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ENERGY-CYCLE ANALYSIS OF A GASIFICATION-BASED MULTI-PRODUCT SYSTEM WITH CO_2 RECOVERY

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ABSTRACT

The DOE is investigating CO_2 recovery from fossil-fuel cycles as a greenhouse gas mitigation strategy. Recognizing this, we used life-cycle analysis tools to compare two integrated gasification combined-cycle (IGCC) plant designs based on the Shell entrained-flow gasifier. One option, called the "co-product case," uses high-sulfur Illinois #6 coal to produce electricity and hydrogen (H_2) as energy carriers. At the same time, 90% of the carbon dioxide (CO_2) is recovered for disposal in geological storage or for use, such as enhanced-oil recovery (EOR). The second option, called the "base-case," is a conventional IGCC power plant releasing CO_2 by combustion of the synthesis gas in a gas turbine. The life-cycle analysis task has been aided by use of LCAdvantage™. Process design has been aided by the use of ASPEN © simulation for critical design areas. Special attention was paid to the transport issues for the CO_2 product, because transportation technology is a determinant of product specifications, which affect plant design. Separating and purifying the H_2 for fuel cell use should yield an impressive gain in overall process efficiency that can offset the losses in efficiency from recovery and compression of CO_2 to supercritical conditions.

GASIFICATION CYCLES

Plant Design Basis

The Shell (entrained-flow) coal gasification system has been selected as the basis for this co-product plant. The energy and environmental performance of the co-product plant are compared with those of a base case plant that also uses the Shell gasification technology but produces only electricity as a salable product. The base case IGCC plant and the co-product plant are substantially different in design. The most significant common elements are the use of the Shell gasifier and the consumption of the same amount and type of coal. Principal features and differences are summarized in Table 1.

Co-Product Plant Description

Figure 1 presents an overview of some of the critical process areas of the co-product plant, clarifying the differences noted in Table 1. The front end of the plant is nearly unchanged through Area 2000; gasification; heat recovery; particulate removal; and COS hydrolysis. Area 3000 is new. Here a shift reactor uses steam to convert the CO component of the raw gas to CO_2 and hydrogen (H_2). In Area 4000, significant modifications are necessary. Hydrogen sulfide (H_2S) is removed from the stream and processed by the Claus and SCOT units to produce marketable sulfur. The Claus Plant converts H_2S to elemental sulfur but leaves a residual of SO_2 and unconverted H_2S, which must be treated by the SCOT process. In the base case, filtered raw gas is used in the SCOT process as a reagent to reduce SO_2 to H_2S, which is then recycled to the Claus Plant. H_2 is the active reductant in the raw gas. The remaining CO from the raw gas reagent is flared and released as CO_2. We propose to use the purified H_2 as reagent, eliminating the need for a flare and associated CO_2 emissions while also reducing equipment costs. Following H_2S recovery, CO_2 is removed from the remaining gases in a glycol-based process. The end use specifically targeted for the CO_2 is EOR. EOR requirements drive the CO_2 product specifications. The gas stream after CO_2 recovery is processed via pressure swing adsorption (PSA) to recover H_2 at high purity so that fuel cell efficiencies are maximized, although there is no restriction on the actual hydrogen end use. The pure hydrogen stream is transported to end users via pipeline. Area 5000 employs the residual gas from PSA – a combination of hydrogen, methane, and others – to generate electricity by combustion turbine combined cycle. Part of the electricity generated supplies the internal needs of the plant, and the excess represents a fourth marketable plant product. Air separation is integrated with the balance of plant through use of N_2 as a diluent in the combustion turbine.

Table 2 presents a comparison of energy and environmental performance for the base and co-product plants. A common approach to comparing alternative plant designs is to set a fixed net power output. For this study, we have set a fixed coal input as the common basis, because the co-product plant outputs include streams other than electricity. The base and co-product cases differ most notably in the greatly reduced net electrical output (110.3 MW vs. 412.8 MW) and the shift in CO_2 output from air emissions to recovered waste stream. The hydrogen product has been reported in terms of equivalent power production at 73% total conversion efficiency, which includes electrical conversion at 46% in a solid oxide fuel cell and subsequent utilization of waste heat.

