## Title
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# COAL-BASED POWER PLANT SYSTEM CONFIGURATIONS FOR THE 21ST CENTURY

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## ABSTRACT

Under the sponsorship of the U.S. Department of Energy/National Energy Technology Laboratory, a multi-disciplinary team led by the Advanced Power and Energy Program of the University of California at Irvine is defining the system engineering issues associated with the integration of key components and subsystems into power plant systems that meet performance and emission goals of the Vision 21 program. Earlier tasks of the program have narrowed down the myriad of fuel processing, power generation, and emission control technologies to selected scenarios that identify those combinations having the potential to achieve the Vision 21 program goals of high efficiency and minimized environmental impact while using fossil fuels. These analyses have been extended to consider coal gasification processes combined with the advanced power cycles previously identified. The technology levels considered are based on projected technical and manufacturing advances being made in industry and on advances identified in current and future government supported research. Examples of systems included in these advanced cycles are solid oxide fuel cells, advanced cycle gas turbines, and membrane separation of gases.

## INTRODUCTION

The overall objectives of the Vision 21 program sponsored by the National Energy Technology Laboratory (NETL) of the U. S. Department of Energy (DOE) are:

- produce electricity and transportation fuels at competitive costs
- minimize environmental impacts associated with fossil fuel usage, and
- attain high efficiency.

The efficiency targets are 75 percent (LHV) for natural gas fueled plants and 60 percent (HHV) for coal fueled plants producing electricity only, that is, plants without $CO_2$ capture nor coproduction of any transportation fuels or $H_2$.

Specifically, the objective of this program being conducted by the multi-disciplinary team led by the Advanced Power and Energy Program (APEP) of the University of California at Irvine is to identify gas and coal based system configurations that meet the above Vision 21 goals with emphasis on attaining the highest performance. The results of this investigation will serve as a guide for the U. S. DOE in identifying the research areas and technologies that warrant further support.

The approach taken in this investigation has been reported previously [Rao, A.D., et al, 2002]. Briefly, it consists of first identifying the sub-systems that make up a complete power plant followed by a screening analysis in order to narrow down the number of possible configurations for more detailed analysis. It was shown that without fuel cells, gas turbine based cycles alone even with very high firing temperatures cannot meet the efficiency goals of the Vision 21 program. These included inter-cooled, reheat, and recuperated cycles (e.g., Ericsson), combined cycles including those incorporating bottoming cycles such as the Kalina cycle, and the Humid Air Turbine (HAT) cycle [Rao, A.D., 1989].

 

Thus, gas turbines integrated with fuel cells (hybrids) are required for these Vision 21 power plants.

## ANALYSIS TOOL

A special steady-state simulation tool – Advanced Power System Analysis Tool (APSAT), developed at the University of California, Irvine is applied along with Pratt and Whitney's proprietary State-of-the–Art-Performance Program (SOAPP) to simulate and analyze these advanced systems.

APSAT was specifically developed to handle complex configurations of advanced energy systems, especially those combining electrochemical and thermo-mechanical components in various thermodynamic cycles. More details about the analytical and computational strategies about APSAT have been described previously [Rao and Samuelsen, 2002]. APSAT was validated by comparing the predicted performance for the Siemens-Westinghouse 220 kW Solid Oxide Fuel Cell / Gas Turbine (SOFC/GT) hybrid located at the National Fuel Cell Research Center to actual operating data collected. The comparison between the predictions made by APSAT with observed data are presented in Table 1.

**Table 1: Comparison of Simulation Results with Measured Data**

| | Measured | Predicted |
|---|---|---|
| **Gas Turbine**<br>Power output, kW | 21 | 21.60 |
| **SOFC Stack** | | |
| Cell Voltage, Volts | 0.639 | 0.633 |
| Stack Voltage, Volts | 244 | 243.1 |
| Current, Amps | 700 | 694.2 |
| DC Power output, kW | 170.8 | 168.78 |
| **Total System** | | |
| Adjusted AC power output, kW | 183.45 | 181.94 |
| System efficiency, % | 52.44 | 51.92 |

SOAPP consists of modules representing components (compressors, turbines, pumps, etc.) which are assembled into a "design" by a powerful preprocessor containing the necessary databases and performance maps. The modules use physical and thermodynamic laws to describe the component and how it functions. Changes in characteristics for a particular module or for many modules can be specified and SOAPP will determine new performance parameters for the overall system. Conversely, target performance goals can be specified and the requirements for various components can be determined.

## SUB-SYSTEM SELECTION

Options for the sub-systems for natural gas and coal are depicted in Figure 1 along with various combinations for linking of the fuel with the fuel processing technology, power generation technology and emissions control technology. The characteristics of pipeline quality natural gas allow it to be used directly in gas turbine based cycles such as an intercooled (ICGT) gas turbine, a combined cycle, a HAT cycle, or combusted in boilers, typically without any fuel processing. Natural gas may also be used in fuel cells after some treatment (desulfurization, humidification and reforming). Among the various power generation options for natural gas as shown in Figure 1, direct combustion in a boiler may be eliminated, the thermal efficiency of the other options consisting of utilizing gas turbines or fuel cells being significantly higher while NOx emissions being lower, especially with the HAT cycle and the fuel cell options. The HAT cycle does not require any form of NOx control because of the large concentration of water vapor present in the combustion air which minimizes the formation of thermal NOx [Bhargava, 1999]. The fuel cells, which oxidize the fuel predominantly by electrochemical reactions, do not require any form of NOx control either; combustion of the depleted fuel leaving the cell produces very low amounts of NOx.

