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Ranking of Enabling Technologies for Oxy-Fuel Based Carbon Capture

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The USDOE National Energy Technology Laboratory (NETL) has begun a process to identify and rank enabling technologies that have significant impacts on pulverized coal oxy-fuel systems. Oxy-fuel combustion has been identified as a potential method for effectively capturing carbon in coal fired power plants. Presently there are a number of approaches for carbon capture via oxy-fuel combustion and it is important to order those approaches so that new research can concentrate on those technologies with high potentials to substantially lower the cost of reduced carbon electricity generation. NETL evaluates these technologies using computer models to determine the energy use of each technology and the potential impact of improvements in the technologies on energy production by a power plant. Near-term sub-critical boiler technologies are targeted for this analysis because:

- most of the world continues to build single reheat sub-critical plants;
- the overwhelming number of coal fired power plants requiring retrofit for CO_2 capture are sub-critical plants.

In addition, even in the realm of new construction, subcritical plants are common because they are well understood, easy to operate and maintain, fuel tolerant, and reliable. Following the initial investigation into sub-critical oxy-fuel technology, future investigations will move into the supercritical range.

Modeling variables investigated include:

- oxygen purity,
- coal fineness,
- recycled flue gas
    - quantity
    - temperature
- recovery of heat of compression,
- process integration within the power cycle,
- excess oxygen.

The technologies examined comprise:

- heat recovery,
- air separation,
- coal delivery and pulverization,
- recirculated flue-gas motivation and processing.

The result of the evaluation will be a ranking of technologies by the change in heat rate of the oxy-fired CO_2-capture process. The screening evaluation of 7 variables for oxy-fuel firing is complete and results have been ranked. The impact of these variables on technologies applied to oxy-fired CO_2-capture is being evaluated.

Background:

NETL is committed to ensuring technologies are available for commercial implementation if carbon constraints, incentives, or penalties are enacted. Oxy-fuel combustion is a competitive technology path that has the potential for retrofit of the existing coal-fired fleet. Oxy-fuel combustion has been around for decades. Originally it was seen as a path to low NOx emissions and production of CO_2 for enhanced oil recovery (EOR). It was not adopted earlier because the energy cost of oxygen makes implementation for these purposes too expensive. However, as soon as the subject of carbon capture arose, people recognized the potential of oxy-fuel combustion to produce a CO_2-rich flue gas which is much easier to process for sequestration than dilute air-fired flue gas.

If carbon constraints are mandated, it will be important to understand the details of the technologies that are used to improve the heat rate of both new and retrofitted power plants. In every case, capture of carbon will pose energy and economic penalties. It is with the idea of minimizing those penalties that this paper addresses potential design-choice impacts on the heat rate when retrofitting an existing pulverized coal power plant. Numerous choices can be made and these choices will make the difference in the competitive advantage of each power producer.

This paper examines the heat rate response of a sub-critical single reheat (2400 psia, 1,004°F, 1,004°F) PC power plant with a base thermal efficiency of approximately 35% which is converted to oxy-fuel firing with CO_2 capture. A standard NETL-developed integrated pollutant removal (IPR™) system[1,2] is applied to provide CO_2 at a delivery pressure of 2,200 psig at the power plant fence line. In this modeling study, the main steam mass flow (3,131,620 lb/hr) was kept constant by varying fuel into the boiler in order to represent the performance of a retrofit system (retrofit implies that the steam side of the system must remain somewhat unchanged in order to use the existing steam turbines, feedwater heaters, etc.). Capture of CO_2 as a supercritical mixture is assumed in these models with co-sequestration of dry supercritical CO_2 and associated minor constituents (N_2, O_2, Ar). FGD (if needed) takes place in the normal IPR™ process. The computer modeling tool used was GateCycle version 5.61[a].

Results and Discussion of Cases:

Figure 1 summarizes the modeled thermal efficiencies for the target retrofit power plant under a variety of conditions. The air-fired and oxy-fired base cases, with HHV thermal efficiencies of approximately 35% and 31%, are at the far left; the effects of individual technical modifications on the thermal efficiency follow, and the last two values represent all of the positive contributions combined in one model and all of the negative contributions in another model. The results range from a low oxy-fuel thermal efficiency of approximately 27.3% to a high thermal efficiency of approximately 32.9%.

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[a] USDOE NETL neither endorses nor recommends specific vendors or products. The mention of a brand name is not an indication of recommendation or endorsement.