LIFE-CYCLE ASSESSMENT METHODOLOGY

Life-Cycle Assessment (LCA) is a tool for analyzing the environmental burden of products at all stages of their life cycle, "from cradle to grave" – extraction of resources; production of materials, product parts, and the product itself; use of the product; and management after discarding, either by reuse, recycling, or final disposal. Over the last decade, the U.S. and European branches of the Society of Environmental Toxicology and Chemistry[1] (SETAC) have led the intensive development of LCA methodologies, producing a "Code of Practice" – the first internationally accepted technical framework for LCA. This SETAC work is the basis for the LCA protocol in the ISO 14000 environmental management standards of the International Organization for Standardization (ISO). SETAC defines the inherent features of LCA as follows [1,2,3]:

- A system-wide or "cradle-to-grave" perspective, implying coverage of the multiple operations and activities throughout a life cycle;
- A multimedia perspective, implying coverage of resource use and emissions to different environmental media (e.g., air, water, and soil); and
- A functional unit accounting system that normalizes energy carriers, material resources, emissions, and wastes across the system (i.e., full fuel cycle) and across media after unit process allocation procedures. Only those percentages of emissions or resource use specific to the function are included in the balance sheet (LCA inventory table).

The methodological framework accepted worldwide for LCA currently recognizes four distinct components of a life-cycle assessment. The first step is a *goal definition and scoping* activity that serves to define the specific objectives and the expected products of a given study, as well as to identify time and spatial boundaries, boundary conditions and assumptions, and impact and improvement objectives. The second step, *inventory analysis*, quantifies and catalogs the materials and energy used and the environmental releases arising from all stages of the life of a product or process, from raw material acquisition to ultimate disposal. The third step, *impact assessment*, examines potential and actual environmental, human health, and resource depletion effects related to the use of resources (energy and materials) and environmental releases. The fourth step (optional) is an *improvement assessment* of the changes needed to bring about environmental, human health, and/or resource management improvements in the product or process. The scope of the current project is limited to the first three steps.

LCA GOAL DEFINITION AND SCOPING

Goals. Two major goals are pursued by the current LCA analysis:

- To create an "environmental footprint" of an IGCC-based multi-product system with CO_2 recovery and
- To compare that footprint with that of a conventional IGCC-based system with only electricity generation.

Scoping. For consistency of analysis, both plants are assumed to be located in Stevens Point, Wisconsin, and fueled by coal from a seam near Sesser, Illinois. To reflect the full life-cycle concept, both analyzed systems include three distinct activity areas, as shown in Figure 2:

1. Production plant (including gasification, gas conversion and purification, and power production by combined cycle).
2. Auxiliary operations and activities (including extraction and processing of coal and other significant major natural resources, transportation of major consumables and construction materials to the power plant, by-

[1] SETAC, a worldwide professional society, was founded in 1979 to provide a forum for individuals and institutions engaged in the study of environmental problems, the management and regulation of natural resources, education, research, and development, and manufacturing and distribution.

products and waste transportation/disposal/reuse, and production of power plant consumables and construction materials).

3. Power plant construction and demolition, as well as construction of hydrogen and CO_2 transportation pipelines.

INVENTORY COLLECTION AND ANALYSIS

To perform the LCA, an inventory of raw materials, products, and emissions associated with activities within this scope was collected for the base and the co-product cases. This inventory has been allocated to the products as described below.

Inventory collection. Inventory collection and analysis were performed by using the LCAdvantage^{TM} computer program developed by Battelle [4]. LCAdvantage^{TM} combines life-cycle modeling features with a graphical user interface, database structure, and calculation engine. The LCAdvantage^{TM} database comprises materials inventories based on U.S. experience for the production of basic commodities, including power generation, fuels production and distribution, and cradle-to-grave operations for such selected products as metals, cement, and basic chemicals. The quantities of materials, consumables, and effluents associated with IGCC process operations, as well as the pollutant emissions from relevant activities, were obtained from various sources, including the Aspen^{TM} simulations, supplemental mass and energy balances, the LCAdvantage database, other reports on LCA analyses, literature, EPA resources, and personal communications with individuals and experts in different industries. The LCAdvantage creates an inventory for all processes involved in construction, operation, and demolition of the plant. The inventory categories are resources, products, and airborne, liquid and solid residues.