These same options consisting of gas turbine based technologies or fuel cells can be used in coal-based plants if the coal is gasified to produce syn gas and the contaminants removed from the syn gas prior to supplying the gas to the power block. Fuel specifications for fuel cells and high performance gas turbines are very stringent (high performance gas turbines have strict limits on levels of contaminants that include sulfur, alkaline metals, vanadium). Alternately, if coal is directly used as in various types of boilers or in indirectly fired cycles, the effluent from the power generation systems will require extensive post combustion emission controls such as flue gas desulfurization, NOx, particulate and trace element removal devices. In gasification on the other hand, the syn gas cleanup to remove contaminants such as the sulfur and nitrogen compounds, and particulates is performed on a gas stream with a significantly smaller volume and with contaminant concentrations significantly higher, making it much easier to remove. Heavy petroleum fractions and biomass must also be processed and cleaned in a similar manner before these fuels can be "integrated" with the power generation system.

The gasification sub-system is further divided into a number of processing units including the oxidant supply unit. Whether the gasification process uses oxygen or air depends on the operating temperature of the gasifier and whether hot syn gas clean up is utilized. With air blown systems, the efficiency of the gasifier (by itself) is lower and larger down stream equipment is required for processing the syn gas which is diluted with nitrogen. For a gasifier operating at high temperatures (in excess of 1000 C), the nitrogen accompanying the oxygen in the air increases the degradation of the chemically bound energy of the coal into sensible heat energy within the gasifier, which is carried away with the syn gas, thus reducing the cold gas efficiency of the gasifier. On the other hand, the air separation unit is eliminated along with its parasitic loads and high capital cost.

This initial Sub-system Selection task eliminated from consideration the direct combustion of the fuels, indicated that fuel processing in case of coal will be either oxygen or air blown gasification depending on the gasifier operating temperature and syn gas cooling, and set the requirements for gas clean up based on the specifications dictated by the high performance gas turbines and fuel cells. Note that the gasification option makes the power cycles fuel flexible.

With respect to the power generation technology option, as mentioned previously cycles based on a gas turbine alone without the fuel cell cannot meet the efficiency goals of the Vision 21 program. The calculated efficiency of an advanced combined cycle utilizing a steam cooled gas turbine, even with a combustor exhaust temperature as high as 1900 C (3450 F), was estimated to be in the neighborhood of 65 percent (LHV), which is significantly lower than the 75 percent (LHV) goal for natural gas. With the HAT cycle, a higher combustor exhaust temperature may be utilized since the cycle is not as constrained by NOx emissions as the combined cycle [Chen, et al., 2002]. Still, the efficiency is limited to less than 70 percent (LHV) for natural gas. Thus, gas turbines integrated with fuel cells (hybrids) are required for these Vision 21 power plants.

## SCREENING ANALYSIS

A power plant with a nominal output of 300 to 400 MW has been selected as representative of the minimum economic size for central power stations, especially those with gasification. Each of the systems has a gas turbine, or a gas turbine-like component. The initial screening analyses identified three categories of natural gas fueled hybrid cycles having the potential to reach the Vision 21 efficiency goal:

1. High-pressure, internally reforming SOFC integrated with a high-pressure ratio intercooled gas turbine
2. High-pressure, internally reforming SOFC integrated with the HAT cycle
3. Near atmospheric pressure, internally reforming MCFC integrated with a high-pressure ratio intercooled gas turbine.

Additionally for the gas-fired systems, two “zero emission” plants, i.e., plants recovering the $CO_2$ for sequestration were also considered:

4. $O_2$ breathing high-pressure SOFC integrated with HAT cycle and $CO_2$ recycle
5. Advanced Rankine cycle (using gas turbine technology) combusting $H_2$ with $O_2$ in rocket engine technology combustor.

The power cycles utilized in the coal-based cases were selected from these cycles. The results of the screening analysis indicated that:

### Natural Gas Cases

- Both the pressurized SOFC hybrids configurations can meet the 75 percent thermal efficiency (LHV) target at ISO ambient conditions while limiting the per-pass fuel utilization to approximately 80 percent.
- The SOFC/HAT hybrid had a significantly higher specific power output than any of the other cycles while achieving the thermal efficiency goal at a more modest cycle pressure ratio of 20 as compared to 50 for the intercooled gas turbine SOFC hybrid.
- The atmospheric pressure MCFC hybrid configurations can achieve the 75 percent thermal efficiency goal when the fuel utilization is increased to approach 90 percent.
- The $O_2$ breathing SOFC hybrid configuration with $CO_2$ recovery can achieve a thermal efficiency of about 60 percent (LHV) while the efficiency of the advanced Rankine cycle combusting $H_2$ with $O_2$ was limited to less than 55 percent thermal efficiency (LHV).

### Coal Based Cases

- Conventional high temperature gasification based hybrids even with high temperature gas cleanup do not quite reach the Vision 21 efficiency goal of 60 percent (HHV) at ISO ambient conditions.
- Lower temperature gasification is required to increase the cold gas efficiency and thus the overall power plant thermal efficiency in order to achieve the Vision 21 efficiency goal as long as reasonable carbon conversions can be maintained within the gasifier.

