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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. The myriad of fuel processing, power generation, and emission control technologies are narrowed down to selected scenarios in order to identify those combinations that have the potential to achieve the Vision 21 program goals of high efficiency and minimized environmental impact while using fossil fuels. 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 and molten carbonate fuel cells, advanced gas turbines, ion transport membrane separation and hydrogen-oxygen combustion.

INTRODUCTION

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

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

The efficiency targets for natural gas fueled plants is 75% on a LHV basis while that for coal fueled plants is 60% on an HHV basis while producing electricity only, that is, without CO_2 capture and sequestration nor coproduction of any transportation fuels, while the goal for coal based plants producing H_2 or transportation fuels only consists of achieving a minimum fuel utilization of 75% on an LHV basis.

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 natural gas and coal based system configurations that meet the above Vision 21 goals. The results of this investigation will serve as a guide for the U. S. Department of Energy in identifying the research areas and technologies that warrant further support.

The approach taken in this investigation 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 cases for detailed analysis as summarized in the following:

1. Sub-system Selection – the selection of the fuel processing, power generation and emission control technology scenarios with potential to achieve the Vision 21 goals.
2. Screening Analysis – analyze and optimize selected technology scenarios at a screening level to select cycle configurations. The optimization includes the selection of the cycle configuration as well as the cycle operating conditions. The approach taken in performing this analysis is to start with basic designs

with relatively near term technology and when the Vision 21 targets are not realized, incorporate more advanced designs.

3. Detailed Analysis – the selected promising cycles are next analyzed to develop detailed design point performance, off-design performance (sensitivity to ambient conditions and part-load performance) and rough order of magnitude capital and operating costs.

The Sub-system Selection task for both natural gas and coal based plants has been completed while the Screening Analysis task has been completed for the natural gas cases. This paper discusses the results of these completed tasks.

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 Humid Air Turbine (HAT) cycle [Rao, 1989], or combusted in steam 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 steam 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 being very stringent (high performance gas turbines have stringent limits on levels of contaminants that include sulfur, alkaline metals, vanadium). Alternately, if coal is directly used as in various types of fluid beds or in pulverized steam 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 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 1000C), 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 has 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, cycles based on a gas turbine alone without fuel cells cannot meet the efficiency goals of the Vision 21 program as evidenced by the efficiencies calculated for various gas turbine based cycles as a function of the combustor exhaust temperature (Figure 2). The efficiency of an advanced combined cycle utilizing a steam cooled gas turbine, even with a combustor exhaust temperature as high as 1900C, is in the mid-to-high 60% (65-68% LHV) range ,which is significantly lower than the 75% (LHV) goal for natural gas. With the HAT cycle, a higher combustor exhaust temperature may be utilized since the cycle is not as much constrained by NOx emissions as the combined cycle [Chen, et al., 2002]. Still, the efficiency is limited to less than 70% (LHV) for natural gas.

Thus, gas turbines integrated with fuel cells (hybrids) are required for these Vision 21 power plants. Three hybrid cycles are identified for the natural gas based plants that have the potential to reach the Vision 21 efficiency goal:

1. High pressure solid oxide fuel cell (SOFC) integrated with a high-pressure ratio intercooled gas turbine
2. High pressure solid oxide fuel cell (SOFC) integrated with the HAT cycle
3. Atmospheric pressure molten carbonate fuel cell (MCFC) integrated with a high-pressure ratio intercooled gas turbine.

Two “zero emission” natural gas based plants, that is, plants recovering the carbon dioxide for carbon sequestration are also identified for the screening analysis:

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

Three cases are identified for the coal-based plants that have the potential to reach the Vision 21 efficiency goal:

1. Shell gasifier with hot gas cleanup providing syn gas to a high pressure SOFC based hybrid
2. Texaco gasifier providing syn gas to a high pressure SOFC integrated with the HAT cycle
3. Foster-Wheeler partial gasifier integrated with a SOFC based hybrid.

Two “zero emission” coal based plants are identified for the screening analysis:

1. Shell gasifier with hot gas cleanup providing syn gas to an O_2 breathing high pressure SOFC integrated with HAT cycle and CO_2 recycle
2. Shell gasifier with hot gas cleanup and H_2 separation using high temperature membranes (precombustion CO_2 recovery) and the advanced Rankine cycle (using gas turbine technology and H_2/air combustor derived from the rocket engine technology).

An additional case that coproduces Fischer-Tropsch liquids (in addition to electric power) is also identified for the screening analysis:

1. Texaco gasifier with cold gas cleanup providing syn gas to a Fischer-Tropsch synthesis unit with unconverted gas supplied to an advanced HAT system.

This case represents an advanced coal-based power system in which a high value liquid fuel is produced along with electric power. Because the main product is the liquid fuel, the power system may not operate as a base load plant and may, in fact, operate with several stops and starts per day. This means that the plant is not tightly integrated and that fuel (syn gas) is delivered “across the fence” to the power system. Because of the probable need for on/off and extensive part-load operation, a lower cost, less complex, but still highly efficient power system such as a HAT would be the choice. The part load performance of the HAT cycle has been compared to that of a combined cycle; the heat rate of an integrated gasification HAT (IGHAT) remains essentially constant down to 50% load whereas in the case of an integrated gasification combined cycle (IGCC), the heat rate increases by as much as 30% on a single train basis [Rao et.al., 1993].

