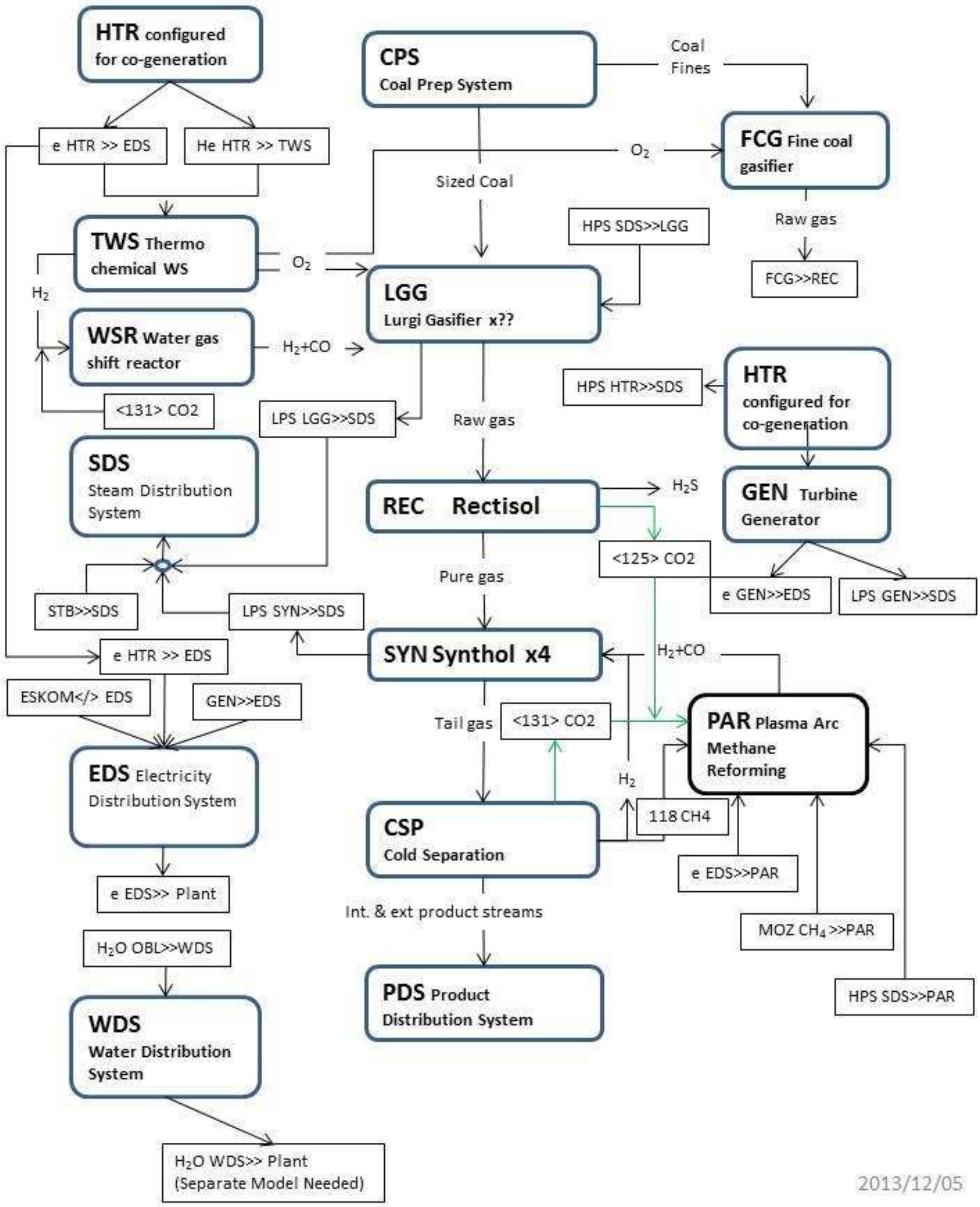
(Implement PAR on top of Scenario 1b - PAR reforming of $CO_2$ Streams 131 and 125)