## DETAILED ANALYSIS

The detailed analysis phase of this study consists of conducting detailed performance analysis of cases that have evolved from the screening phase, the ultimate goal being to prove a definition for the fuel cell and the gas turbine design parameters along with the interface conditions between the fuel cell, the gas turbine and the balance of plant. Rough order of magnitude plant installed costs will also be developed after completion of the process design to set targets for the sub-systems (e.g., fuel cell) developers such that these plants can produce electricity or coproduce transportation fuels at competitive costs.

These selected coal based cases for the detailed analysis are described in the following while the natural gas based case selected for detailed analysis has been described previously [Rao, Samuelsen and Yi, 2003]. The design basis for this study has also been presented previously [Rao et. al., 2003] utilizing guidance provided by Pratt and Whitney for the gas turbine. It should be noted, however, that the gas turbine firing temperature for the hybrid cases was significantly lower than the upper limit set in the design basis since the efficiency of hybrid systems investigated was maximized as the turbine inlet temperature was minimized for a given air (or humidified air) to fuel ratio in the fuel cell.

### Coal Based Advanced Transport Reactor (ATR) Gasification SOFC Hybrid

The ATR, which has features of a circulating fluidized bed gasifier, is being developed under sponsorship of the DOE at Wilsonville, Alabama [Leonard et.al., 2001]. A smaller scale ATR is also operated by the Energy and Environmental Research Center at the University of North Dakota [Swanson and Hajicek, 2002]. The ATR has the potential for achieving the overall plant efficiency goals of Vision 21, the main reasons being that (1) the raw syn gas leaves the gasifier at a lower temperature (thus a lower fraction of the coal bound energy is degraded to thermal within the gasifier), and (2) a correspondingly lower oxidant demand. Furthermore, the lower raw syn gas temperature requires less cooldown, making the syn gas coolers less expensive.

Emission of mercury from coal-based power plants has gained much attention in the recent past. Mercury may be removed from the syn gas very effectively by passing the gas through a sulfided activated carbon bed where the mercury is adsorbed. The activated carbon bed is also expected to capture any arsenic present in the syn gas. The effectiveness of the carbon bed is at operating temperatures that are near ambient temperatures and thus cannot be utilized with hot gas cleanup. Thus, the syn gas treatment system as depicted in Figure 2 consists of cold gas cleanup. Preheating of the treated syn gas against the raw gas to improve the overall system efficiency is included but in order to avoid any leakage of the raw gas into the clean syn gas, the syn gas is compressed prior to being supplied to the heater.

In this system, a small fraction of the gas turbine compressor discharge air is sent to an aftercooler, boosted in pressure, recuperated and sent to the mixing zone of the ATR gasifier. Steam is also injected at this point. Coal along with limestone for in-bed sulfur capture (about 85 percent of the sulfur is expected to be captured along with over 90 percent of the chlorine) is added to the upper stage of the mixing zone. The gas exits the top of the gasifier riser and goes to a primary cyclone that is connected to a standpipe that receives the unburned char and ash/bed material for recirculation back to the mixing zone. A purge stream, which maintains inventory, is removed and mixed with discharge from the downstream filter for use in a char burner. The syn gas leaves the gasifier at approximately 1040 C (1900 F) and is cooled to 590 C (1100 F) by superheating/reheating steam in a gas cooler. It then goes to a barrier filter where over 99.99 percent of the remaining particulates are removed. The gas after further cooling against clean syn gas is scrubbed and then fed to the low temperature heat recovery unit. This unit includes additional heat recovery and the mercury removal system. The cooled gas is next treated in a Sulferox® unit to remove the residual portions of the sulfur compounds present in the syn gas while elemental sulfur is produced. The desulfurized syn gas is supplied to the SOFC at a pressure of 1,880 kPa after it is compressed and preheated against the raw gas. The bottoming cycle in the power block consists of a combined cycle. Char and purged bed material are fed to an atmospheric fluid bed boiler and the heat is recovered by generating superheated steam which is supplied to the combined cycle unit. The resulting overall plant net efficiency meets the Vision 21 goal of 60 percent (HHV) at ISO ambient conditions.

### Coal Based "Zero Emission" Plant with Vision 21 Technology

The schematic for the power block integrated with the gasification and cleanup is shown in Figure 3. In this system, coal, bed material (essentially limestone with small amounts of dolomite), steam, and oxygen [supplied by an Ion Transport Membrane (ITM) or Oxygen Transport Membrane (OTM) unit] are fed to the ATR. The hot fuel gas, which has had 85 percent of the sulfur removed in-situ, is cooled from 1070 C (1960 F) to nominally 535 C (1000 F) before going to a chloride guard (Nacholite) bed, which also removes any other remaining halides. From the chloride guard bed, the fuel gas goes to a high-temperature cleanup made up of a zinc titinate bed and final particulate filter. The fuel gas, which has been heated somewhat by the cleanup reactions, then goes to the SOFC unit at a pressure of 1,880 kPa.

 

The fuel cell is used not only to generate power, but also to provide hot air (cathode exhaust gas) at a pressure of 1,730 kPa for the ITM (or OTM) unit for the separation of air. The anode exhaust is cooled against steam and enters a shift reactor to convert the remaining CO to $CO_2$ while producing $H_2$. The shifted gas, now mainly $CO_2$ with some $H_2$ and a small concentration of CO goes to a $H_2$ membrane separator to capture 80 percent of the $H_2$ for recycle to the SOFC. Alternately, a membrane shift unit can be utilized. The non-permeate is fed to a catalytic combustor using $O_2$ from the ITM/OTM oxygen plant to fully remove the small amounts of any remaining CO and $H_2$, leaving only $CO_2$, $H_2O$, and a very small amount of $O_2$ in the stream. This stream is cooled, the Hg is removed in the sulfided activated carbon bed and the cooled $CO_2$ stream is compressed to the supercritical pressure of the $CO_2$. Next it is dehydrated and then pumped to the pipeline pressure of 13,900 kPa.