SCREENING ANALYSIS – NATURAL GAS CASES

The nominal power output for the plant has been selected as 300 MW to be representative of the minimum economic size for central power stations, especially those with gasification. Each of the systems has a gas turbine component. The design values for the turbines used in the screening analyses are given in Table 1. Note that the screening analyses considered a variety of gas turbine and fuel cell configurations and operating conditions. The complex interaction of air/steam/fuel streams often resulted in several configurations for each case that had similar performance, i.e., efficiencies within +/- 2%, well within the “noise” of the analyses. The results presented below are for the configurations with the highest efficiency for each case and may not represent the best configuration when all operating constraints are considered. That is the goal of the next task of this study – a more detailed analysis of selected configurations to identify operability and economic considerations.

Table 1: Gas Turbine Design Basis

Ambient Conditions	ISO
Firing Temperature	$\leq$ 1700 C
Compressor Isentropic Efficiency	$\geq$ 90%
Turbine Isentropic Efficiency	$\geq$ 93%
Turbine Materials	Ceramics and Thermal Barrier Coatings

High Pressure SOFC Integrated with High Pressure Ratio Intercooled Gas Turbine

The system as depicted in Figure 3 consists of an intercooled gas turbine integrated with a pressurized tubular SOFC. Atmospheric air is compressed in an intercooled compressor, comprised of a low pressure compressor (LPC) and a high pressure compressor (HPC). The discharge air from the high pressure (HP) compressor is supplied to the SOFC as its oxidant. The fuel utilization in the SOFC was set at 85%. Desulfurized fuel is humidified in a column where it is counter-currently contacted with hot water. A portion of the water is evaporated into the fuel stream, the heat required for the humidification operation being the heat recovered from the intercooler and the stack gas by circulating water leaving the humidifier. The humidified fuel is then preheated in the turbine exhaust and supplied to the SOFC. The exhaust from the cells, consisting of the depleted air and the depleted fuel is supplied to a combustor that may physically be part of the SOFC system or the gas turbine. The exhaust from the combustor enters the high pressure turbine (HPT) which drives the HP compressor and is expanded to a pressure which is higher than atmospheric. The exhaust from the HP turbine is supplied to the low pressure turbine (LPT) where it is expanded to near atmospheric pressure and then supplied to the heat recovery unit. The LP turbine drives the low pressure (LP) compressor and the generator.

It was determined that in order to reach the efficiency goal of 75% (LHV), the SOFC had to operate with a fuel to air ratio approaching stoichiometric. If higher air to fuel ratio were used in the HP SOFC, then in order to meet the efficiency goal, an alternate approach consisting of installing a second SOFC between the HP and LP turbines would be required (a "reheat cycle"). This alternative configuration, however, did not significantly improve performance and would increase plant cost and complexity.

The optimum efficiency of the cycle occurred at a pressure ratio greater than 50, while the gas turbine firing temperature was modest, <1200 C. As mentioned above, several configurations resulted in nearly equal performance, e.g., a non-intercooled gas turbine with a pressure ratio of 20 had an efficiency only 0.3 points lower, well within computational error. When efficiency was a toss up, the intercooled gas turbine was chosen because of its higher power density (kW/air flow), a factor that would mitigate the system costs. This is especially true with the hybrid since the optimum cycle efficiency occurs when the only heat to the gas turbine is from the SOFC – the hot exhaust further heated by catalytic combustion of the remaining hydrocarbons in the exhaust. Since these temperatures seldom exceeded 1150 - 1200 C, power (kW/air flow) is somewhat limited.

High Pressure SOFC Integrated with HAT

The system as depicted in Figure 4 is similar to the previous case consisting of an intercooled gas turbine integrated with a pressurized tubular SOFC except that it incorporates humidification of the air and the humidified air is preheated in a recuperator in the turbine exhaust before it is fed to the SOFC. The fuel utilization in the SOFC was again limited to 85%. The air leaving the HP compressor is first cooled in an aftercooler and then introduced into the humidifier column where it comes into counter-current contact with hot water. A portion of the water is evaporated into the air stream, the heat required for the humidification operation being recovered from the intercooler and the stack gas by circulating water leaving the humidifier. The desulfurized fuel is also humidified in a similar manner.

It was determined also for this configuration that in order to reach the efficiency goal of 75% (LHV), the SOFC had to operate with a fuel to air ratio approaching stoichiometric while if higher air to fuel ratios are to be utilized in the SOFC, then in order to meet the efficiency goal, the alternate approach consisting of installing a second SOFC between the HP and LP turbines is required. This alternate cycle configuration as pointed out earlier would increase the plant cost and complexity and was discarded from further consideration.

The optimum efficiency of the cycle occurred at a pressure ratio of approximately 20, which is much lower than the previous case, while the gas turbine firing temperature remained at a modest value of <1200 C.