# Scenario 3a

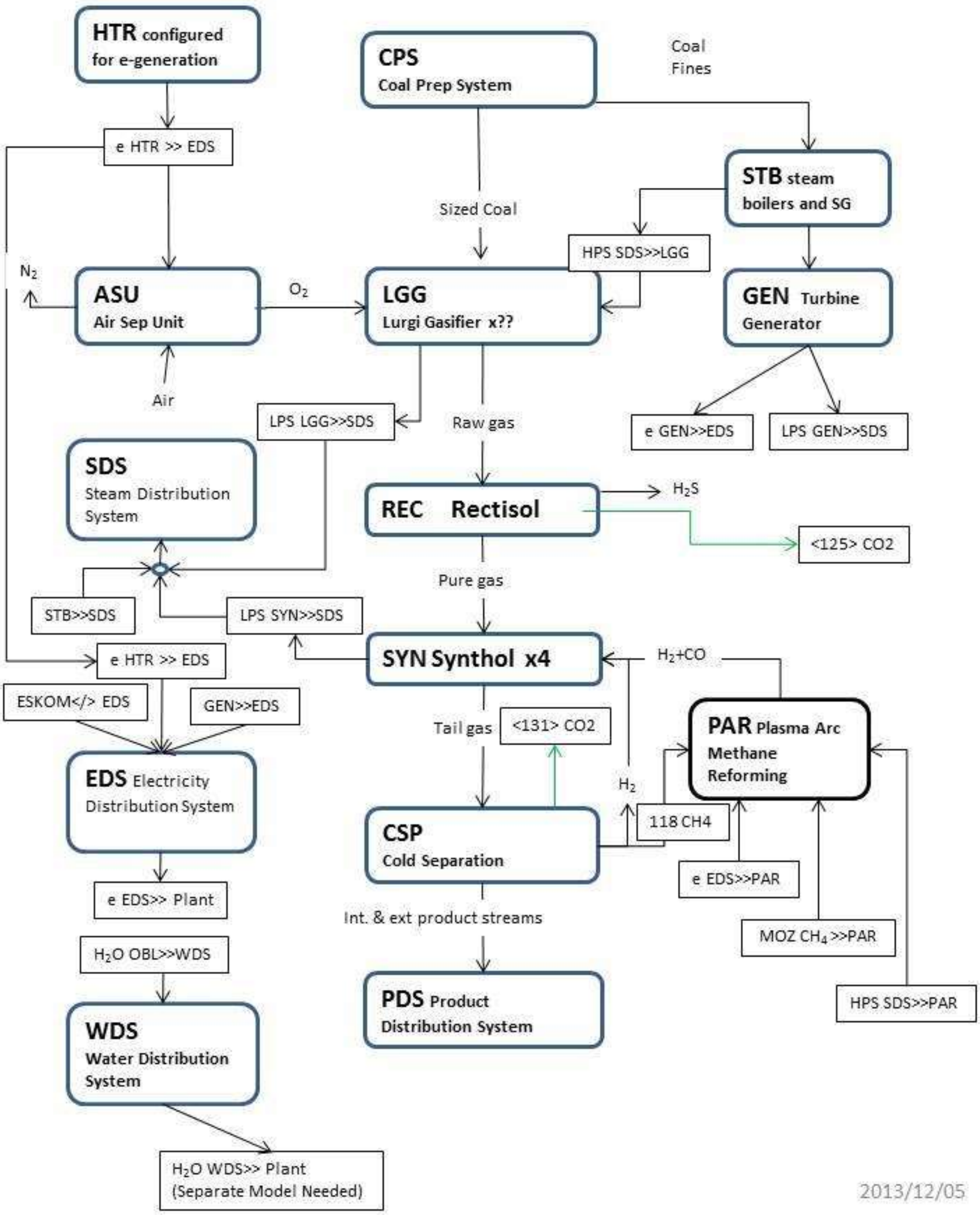
## Eliminate ASU with thermo-chemical water splitting (TWS)

(Implement PAR on top of Scenario 1c - PAR reforming of $CO_2$ Streams 131 and 125)