On the cathode side, the compressed air, at approximately 2,000 kPa, is heated in a regenerator within the SOFC system. The hot depleted air exiting the cathode enters the hot side of the regenerator and is cooled to 900 C (1650 F), the temperature required by the ITM/OTM unit for air separation. In this membrane unit, $O_2$ is removed from the already vitiated air and exits the unit at sub-atmospheric pressure. The $O_2$, assumed to be 100 percent, is cooled and compressed to gasifier pressure with a small side stream going to the catalytic "cleanup" burner. The non-permeate, now reduced in mass flow and pressure, is expanded in the turbine and exhausts to an HRSG. The gas turbine output is significantly reduced because of its low firing temperature, essentially 900 C (1650 F) and the reduced flow. A parametric analysis of the effect of overall compression ratio indicated that pressure ration around 20 was the most desirable in this configuration.

The configuration includes a small CFB combustor that recovers energy from the unburned carbon and also oxidizes the CaS. A small fuel gas stream is also burned in the combustor to maintain it at a temperature of 870 C (1600 F). Steam is raised in this system. The steam system in addition to utilizing heat from the CFB and the gasifier effluent, utilizes various heat exchangers throughout the plant.

The resulting overall system efficiency of greater than 50 percent on a HHV basis is quite impressive for a system that captures essentially 100 percent of the $CO_2$ in the process. The use of the ITM/OTM reduces some of the power requirements normally associated with $O_2$ production, although it compromises the gas turbine operation.

## Coal Based "Zero Emission" Plant with Near Term Technology

This case is included in the analysis in order to provide a benchmark for quantifying the improvement in the performance and cost achieved by the previous case incorporating the Vision 21 technology over near term technology. As depicted in Figure 4, the high pressure $O_2$ blown slurry fed entrained bed "total quench" gasifier (ChevronTexaco type) with cold gas cleanup is utilized while shifting the scrubbed sour syn gas (pre-combustion $CO_2$ recovery) followed by desulfurization of the syn gas as well as $CO_2$ removal/capture in a Selexol® unit. The acid gas generated in this unit is supplied to a Claus sulfur recovery unit and the tail gas from the Claus unit (after hydrogenation) is recycled back to the Selexol® unit. The $CO_2$ is produced in the Selexol® unit at 930 kPa and some at 140 kPa. It is first compressed to the supercritical pressure of the $CO_2$ and then it is dehydrated and pumped to the pipeline pressure of 13,900 kPa.

The power block consists of the HAT cycle which was chosen because it integrates synergistically with the "total quench" gasifier [Rao, et. al., 1993].

An overall plant net efficiency of about 33 percent (HHV) is achieved at ISO ambient conditions while capturing 85 percent of the gaseous carbon compounds present in the syn gas. This efficiency is significantly lower than that of the previous case that utilizes the Vision 21 technology.

## Coal Based $H_2$ Coproduction with $CO_2$ Capture (Advanced FutureGen)

Recently, the DOE has made announcements regarding the building of a FutureGen plant, coproduces $H_2$ while recovering the $CO_2$. $H_2$ is being touted as the clean transportation fuel of the future for automobiles powered by fuel cells. Thus, this case is included in the analysis in order to quantify the coproduction of merchant grade $H_2$ for Pt-based catalyst end uses (CO limited to 10 and 5-"nines" purity) while all emissions including $CO_2$ are controlled. This coproduction plant should be able to duty cycling between fuel production versus power and while taking advantage of other synergies of coproduction such as energy integration.

This plant applies Vision 21 technology and the major features of this configuration include a shift converter and $H_2$ separation membrane in the fuel gas stream and a $H_2$ compression system. Essentially 100 percent of the $CO_2$ is also removed as in the previously described Zero Emission Plant with V21 Technology. For comparative purposes, the coal flow rate is set at the same rate as this previous case.

The $H_2$ membrane separation efficiency is again assumed to be 80 percent at design point (the economic optimum according to some of the membrane developers).

Such a plant is conceptualized in Figure 5 while incorporating the advanced Vision 21 technology. It consists of an $O_2$ blown ATR with hot gas cleanup followed by a high temperature membrane unit where some shifting of the syn gas also occurs. This membrane unit separates the $H_2$. The non-permeate gas from the membrane unit consisting primarily of CO, $CO_2$, remainder of the $H_2$, $H_2O$ and inerts such as $N_2$ and Ar is fed to the anode side of a SOFC. Air to the cathode side of the SOFC is supplied by the compressor of a gas turbine. The anode exhaust gas after heat recovery is fed to a shift unit where additional $H_2$ is formed by shifting the remaining CO. The shifted gas, now mainly $CO_2$ with some $H_2$ and a small concentration of CO goes to a $H_2$ membrane separator to capture the $H_2$ for export. Alternately, a membrane shift unit can be utilized. The non-permeate is fed to a catalytic combustor using $O_2$ from the ITM/OTM oxygen plant to fully remove the small amounts of any remaining CO and $H_2$, leaving only $CO_2$, $H_2O$, and a very small amount of $O_2$ in the stream. This stream is cooled, the Hg is removed in the sulfided activated carbon bed and the cooled $CO_2$ stream is compressed to the supercritical pressure of the $CO_2$ after which it is dehydrated and pumped to the pipeline pressure of 13,900 kPa.