Atmospheric Pressure MCFC Integrated with Intercooled Gas Turbine

A number of configurations of the atmospheric MCFC were considered including several in which the exhaust of the MCFC was cooled, compressed to gas turbine operating conditions, recuperated and further heated by combusting the remaining hydrocarbons. The configuration with the best performance, however, is that shown in Figure 5. This system consists of an intercooled gas turbine integrated with an atmospheric pressure MCFC. Atmospheric air is compressed in an intercooled compressor, comprised of a LP compressor and a HP compressor. The discharge air from the HP compressor is preheated in a high temperature heat exchanger transferring the heat released from combustion of the depleted fuel leaving the MCFC (MCFC anode exhaust gas). This hybrid case may require a catalytic combustor because the depleted fuel is at lower temperature (typically in the neighborhood of 600C in the case of MCFC versus 1000C in the case of SOFC) and also lower pressure when compared to the SOFC based hybrids. Furthermore, it was found that in order to reach the 75% (LHV) efficiency target for this hybrid case, the fuel utilization had to be increased from the 85% value that was employed in the two SOFC hybrid cases to 90% fuel utilization resulting in a correspondingly lower heating value for the depleted fuel for the MCFC hybrid.

A blower provides the required amount of air for the combustion of the depleted fuel gas; the combustion air being first preheated against the MCFC cathode exhaust gas and then against the combusted depleted fuel gas. This configuration was found to be more efficient than a configuration where the combustion air is also supplied by the gas turbine exhaust; utilizing a separate combustion air blower increases the amount of heat that may be recovered from the cathode exhaust gas. In addition to providing heat for preheating the depleted fuel combustion air, the cathode exhaust gas provides heat for preheating the humidified fuel gas supplied to the MCFC. Preheating of the circulating water for the humidification of the desulfurized natural gas is accomplished by heat exchange against the combusted depleted fuel gas. A portion of the heat rejected by the intercooler is also recovered for the humidifier.

The optimum pressure ratio for the gas turbine from an efficiency standpoint for the proposed selected case was 25 while the gas turbine inlet temperature remained at a modest value of less than 1100C.

O_2 Breathing High Pressure SOFC Integrated with HAT cycle

This case as depicted in Figure 6 is similar to the previously described HP SOFC integrated with the HAT cycle except that the SOFC utilizes pure O_2 supplied by an ion transport membrane (ITM) unit [Richards, 2001] instead of air. The exhaust gas consisting of water vapor and CO_2 is cooled by direct contact with circulating water in a dehumidifier after heat recovery, a portion of the CO_2 is purged from the cycle while the remainder is combined with the O_2 supplied by the ITM unit and recycled to the suction of the HAT (assisted by the induced draft fan) in order to moderate the temperature within the SOFC. The CO_2 purged from the cycle may be compressed and to a pressure dictated by the ultimate disposal method chosen for sequestration. For this evaluation, a pressure of 60 bar was used in order to make a direct comparison with the advanced Rankine cycle case described next which produces the CO_2 at 60 bar. This cycle in addition to producing CO_2 also produces water on a net basis for export. The resulting efficiency of the cycle is > 60% on a LHV basis.

The pressure ratio for the cycle and the gas turbine firing temperature were kept at the same values as those for the SOFC/HAT hybrid case. The SOFC operating temperature sets the amount of CO_2 recycled.

Advanced Rankine Cycle Combusting H_2 with O_2

This cycle as depicted in Figure 7 utilizes a high temperature and high pressure reheat steam turbine operating with inlet conditions of 1760C and 222 bar to expand the steam produced by combustion of H_2 with stoichiometric amount of O_2 in rocket engine technology derived combustor [Anderson, 2001]. The H_2 is produced in a steam/methane membrane reformer [Lou, 2001] in which the H_2 chemically diffuses through a high temperature membrane as it is formed. Thus, the membrane reformer not only provides a separated pure H_2 product stream but also drives the reforming reaction to completion since one of the products of reaction (H_2) is continuously removed from the reaction mixture. The O_2 is produced in an ITM unit similar to the previous case. The steam turbine is similar to the turbine of a gas turbine because of the very high temperature of the working fluid. Both the HP and the reheat combustors utilize water injection to moderate the combustion temperature.

The CO_2 is recovered from the membrane reformer effluent for export at a pressure of 60 bar. The resulting efficiency of the cycle is 52% on a LHV basis.

SUMMARY AND CONCLUSIONS

A multi-disciplinary team led by APEP 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 sponsored by the NETL of the U. S. Department of Energy. Specifically, the objective of this program is to identify natural gas and coal based system configurations that meet the Vision 21 goals. The results of this investigation will serve as a guide for the U. S. Department of Energy in identifying the research areas and technologies that warrant further support.

The various types of fuel processing, power generation, and emission control technologies are narrowed down to selected scenarios to identify those combinations that have the potential to achieve the Vision 21 program goals.

Gas turbines integrated with fuel cells (hybrids) are required for these Vision 21 power plants fueled by either natural gas or coal. In the case of coal based plants, 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 being very stringent.

Three hybrid cycles are identified for the natural gas based plants for the screening analysis:

1. High pressure solid oxide fuel cell (SOFC) integrated with a high-pressure ratio intercooled gas turbine
2. High pressure solid oxide fuel cell (SOFC) integrated with the HAT cycle
3. Atmospheric pressure molten carbonate fuel cell (MCFC) integrated with a high-pressure ratio intercooled gas turbine.

Two “zero emission” natural gas based plants are also identified:

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.

Three cases are identified for the coal-based plants:

1. Shell gasifier with hot gas cleanup providing syn gas to a high pressure SOFC based hybrid
2. Texaco gasifier providing syn gas to a high pressure SOFC integrated with the HAT cycle
3. Foster-Wheeler partial gasifier integrated with a SOFC based hybrid.