1. Production Plant

- Major resource inputs: coal, water, MDEA and Selexol (used for removal of H_2S and CO_2 from flue gas), catalyst for the reduction of H_2S to elemental sulfur (Claus process), catalyst for chemical reduction of SO_2 to H_2S (SCOT process) to improve total sulfur removal by the Claus plant, and auxiliary electricity.
- Major products: electricity, hydrogen, CO_2, and by-product sulfur.
- Solid waste: coal slag, spent Claus and SCOT catalyst, dewatered sludge from raw water coagulation process.
- Liquid waste: gasifier blowdown, scrubbing processes blowdown, HRSG blowdown, cooling tower blowdown, water treatment unit blowdown.
- Airborne residues: SO_2 and CO_2 from SCOT plant stack (base case only), stack gas from combustion turbine, de-aerator vent, N_2 from the air separation unit, solid particulate drift from the cooling tower.

2. Auxiliary Operations and Activities

Both cycles include the following processes: coal mining, coal cleaning, coal transportation to the power plant, solid waste collection and transportation, power generation and transmission, and wastewater treatment. In addition, for the multi-product system we include separation of H_2 and CO_2 and delivery of these products to clients via pipelines.

Run-of-mine Illinois #6 coal, mined underground at Sesser County in Illinois, is used in the ASPEN modeling to fuel both plants. Coarse cleaning at the mine mouth is assumed, with refuse returned to the mine. Coal is transported to the plant by rail only. Emissions associated with coal transportation to the power plant include those from diesel fuel use and open rail cars loaded with crushed coal. We do not include emissions associated with manufacturing of diesel fuel and with manufacturing and maintaining rail cars.

It is assumed that power plant solid waste (slag, solids from water treatment, and spent catalysts) is collected in a dewatering pond located on the plant site. After dewatering, this waste is transported to a landfill 40 to 80 km from the power plant. The landfill is designed to prevent leachate, so emissions from solid waste collection and landfill are only from the fuel used for solid waste transportation by rail. Usually, sulfur produced in the Claus cycle is stored at the power plant and sold to clients. No emissions are expected from the sulfur storage process. Finally, depending on the selected water treatment process, most wastewater does not require treatment before being discharged.

3. Construction and Demolition of the Power Plant and Hydrogen and CO_2 Transportation Pipelines.

The power plant construction and demolition analysis applies to both power plant cases. The amount of materials required for the construction of a power plant is broadly proportional to the size and complexity of the plant. The bulk construction materials required are steel, cement, and aggregates in the ratio 1:1:6. Other materials include aluminum, copper, glass, and iron, but in insignificant amounts compared to the first three materials. We have assumed that construction of the co-product and base case plants would require equal amounts of construction materials. The gasifier sections for these plants are identical. Also, the reduction in material use for the power island of the co-product case is offset by the increase in material use for enhanced gas treatment. Fuel use and emissions from the production of these construction materials have been estimated based on the energy required to produce the materials. In addition, we have included fugitive emissions of particulates during construction. Decommissioning will involve some expenditure of energy, depending on the future use of the site. One study advised [5] that the net energy consumption for decommissioning is approximately 10% of the energy consumed in construction. There are two primary solid waste outputs from decommissioning. One of them is scrap metal, which will be partially reused for steel manufacturing. The second is spent shift, SCOT, and Claus catalyst, plus resins from the water treatment unit. This flow of material will be directed to the solid waste module.

Calculations of amounts of materials and energy required for power plant construction and demolition activities, as well as emissions associated with these activities, were performed based on information presented in Gorokhov et al. [6]. All emissions associated with plant construction and demolition were distributed over the assumed 30-yr plant life (alternatively, they could be assigned to the construction period before power plant commissioning and to a demolition period after plant decommissioning).

Construction of H_2 and CO_2 pipelines is included in the scope of analysis. Both pipelines are assumed to be 100 km long. Initial pressurization of both gases before they are sent from the power plant enables delivery without booster compression. Resources used in the LCA analysis for these pipelines include steel and concrete, as well as energy for manufacture and delivery. Accordingly, emissions associated with construction of pipelines include emissions from manufacturing and delivery of materials. We assume that the pipelines will not be demolished.