On the cathode side, the compressed air, at approximately 2,000 kPa, is heated in a regenerator within the SOFC system. The hot depleted air exiting the cathode enters the hot side of the regenerator and is cooled to 900 C (1650 F), the temperature required by the ITM/OTM unit for air separation. In this membrane unit, $O_2$ is removed from the already vitiated air and exits the unit at sub-atmospheric pressure. The $O_2$, assumed to be 100 percent, is cooled and compressed to gasifier pressure with a small side stream going to the catalytic "cleanup" burner. The non-permeate, now reduced in mass flow and pressure, is expanded in the turbine and exhausts to an HRSG. The gas turbine output is significantly reduced because of its low firing temperature, essentially 900 C (1650 F) and the reduced flow. Again, a parametric indicated that a compression ratio around 20 was the most desirable in this configuration and the fuel cell as well as the ITM/OTM unit operate at the same pressures as the previously described Zero Emission Plant with V21 Technology.

The configuration includes a small CFB combustor that recovers energy from the unburned carbon and also oxidizes the CaS. A small fuel gas stream is also burned in the combustor to maintain it at a temperature of 870 C (1600 F). Steam is raised in this system. The steam system in addition to utilizing heat from the CFB and the gasifier effluent, utilizes various heat exchangers throughout the plant.

The overall thermal efficiency of this coproduction facility is about 65 percent utilizing the following expression while exporting about 55 percent of the energy content of the coal in the form of $H_2$:

Thermal efficiency = (net export electric power + HHV contained in exported $H_2$) / (HHV contained in the total coal feed).

## DISCUSSION

The gas turbine technology needs for hybrid system use differ significantly from those for non-hybrid use. Programs such as the DOE Advanced Turbine Systems (ATS) have resulted in the development of sophisticated high-temperature (1425 C / 2600 F+) turbines aimed specifically at combined cycle application on both natural gas and syn gas. These systems have projected efficiencies of greater than 60 percent (LHV) with natural gas fuel and overnight installed costs estimated to be under U. S. $500 / kW. For hybrid use, the emphasis will be on increasing gas turbine power density, through intercooling and / or moisture addition, and through reduction of turbine cooling requirements where turbine cooling is required (the firing temperature of the gas turbine in hybrid applications being modest, less than 1000 C (1830 F). The reason for these developments is not so much for performance gain, but for cost reduction.

Other development needs include, as a minimum, large (greater than 100 MW) recuperative type of gas turbines, i.e., with the capability of taking the air out from the compressor so that it may be supplied ultimately to an off-board pressurized fuel cell, and combustors accepting hot / depleted fuel and hot / vitiated air.

The costing issues are currently being addressed. Fuel cell costs for large-scale applications (i.e., for central station applications) are ill defined. At this point, current technology fuel cells, which have been offered commercially for over a decade, have costs that are excessively higher than those of large-scale gas turbine based combined cycles. While it is projected that these costs will be reduced through manufacturing advances and large-scale production, fuel cell costs may not come down to the same level of large-scale combined cycle costs. Increasing gas turbine participation can reduce hybrid system costs, however. For natural gas-fueled hybrids, the fuel cell power to gas turbine power ratio ranges from 2.5 to 4; this ratio being lower for gas turbine cycles with intercooling (HAT had the lowest ratio). In the configurations with gasification, fuel cell participation is lower; in the range of 1.2 to 1.6, again those systems with intercooling or HAT have the lowest values.

## SUMMARY AND CONCLUSIONS

The following summarizes the major findings up to date:

- Technology Selection. Fuel cell based hybrids are required to achieve the Vision 21 efficiency goals for both natural gas and coal based power plants. In the case of coal, gasification is required in order to use the hybrid technology for the power island.

- Required Plant Configurations. The following plant configurations have the potential to meet the Vision 21 efficiency goals:
  - Natural gas based hybrid configurations consisting of a pressurized SOFC integrated with an intercooled gas turbine or HAT can result in net plant efficiency of 75 percent (LHV). The operating pressure of the SOFC in the case of the HAT based hybrid is however, much lower than that in the case of the intercooled gas turbine SOFC hybrid.
  - It is difficult to meet the Vision 21 efficiency goals with conventional high temperature gasification even with incorporation of high temperature gas cooling and the hybrid technology in the power island. Gasifier with lower operating temperature (i.e., temperature of raw gas leaving the gasifier) and a non-water slurry based feed system is required such as the ATR or a two-stage gasifier (E-Gas type gasifier but with dry feed) to meet the Vision 21 thermal efficiency goal, as long as high carbon conversion may be maintained.

- Coal based ATR - SOFC Hybrid. The performance of the ATR-based system with low temperature gas cleanup is not significantly different from the system with the high temperature gas cleanup – net plant heat rate is increased by less than 1 percent. This is mainly due to (1) preheating the clean gas against the raw gas to a high temperature and (2) the significant amount of sulfur removal during gasification, which minimizes any downstream cleanup (allowing the use of the simple SulFerox® process to be used with its low utility requirements) in the case of the low temperature gas cleanup.