Two “zero emission” coal based plants are identified:

3. Shell gasifier with hot gas cleanup providing syn gas to an O_2 breathing high pressure SOFC +integrated with HAT cycle and CO_2 recycle
4. Shell gasifier with hot gas cleanup and H_2 separation using high temperature membranes (precombustion CO_2 recovery) and the advanced Rankine cycle (using gas turbine technology and H_2/air combustor derived from the rocket engine technology).

An additional case that coproduces Fischer-Tropsch liquids is also identified:

5. Texaco gasifier with cold gas cleanup providing syn gas to a Fischer-Tropsch synthesis unit with unconverted gas supplied to an advanced HAT system.

The results of the screening analysis performed on the natural gas cases are summarized in Table 2. Pressurized

SOFC hybrid configurations with efficiencies greater than 75% on a LHV basis have been identified in this investigation while limiting the fuel utilization within the SOFC to 85%. The gas turbine cycles required for reaching this Vision 21 efficiency goal are of the intercooled-recuperative type. Gas turbine combustors accepting the depleted fuel and air from a fuel cell if the fuel is combusted in a gas turbine combustor rather than in "a fuel cell combustor" will require the capability of being able to burn low Btu but hot fuel gas with hot air (in the neighborhood of 1000C in the case of SOFC hybrids).

Table 2: Summary of Performance Estimates - Screening Analysis of Natural Gas Cases

	Efficiency Maximization Cases			CO_2Rrecovery Cases	
	SOFC + ICGT Hybrid	SOFC + HAT Hybrid	MCFC + ICGT Hybrid	SOFC + HAT Hybrid	Adv. Rankine Cycle
Fuel Cell Power, %	72	68	74	68	-
Gas Turbine Power, %	28	32	26	32	100
Thermal Efficiency, % LHV	>75	>75	70	>60	52
Specific Power, kW/lb/s	985	1000	830	800	-

The operating pressure of the SOFC has to be significantly higher than what has been demonstrated so far, in the neighborhood of 50 bar if integrated with the intercooled gas turbine or in the neighborhood of 20 if integrated with the HAT cycle. Air to fuel ratios approaching stoichiometric are required if gas turbine development is to be limited to nonreheat cycles. The air supplied to the fuel cell in addition to providing the oxidant to the cell also provides a means for removing the heat generated within the cell to limit its operating temperature. For example, with the Siemens-Westinghouse tubular SOFC design [Bevc and Parker, 1995], the air is supplied to a central injection tube located within each of the tubular cells where the air is preheated to the operating temperature of the cells by absorbing the heat generated within the cells. As the amount of air supplied to the cells is reduced, management of the heat generated within the cells becomes more challenging. Internal reforming of the natural gas to absorb the heat generated by the cells will be required as practiced by FuelCell Energy's MCFC. Reducing the temperature of the preheated air supplied to the central injection tube located within each of the tubular cells (where the air is further preheated to the operating temperature of the cells) increases the amount of heat that may be absorbed by the air. Large temperature gradients within the injection tube should, however, be guarded against. Addition of large amounts of water vapor to the natural gas stream entering the cells also assist in absorbing the heat generated within the cell. Note that in case of the HAT cycle, the water vapor added to the air supplied to the cells further assists in absorbing the released heat. The water vapor also increases the amount of motive fluid for expansion within the turbines. Note that this water vapor is introduced into the natural gas or air streams in a thermodynamically efficient manner, by utilizing a counter-current humidifier operating on low temperature heat generated within the cycle.

With the atmospheric pressure MCFC based hybrid, the Vision 21 efficiency goal may be realized if the fuel utilization approaches 90% economically. Note that as the fuel utilization increases, the chemical potentials remaining for driving the electrochemical reactions within the cells decrease which in turn decrease the current density. As the chemical potentials decrease the Nernst potential also decreases and the cell polarizations increase resulting in a decrease of the cell voltage for a given current draw.

In order to limit the physical size of the fuel cells which would be required to have outputs in excess of 200 MW for large central station power plant applications (of total output in the neighborhood of 300 MW) to physical sizes that may be considered practical and to limit the number of stack modules to minimize the piping and any mal-distribution, research and development is required in the area of fuel cell materials such that significantly higher current densities may be achieved. The cost of the fuel cell which is one of the major barriers for its wide-spread commercialization at the present time will also be reduced as materials with higher current densities are developed for fuel cell applications as long as these materials do not contain high concentrations of exotic materials.

The zero emission HAT integrated with the O_2 breathing HP SOFC resulted in an efficiency of >60 % on a LHV basis which is significantly higher than the advanced Rankine cycle combusting H_2 with O_2 which had an efficiency of 52% on a LHV basis.