Emissions allocation. A consistent way to compare the environmental performance of alternative plants is to report emissions per unit of production (e.g., per kilowatt-hour output for the power generating plant). In the case of multi-product plants, emissions should be somehow allocated to the various products. Then these unit emissions can be compared with those from alternative systems for producing the same products. Unfortunately, there is no standardized or unified system that can be recommended to accomplish this allocation. Our approach is to regard hydrogen and fuel gas as two product fuel streams and allocate emissions according to the energy content of each stream. This allocation is applied to (1) all emissions associated with plant operation before separation of H_2 and CO_2, (2) solid waste collection and transportation, (3) plant construction and demolition, and (4) emissions associated with the construction of the CO_2 transportation line. We view CO_2 as a waste stream, which is to be stored underground. If CO_2 were viewed as a product, the allocation scheme would be more difficult. All emissions associated with operation of the combined cycle are allocated to electricity production (including gas and steam turbines, plant water treatment, and the cooling tower); note that this includes the emissions already allocated to the fuel gas. All emissions associated with construction of the hydrogen transportation line are allocated to the hydrogen flow. This allocation scheme facilitates comparison of the environmental performance of the power production part of the co-product plant with the base case IGCC plant that only produces electricity.

In principle, we could compare the emissions allocated to the H_2 stream with the performance of some common hydrogen-manufacturing processes. However, that comparison is not included in this paper. The H_2 product is assumed to be used for electricity generation by a solid oxide fuel cell [7]. Such a fuel cell has demonstrated 46% efficiency for power generation. In addition, the same demonstration plant produces thermal energy (in the form of hot water) at a rate of about 27.2% of the energy available in hydrogen flow. All emissions associated with the hydrogen flow are allocated to electric and thermal energy flows from the fuel cell. Thus, emissions allocated to the electric energy flow from the fuel cell (85,536 kW) and converted to the "per kWh generated" basis can now be fairly compared with the environmental burden per kilowatt-hour generated in the combined cycle of the co-product plant or the base case.

Emission Inventory Analysis. Bituminous coal and water are the major material inputs. Other fuels and electricity are used mostly for coal extraction and transportation and for solid waste transportation. Although the amounts of steel and concrete needed for plant construction are significant, the per-kWh amounts, distributed over the 30 years of expected plant life, are several orders of magnitude lower than the amounts of coal and water used for production of electricity.

Emission inventory results for some components are presented in Figure 3. Contributions to emissions by each phase of the process are presented as percentages of the total for each emitted species. On a mass basis, CO_2 is the dominant gaseous emission for the base case power plant. Most of this CO_2 is produced in the power cycle. In the multi-product plant, more than 90% of the potential CO_2 is captured. Coal extraction and transportation processes result in the next largest emissions stream, though that stream is two orders of magnitude smaller than the emissions from the power cycle; consequently, total CO_2 emissions from the multi-product cycle are significantly lower. CO_2 emissions are followed in magnitude by CO emissions, also released mainly in the power cycle. Methane released via coal mining represents the third largest emission. NO_x emissions are associated mostly with coal extraction and transportation, while SO_x emissions are generated only from the power cycle. Almost all organic emissions identified in the inventory assessment are associated with fuel use for extraction of coal and transportation of coal, waste, and construction materials.

As expected, significant particulate matter emissions are associated with coal extraction and transportation and with the construction/ demolition processes. Note that when the construction and demolition particulates are levelized over the power plant life cycle, the amount (per kWh) is of the same order of magnitude as from extraction and transportation of coal, probably because the construction process includes all emissions associated with extraction of iron ore, development of cement and coke, transportation of these materials, and particulates from the construction site itself. In this analysis, these emissions are distributed over the 30-yr power plant life, while in reality all these emissions are released to the air shed in about a two- to four-year period during power plant construction. Thus, the local impact of these emissions can be very significant. Slag, the most significant solid emission, is expected to have minor impacts, especially since it is a useful by-product.

LIFE CYCLE IMPACT ASSESSMENT (LCIA)

LCIA is a technical, quantitative, and/or qualitative process of characterizing and assessing the environmental effects of plant resource requirements and environmental loadings identified in inventory collection. Strictly speaking, it should address all human health, ecological, and resource depletion impacts. This assessment reports the inventory results as a distillation of inventory loadings and resource use assigned to specific impact categories.