- Coal based $CO_2$ Capture. Using a combustor exit temperature of 1705 C (3100 F) (identified in the DOE-sponsored Advanced Turbine System Program), the estimated efficiency for the Zero Emission Plant with Near Term Technology is about 33 percent (HHV). Incorporation of the Vision 21 technologies such as the SOFC, the ionic membrane air separation and high temperature membrane for $H_2$ separation into such a plant increases the plant net efficiency to much higher values; greater than 50 percent (HHV) while the gas turbine firing temperature remains at a modest value.

- Advanced FutureGen. The Vision 21 technologies such as the SOFC, the ionic membrane air separation and high temperature membrane for $H_2$ separation can be synergistically included into a coal based coproduction facility exporting $H_2$ while capturing the $CO_2$.

- Gas Turbine Development Needs. The development needs for the gas turbine in these hybrid applications based on the currently available information from this study have identified large (~100 MW) gas turbines with the following attributes:
  - Recuperation
  - Low firing temperature
  - Intercooling (a desirable feature for high specific power and enhancing cycle thermal efficiency for the natural gas SOFC/HAT hybrid and potentially for coal based plants)
  - Combustors accepting hot and depleted fuel and air when gas turbine combustors are used for oxidation of the anode exhaust gas
  - Oil free bearings.

- Fuel Cell Development Needs. The development needs for the fuel cell systems have been identified:
  - SOFCs with high operating pressures (in the region of 1,800 to 2,000 kPa) in order to increase the thermal performance as well as increase the current density in the fuel cell while decreasing the size of equipment including that of the heat exchangers and the ITM / OTM.
  - Higher current density materials without extensive use of exotic/expensive materials in order to limit the physical size of the fuel cell stack modules and also minimize the high temperature piping and manifolding, and thus reduce the overall cost of the system.
  - Separate anode and cathode exhausts from the SOFC for zero emission plants (plants with $CO_2$ capture).

- Fuel cells operating with low air to fuel ratio in order to achieve the Vision 21 efficiency goals when the gas turbine development needs are limited to non-reheat systems. Management of heat generated within the cells becomes more challenging and internal reforming will help.

- Balance of Plant System Development Needs. The development needs for the balance of plant systems have also been identified:
  - Cleanup requirements for syn gas suitable for the fuel cell consist of removing sulfur species, alkalies, chlorides, $SiO_2$, $NH_3$ and HCN (to avoid any potential for NOx generation)
  - Other technology development requirements consist of ionic membrane separation of air, lower temperature gasifiers while maintaining high carbon conversion
  - High temperature gas cooling and high temperature shift / membrane separation of $H_2$ in the case of high efficiency $H_2$ coproduction and / or zero emission plants.

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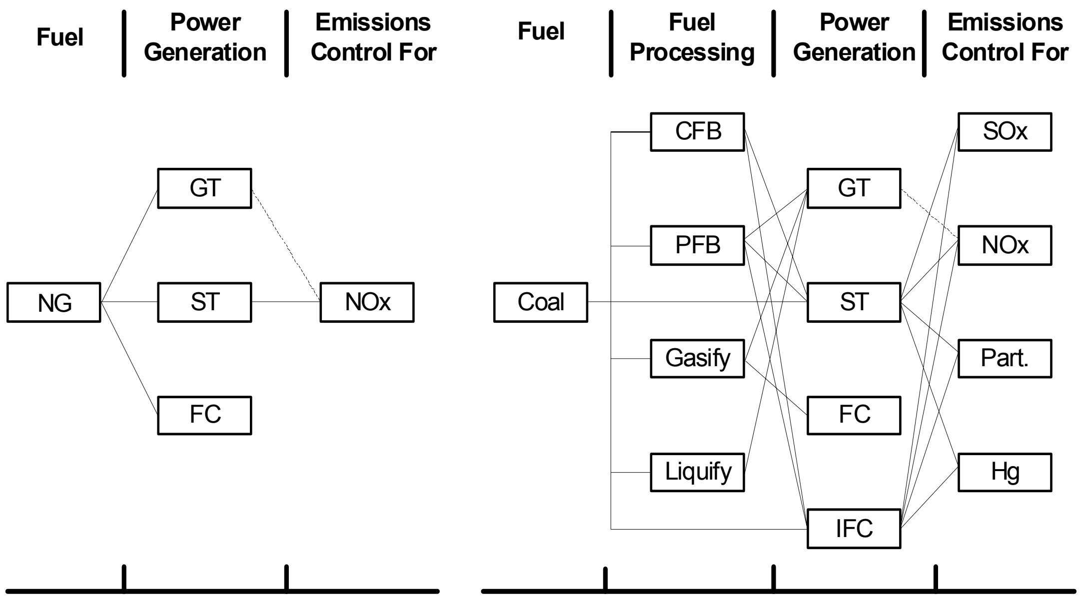


(a) Natural Gas Fueled

(b) Coal Fueled

NG-Natural Gas
CFB-Circulating Fluided
FC-Fuel Cell
GT-Gas Turbine
PFB-Pressurized Fluid Bed
IFC-Indirectly Fired Cycle
ST-Steam Turbine