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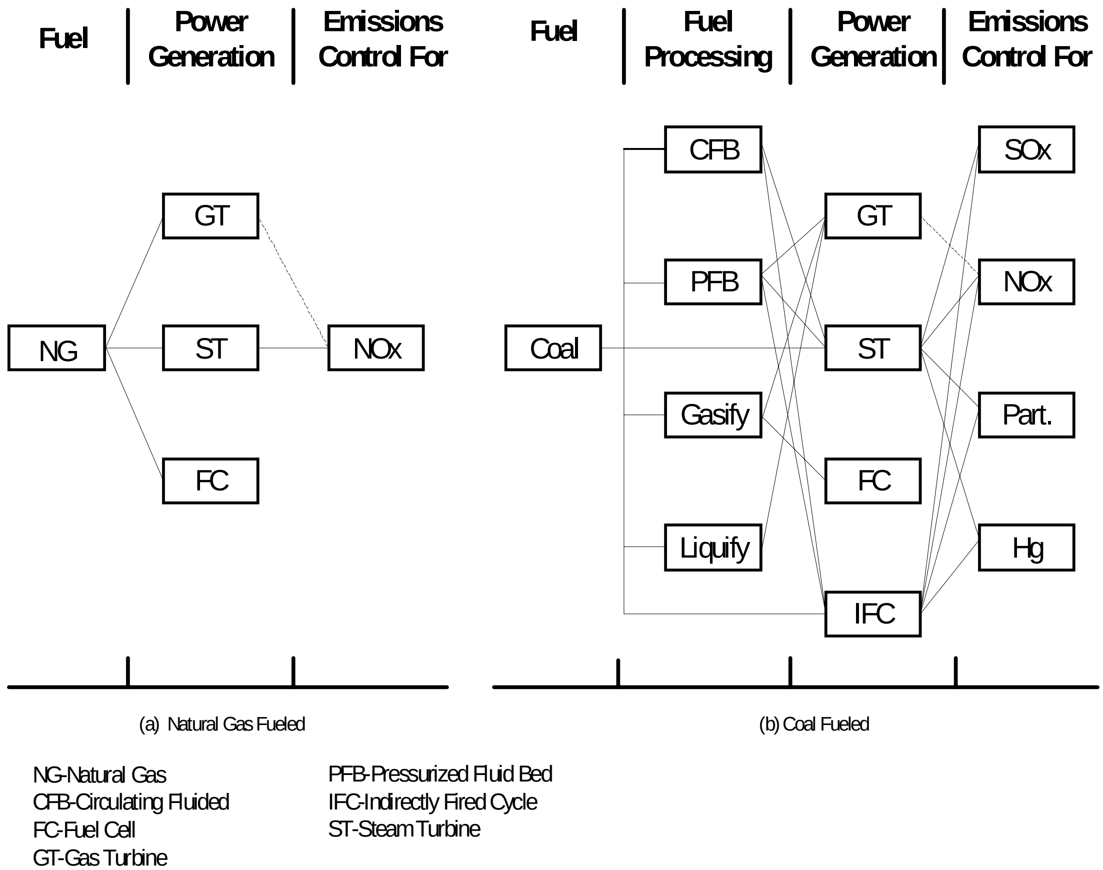