A broad spectrum of impact categories has been developed in the practice of LCIA. The number of selected categories and their nature generally influence the amount of work required to perform the LCIA. Based on previous experience [6], 12 categories are selected as the most important for the evaluation of power cycles. These are identified below, aggregated into three broad impact groups:

Natural Environment - *Acidification, eutrophication, smog, global climate changes, and ecotoxicological impacts (aquatic and terrestrial toxicity);*
Human Health - *Toxicological impacts, PM_{10} inhalation effects, and carcinogenic impacts*; and
Natural Resources- *Depletion of fuels and water.*

Some products, resources, or emissions can be involved in more than one impact category. The same emission/product may contribute to two or more exclusive categories in a parallel or sequential manner, and the emission should be divided or allocated to the relevant categories to avoid double counting. It is also possible that the product or result of an effect in one impact category may be the starting point for another effect in another impact category. To deal with such complexities, LCIA procedure in this project was simplified by (1) accounting for primary emission impacts only and (2) not distributing a particular product/emission among a number of different applicable impact categories, but rather assigning the full value of that product/emission to each applicable category, to determine the worst case impact.

The relative significance of each environmental loading is represented by category indicators, which usually incorporate a spectrum of results ranging from technical values to subjective judgments. These indicators are the basis on which comparisons can be made, so the value of a comparison depends on the varying technical strength and relevance, as well as the degree and type of subjective judgment used to derive a particular indicator. Some indicators can be estimated as a total amount of a single material or emission, such as water use or PM_{10} emission. Other indicators can represent the total amount of different species. For example, land depletion resulting from landfill of waste can be represented by the total space occupied by all types of landfilled solid waste. In many cases, data on individual chemicals or resources within an impact category must be combined, using so-called "equivalency factors." These equivalency factors express the relative hazard potential of different chemicals within an impact category, but they do not represent actual environmental impact. SETAC and other organizations have developed numerous equivalency factors and provided recommendations for development of new equivalency factors. A brief description is provided below for each impact category, together with the list of inventory items assigned to this category, as well as a basis for calculating category indicators with the relevant equivalency factors.

Acidification. Acidifying substances cause a large diversity of impacts on soil, groundwater, and surface water organisms, ecosystems, and materials (buildings). The most important acidifying compounds are SO_2, NO_x, and NH_3. Acidification potentials (APs) based on H^+ equivalents are used as equivalency factors to calculate the total indicator for acidification. The total indicator score is expressed in kilograms of SO_2 equivalents.

Eutrophication. This category includes all impacts caused by excessively high levels of macronutrients in the environment. Nitrogen (N) and phosphorus (P) are the most important eutrophicating elements. Eutrophication potentials (EPs) are used as equivalency factors to calculate the total indicator for eutrophication. The EPs reflect the potential contribution of a substance to biomass formation and are expressed in kilograms of PO_4^{3-} equivalents. Major contributors to this impact for both power cycles are ammonia and NO_x.

Smog or Photo-Oxidant Formation Impact. Photo-oxidants can be formed in the troposphere via photochemical oxidation of volatile organic compounds (VOCs) or carbon monoxide (CO) in the presence of NO_x and under the influence of UV light. Ozone is considered to be the most important oxidant. The Maximum Incremental Reactivity (MIR) scoring system, developed by W. Carter, is used to calculate the total indicator for the formation of photo-oxidants, converted to kilograms of ozone formed [3].

Global Climate Changes. Global warming is the impact of fossil fuel emissions on heat radiation absorption in the atmosphere. Major contributors are CO_2, methane, and N_2O. Global Warming Potentials (GWPs) are used as equivalency factors, to convert all emissions into kilograms of CO_2-equivalent [3].

Ecotoxicological Impacts. These impacts are the effects of toxic substances on aquatic and terrestrial ecosystems. Only emissions to water and soil are taken into account in this category. Emissions to water are considered to be toxic only for aquatic ecosystems, and emissions to soil are considered to be toxic only for terrestrial ecosystems. Toxicity factors for these toxicity impact criteria were calculated using a combination of the toxicity, persistence, and bioaccumulation properties of the inventoried chemicals to assess their potential fate and environmental effects. Data used for terrestrial toxicity and aquatic toxicity were lowest rodent LD_{50} (mg/kg) and lowest fish LC_{50} (mg/L) [8,9].

Toxicological Impacts on Human Health. This impact category reflects the effects of toxic substances on humans. There are different ways for these substances to enter the human body (inhalation, water, food, etc.), but only the inhalation and water effects are evaluated here. Factors for these toxicity impact criteria were calculated using Toxic Equivalency Potentials (TEPs), which indicate the relative human health risk associated with the release of one pound of a chemical, compared to the risk posed by release of a reference chemical. In this risk scoring system, all releases of carcinogens are converted to pounds of benzene-equivalents; all releases of chemicals that cause non-cancer health effects are converted to pounds of toluene-equivalents [3].