Figure 1 – Sub-system Selection

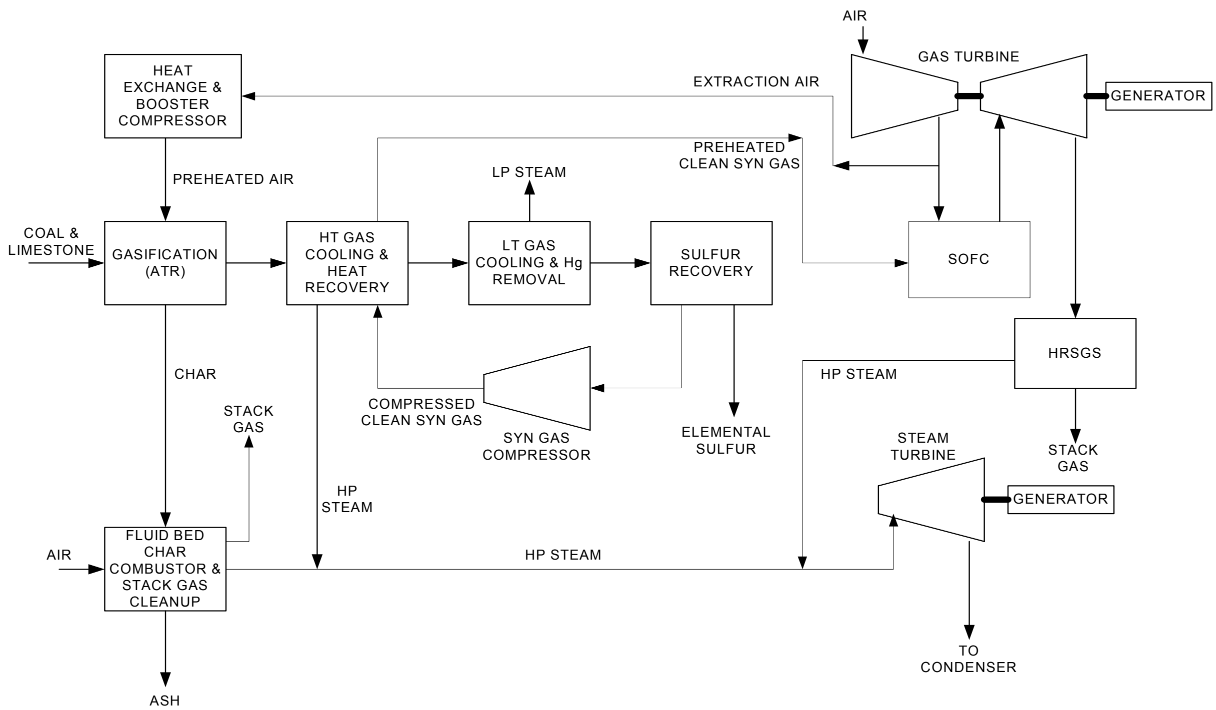


Figure 2 – Coal Based ATR based SOFC Hybrid

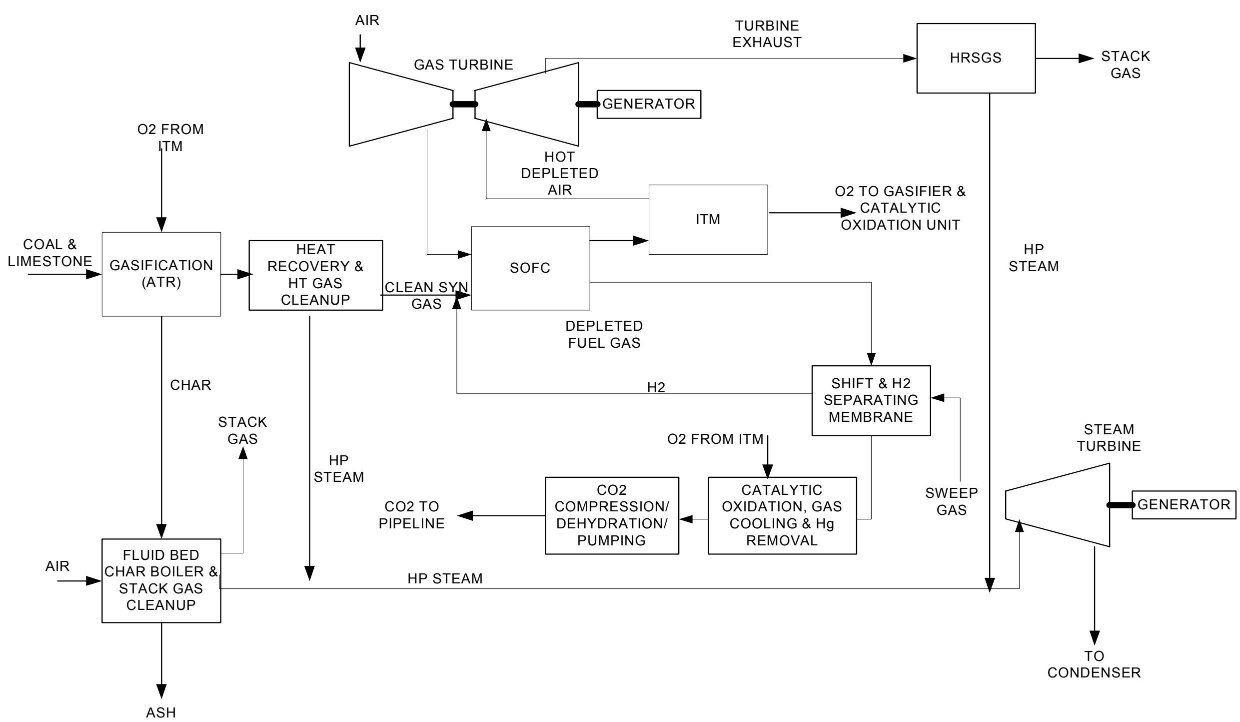


Figure 3 – Coal Based “Zero Emission” Plant with Vision 21 Technology