Figure 1 – Sub-system Selection

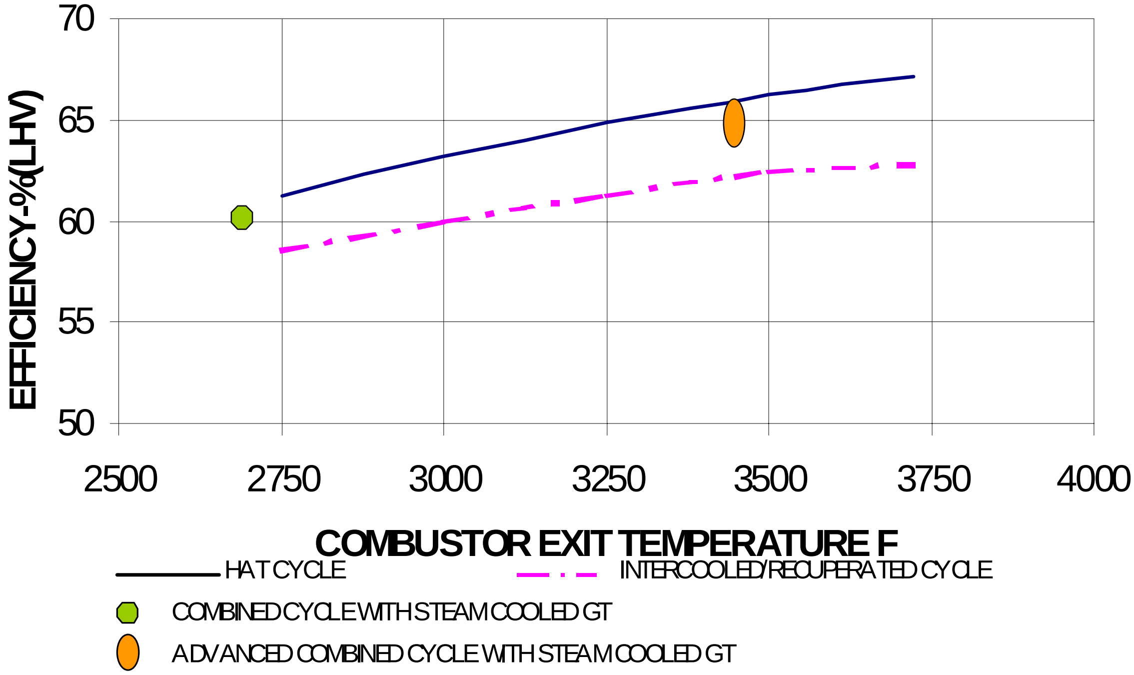

Figure 2 – Thermal Efficiency of Various Gas Turbine based Cycles

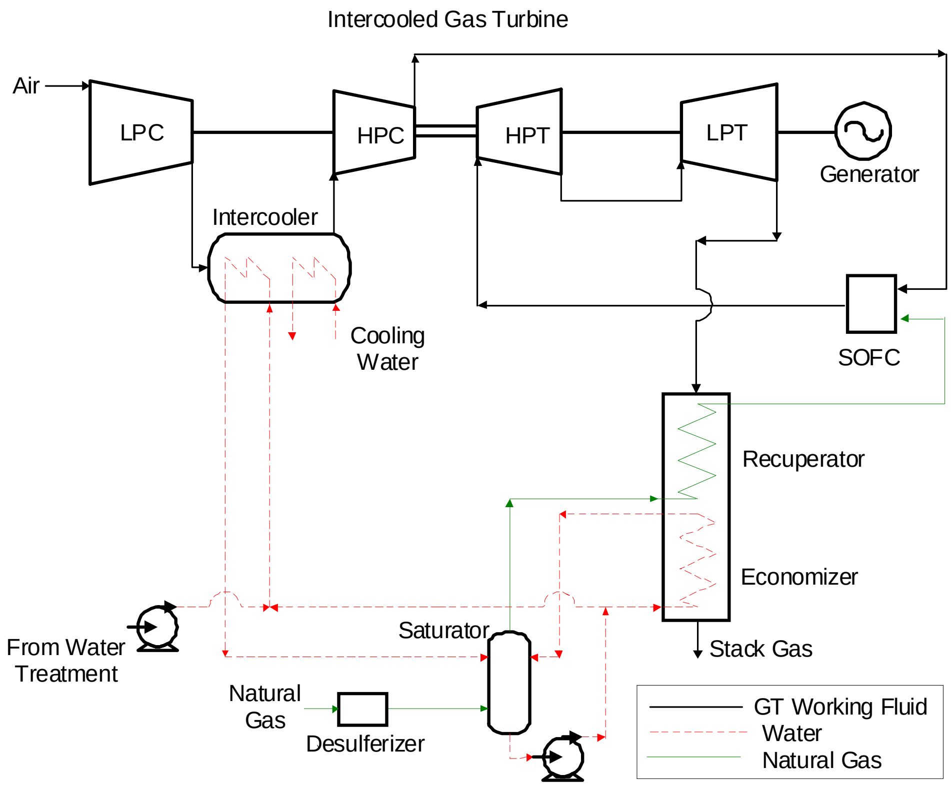

Figure 3: High Pressure SOFC/Intercooled Gas Turbine Hybrid