PM_{10} Inhalation Impact. PM_{10} inhalation affects human health via chronic and nonchronic (short-term) respiratory diseases, increasing both human mortality and morbidity rates in exposed areas. The equivalency factor was estimated as the total weight of solid particulate matter released to the atmosphere.

Depletion of Fuel and Water. These categories characterize depletion of so-called abiotic resources. The basis for resource depletion equivalency factors is the inverse of sustainability, which can be expressed as the world annual production of a mineral or a fossil fuel divided by the world reserve base [3,8]. For example, the fossil fuel data, based on global reserves and production, were obtained from Ref. 10. The calculations include all types of fuel used in the power cycle, as well as in all other activities for manufacturing and transportation of all materials included in the inventory.

Depletion of Land. This impact category focuses only on the loss of land as a result of coal mining or other fuel development operations, and the use of land for landfilling of waste. Because no specific place and type of coal mining were chosen, only use of land for waste landfills was evaluated in this project. The land-use equivalency factors for solid waste disposal are based on the estimated volume calculated using the specific gravity of each type of solid waste. Inventory data for solid waste are expressed in kg/kW; multiplication of the weight and the inverse of the specific gravity give an indicator of the waste volume per kilowatt, and thus, the landfill volume required per kilowatt of developed energy.

LCIA RESULTS

A comparison of unweighted impact scores for all impact categories is presented in Table 3 for three power cycles – base-case IGCC cycle (column 1), multi-product IGCC cycle with separation of CO_2 (Columns 2,3,4), and an electricity-generating IGCC cycle with CO_2 separation modeled by the IEA [5] (Column 5). Column 2 presents data for the combined-cycle part of the multi-product system. Column 3 contains data for electricity generated by fuel cells from H_2. Column 4 contains average weighted data for columns 2 and 3. The last four columns in this table represent a shorthand way of comparing the base-case IGCC and multi-product IGCC cycles in terms of environmental impacts. If values in this column are substantially larger than one, the alternative cycle has greater environmental impact than the base case cycle. Values within 20% of unity indicate that the impact potentials of the two cycles are not distinguishable [13]. For example, results in the column B/A show that the combined cycle of the multi-product system has significantly higher environmental performance than the base case in such categories as eutrophication and toxicity (better reduction of acids and NO_x), GCC (more than 90% of CO_2 captured), and water use (steam generating cycle significantly smaller than in the base case). On the other hand, its impact in such categories as PM_{10}, smog, air toxicity, land use, and resource depletion is much higher, because overall efficiency of the cycle is less due to the additional auxiliary power required for CO_2 pressurization. Results in the column D/A show that overall performance of the multi-product plant (for both flows of electricity generation – from combined cycle and from H_2 – fuel cell cycle) is even worse. Only GCC and terrestrial toxicity impacts are lower in this case, because the greatest amount of CO_2 is captured. The generation of electricity from H_2 through the fuel cell has maximum environmental impacts in all categories except GCC. Performance of the IEA-developed IGCC cycle with CO_2 capture is similar to that of the combined cycle part of the multi-product system.

CONCLUSIONS

- This process design employs a Shell IGCC cycle in a "Vision 21" multi-product plant with a low greenhouse impact. Hydrogen can be cogenerated with electricity and delivered to consumers at very high purities. The selection of a very high purity hydrogen product stream benefits the high-efficiency performance of fuel cells while still meeting the internal power needs of the IGCC and having a revenue stream from electricity sales. The introduction of "Shift" to increase the hydrogen content of the gasifier product also benefits the CO_2 recovery, which has inherent cost advantages if it is largely removed prior to the combustion turbines.
- Based on emission inventory analysis, the most CO_2, CO, and SO_2 are generated in the IGCC cycle, methane emissions are mostly associated with coal mining, and particulate matter is mostly generated in construction and demolition of the plant and pipelines. Transportation and mining are responsible for NO_x emissions.
- Environmental performance of the electricity-generating part of the co-product system is similar to that of the IGCC-based cycle with CO_2 removal. However, the co-product plant has larger environmental impact than a base case IGCC system without CO_2 removal in almost all impact categories, because of the higher auxiliary power requirement connected to CO_2 pressurization before its output from the power plant. Removal of CO_2 and deeper reduction of acid gas emissions makes the multi-product system better in the GCC, toxicity, and eutrophication categories.