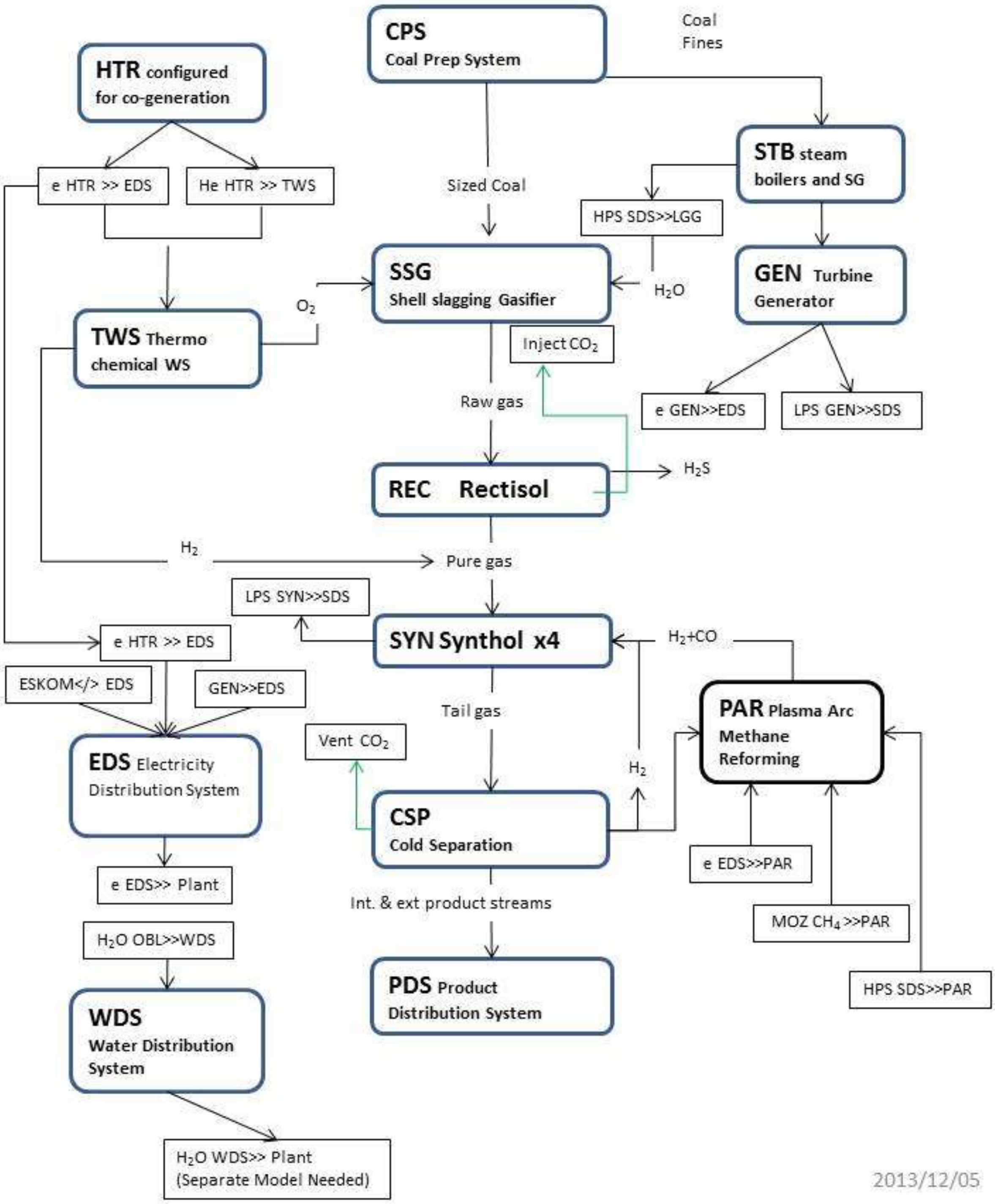


# Scenario 4a

## $CO_2$ Lean Gasification with Plasma Arc Reforming



# Scenario 4b
# $CO_2$ Leaner Gasification



# Scenario 4c
# $CO_2$ Leanest Gasification