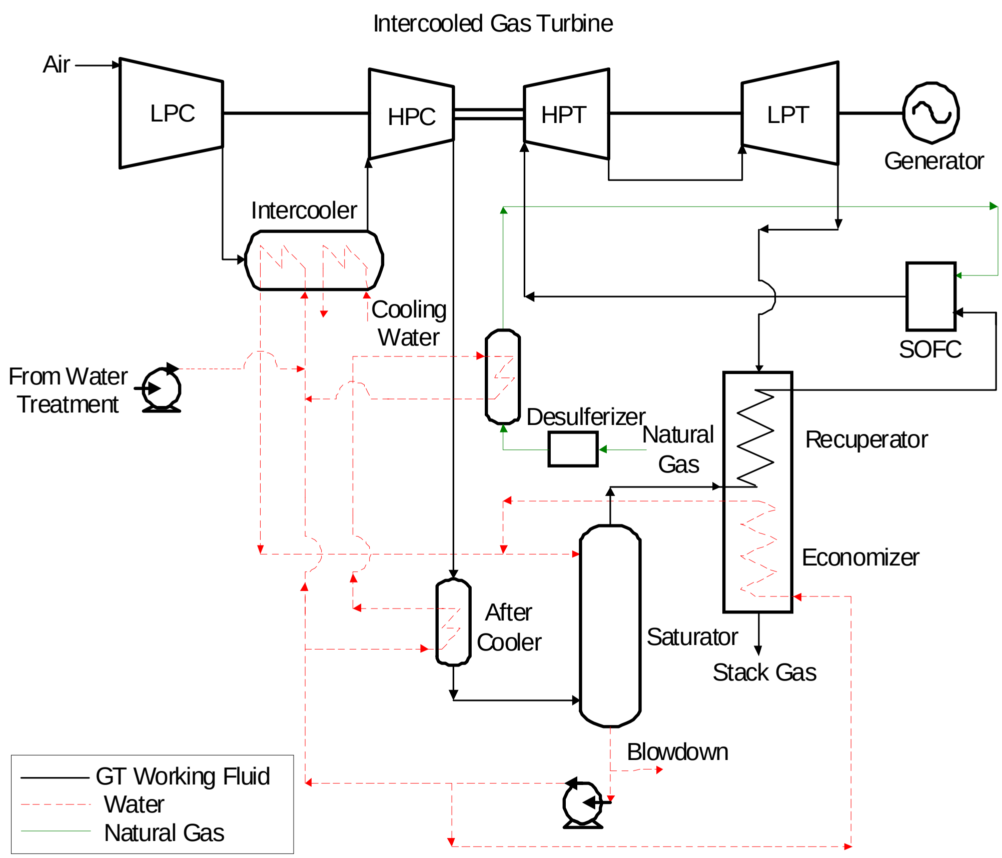

Figure 4: High Pressure SOFC/HAT Hybrid

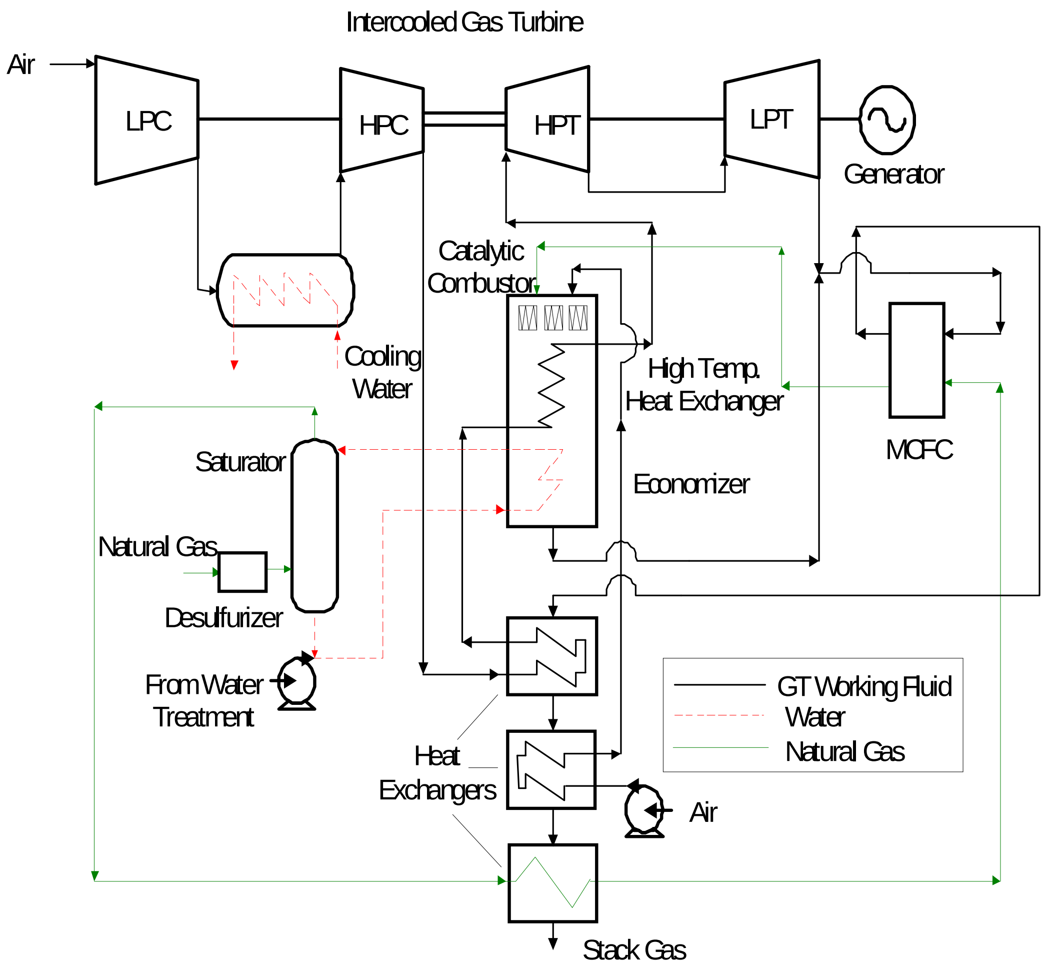

Figure 5: Atmospheric Pressure MCFC/Intercooled Gas Turbine Hybrid