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Table 1. Comparison of Design Basis for Base and Co-Product Cases

Process	**Base Case**	**Co-Product Case**
Gasification	Both facilities use Shell gasification with cold gas cleanup. Raw gas is produced at 1844°F and 352 psia.	
Ash removal	This is a slagging gasifier with slag quench.	
Air separation	Cryogenic air separation with partial integration (N_2 used as diluent for combustion turbine)	
High-temperature gas cooling/particulate removal	Used to raise high-pressure, superheated steam	Also used for combustion turbine fuel gas preheat
COS hydrolysis	Single stage to form H_2S and CO_2	
Shift reaction	Not applicable	Two-stage shift to convert raw gas to high H_2 and CO_2 content
H_2S recovery	MDEA	Glycol used for improved selectivity (H_2S vs. CO_2)
Acid gas treatment	Claus-SCOT using filtered raw gas as SCOT reagent	Claus-SCOT using H_2 product as reagent
CO_2 removal	Not applicable	Glycol
H_2 purification	Not applicable	Pressure Swing Adsorption
Combustion turbine fuel	Synthesis gas cleaned of sulfur and particulates	Residual gas rejected by PSA
Steam cycle heat source	Gas turbine exhaust	Gas turbine exhaust and heat recovery from shift reaction

Table 2 Comparison of Plant Performance for Base and Co-Product Cases

Item	Base Case	Co-Product Case
Coal consumption, ton/day	3171.0	3171.0
Gas turbine power, MW	272.3	143.3
Steam cycle power, MW	188.8	44.4
Internal power consumption, MW	- 48.3	-77.4
Net electricity, MW	412.8	110.3
H_2 production (equivalent MW)	0	423.2 – 100% effic. 275.1 – 65% effic. 194.7 – 46% effic.
CO_2 product, ton/day	0	6855.0
CO_2 emissions, ton/day	7412.0	548.0

Table 3. Comparison of Unweighted Impact Scores for Three Power Cycles

Impact Category	Base Case Cycle (Case A)*	Multi-Product Cycle, Combined Part (Case B)	Multi-Product Cycle, Hydrogen Part (Case C)	Multi-Product Cycle, Average (Case D)	IEA IGCC Cycle with CO_2 Separation (Case E)	B/A	C/A	D/A	E/A
Global Climate Change	1.56E+00	4.90E-01	1.35E-01	3.83E-01	2.80E-01	0.31	0.09	0.25	0.18
Acidification	5.03E-04	3.19E-04	4.09E-04	3.46E-04	3.46E-04	0.63	0.81	0.69	0.69
Eutrophication	8.72E-01	9.43E-01	7.77E-02	6.83E-01	1.13E+00	1.08	0.09	0.78	1.29
Particulate Matter (PM_{10})	3.27E-04	3.31E-04	4.39E-04	3.63E-04	4.17E-04	1.01	1.34	1.11	1.28
Smog	1.89E-03	2.70E-03	5.03E-03	3.40E-03	5.10E-03	1.43	2.67	1.80	2.70
Terrestrial Toxicity	8.27E-06	6.55E-07	1.15E-06	8.02E-07	1.07E-06	0.08	0.14	0.10	0.13
Aquatic Toxicity	8.00E-06	1.19E-05	1.95E-08	8.33E-06	1.69E-08	1.49	0.00	1.04	0.00
Human Toxicity (Air)	1.11E-02	1.08E-02	1.36E-02	1.16E-02	1.05E-02	0.97	1.23	1.05	0.95
Human Toxicity/ (Water)	2.16E-08	3.21E-08	5.30E-11	2.25E-08	4.26E-08	1.49	0.00	1.04	1.97
Carcinogenicity (Air)	2.02E-08	1.69E-08	2.49E-08	1.93E-08	1.17E-08	0.84	1.23	0.96	0.58
Resource Depletion	5.66E-03	5.53E-03	6.98E-03	5.97E-03	3.64E-03	0.98	1.23	1.05	0.64
Land Use	1.09E-01	1.06E-01	1.33E-01	1.14E-01	8.69E-02	0.97	1.22	1.05	0.80
Water Use	1.43E+00	2.18E+00	2.11E-01	1.59E+00	3.56E+00	1.53	0.15	1.11	2.50

(*) A – Base case IGCC cycle without H_2 and CO_2 separation; net power output – 412.8 MW. B – Multi-product system, combined cycle only; net power output – 110.3 MW. C – Multi-product system, hydrogen – fuel cell cycle only (46% efficiency); net power output – 85.5 MW. D – Multi-product system, aggregated combined cycle and hydrogen cycle; net power output – 195.8 MW. E – IEA IGCC cycle with separation of CO_2; net power output – 646 MW.