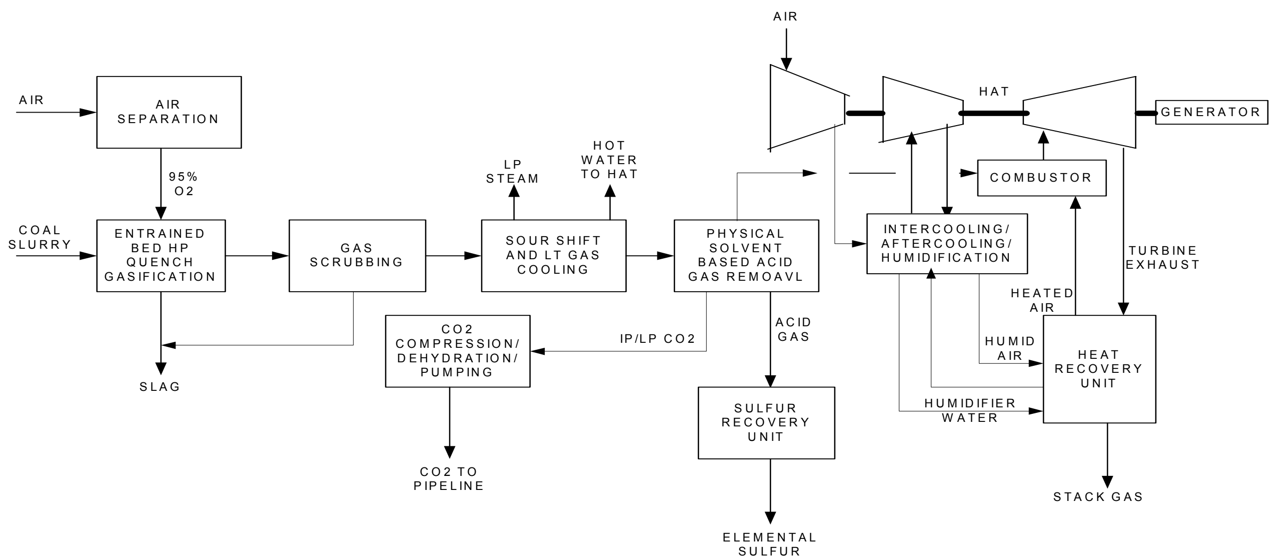


Figure 4 – Coal Based "Zero Emission" Plant with Near Term Technology

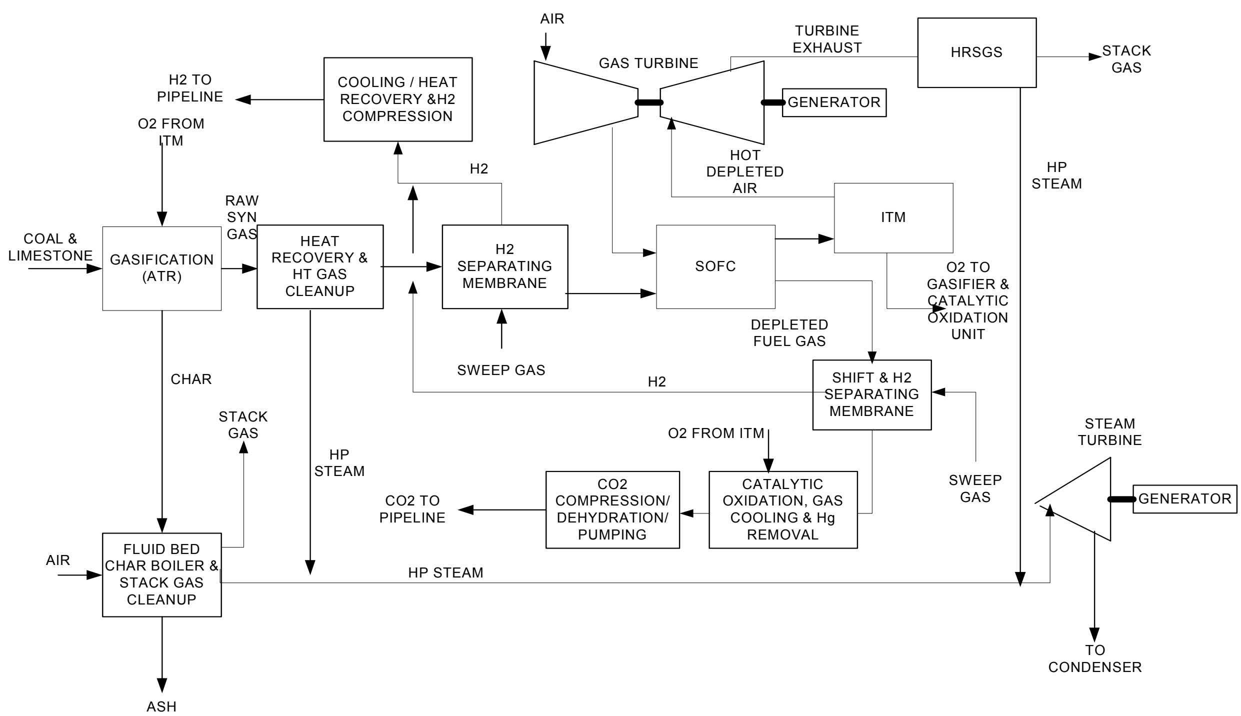


Figure 5 – Coal Based $H_2$ Coproduction with $CO_2$ Capture (Advanced FutureGen)