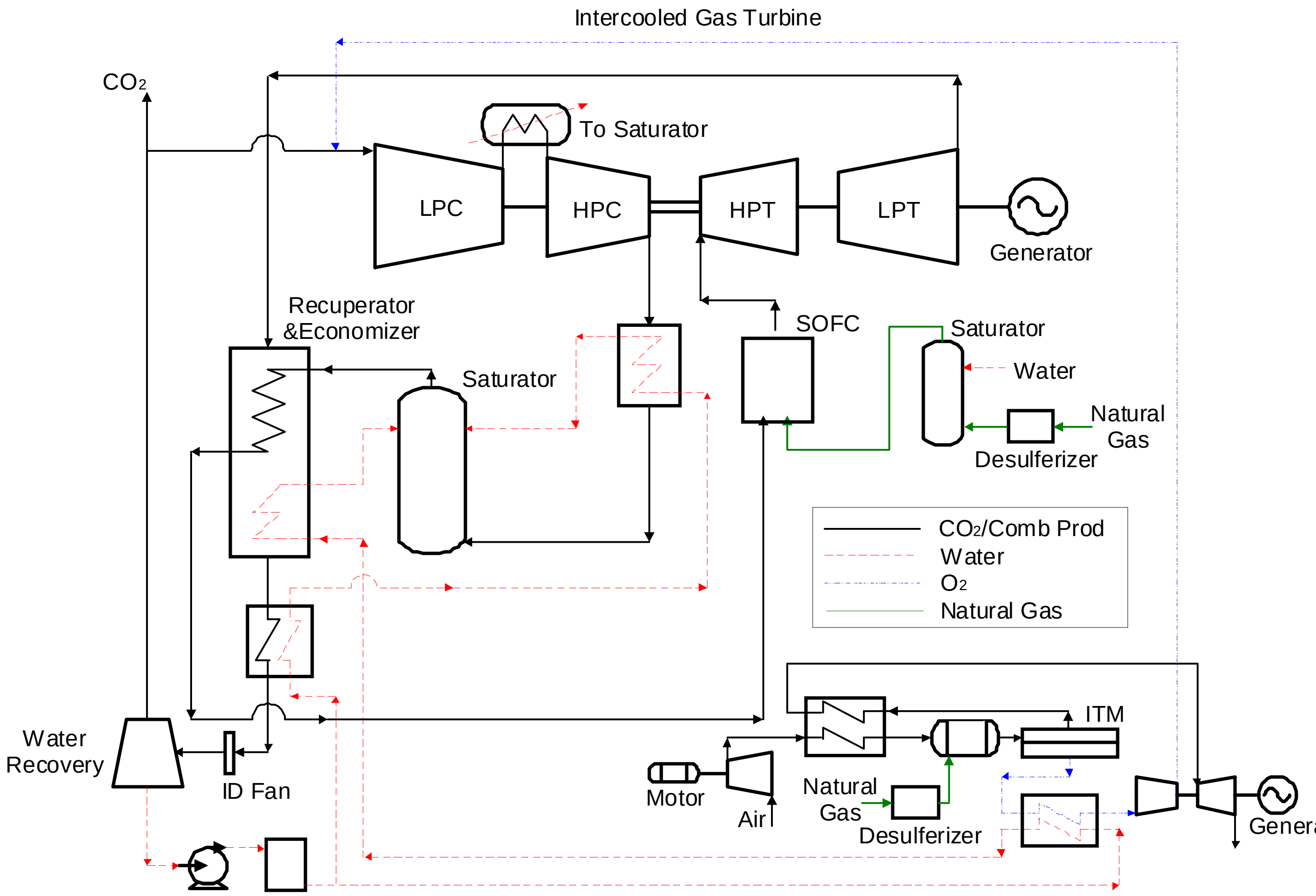

Figure 6: O_2 Breathing High Pressure SOFC/HAT Hybrid with CO_2 Recycle

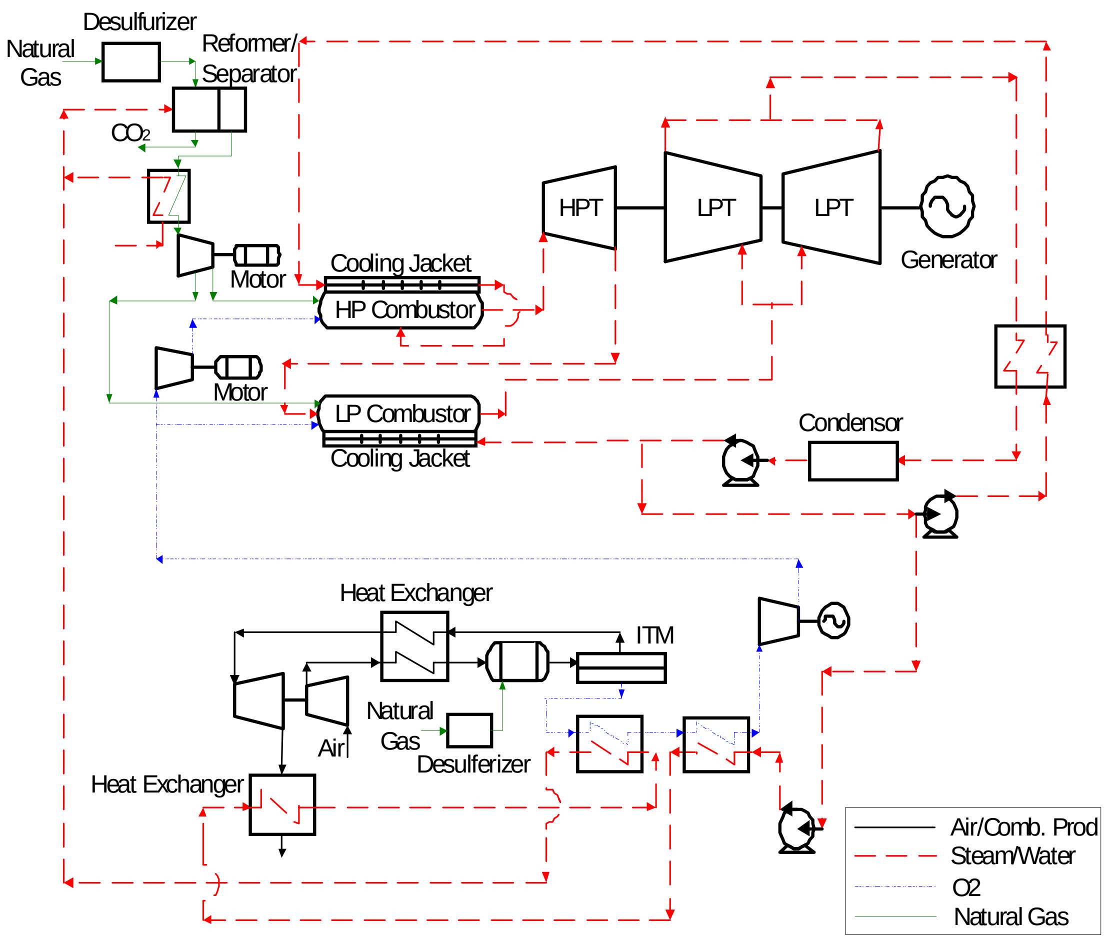

Figure 7: Advanced Rankine Cycle/Combusting of H_2 with O_2