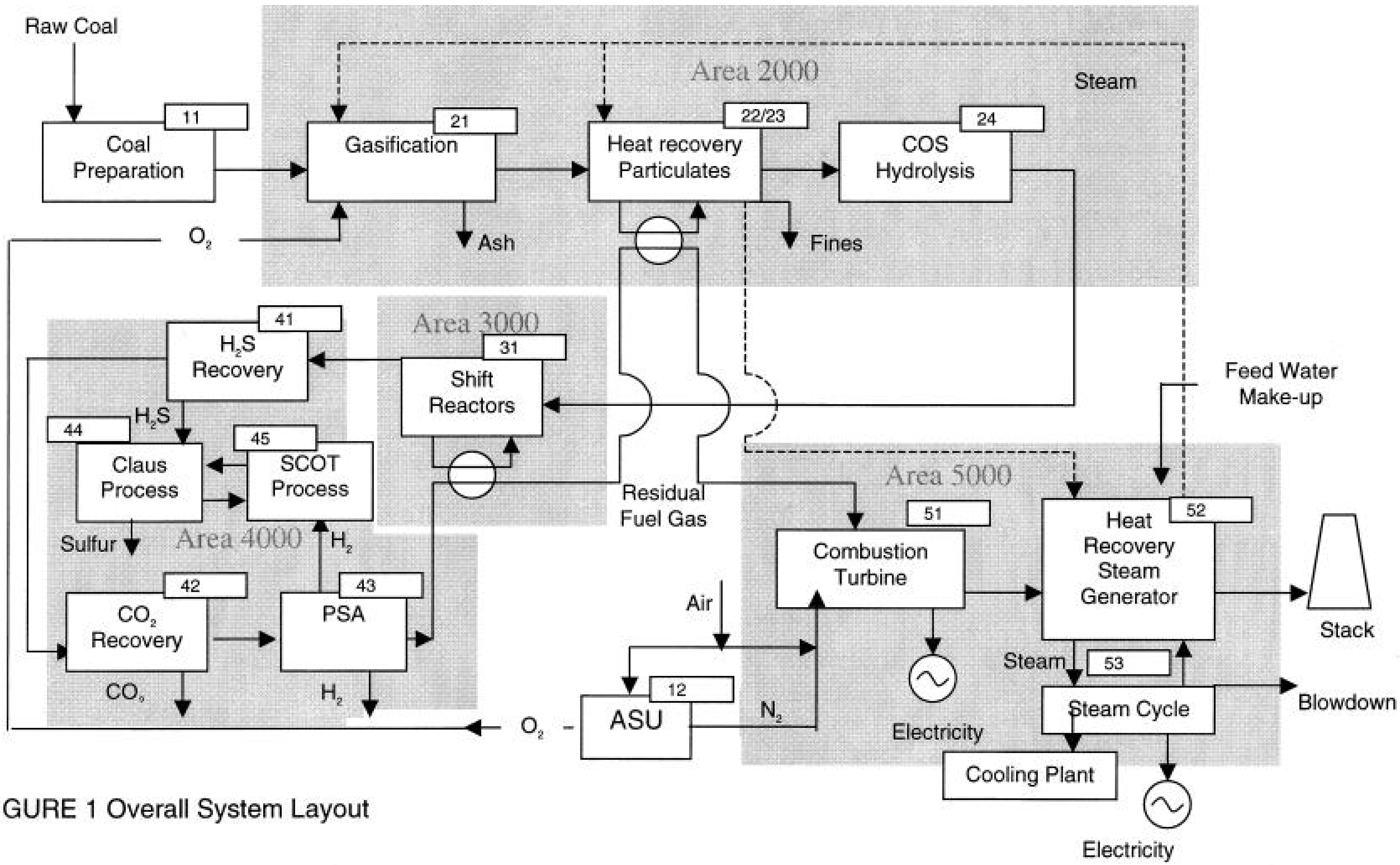

FIGURE 1 Overall System Layout

Fig. 2.Coal-fired IGCC-based Multi-product System