The technologies that are quantified in the computer models include:

1. Lower-energy (improved) oxygen production (advanced technologies entering the market)
2. Reduced excess O_2 in oxy-fueled exhaust products (from 3.5% wet to 1.0% wet)
3. Reduced flue gas recirculation to the boiler (requires heat transfer surface modifications in a retrofit system) from 0.58 to 0.34 (increasing O_2 concentration in the comburent from 38% to 61% O_2, respectively)
4. Improved LOI (loss on ignition) by improving carbon burnout for oxy-fuel systems from 1% unburned carbon in the base case to 0.5%
5. Reduced oxygen purity from 99% O_2 (base case) to 95.5% O_2
6. NETL IPR™ (Integrated Pollutant Removal) system – with and without heat recovery.
7. Flue gas desulfurization (FGD) during recycle (there is an active discussion over the need for FGD in the recycled flue gas to prevent SO_2 related corrosion)

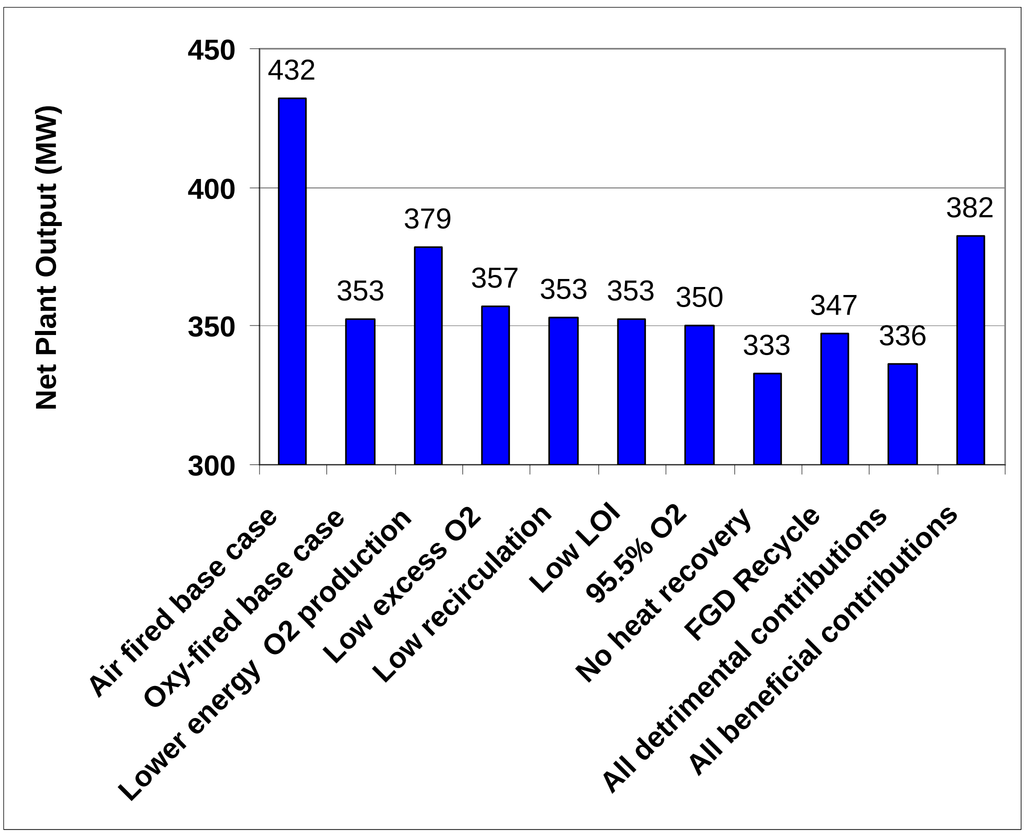

Figure 1: HHV thermal efficiencies of a retrofit power generation system using different technologies.

Air-fired base case: The air-fired base case is based on the AEP Conesville power plant unit 5 as defined in an earlier investigation by NETL[3]. The coal for all modeling runs was Conesville #5 as defined in the prior report. The model produced a net 432MW power output for the plant corresponding to the maximum continuous rating (MCR) equal to 105% design mode used in the previous study. The FGD/SCR load was estimated at 12MW.

Oxy-fired base case: The oxy-fired base case was designed with a flue gas recycle ratio of 0.58 to maintain heat transfer conditions similar to those of the air-fired case and to avoid any significant modifications to the boiler. Main steam output was kept constant at 3,131,620 lb/hr to allow the steam turbines to operate as designed. Energy recovery in the IPR™ system was modeled to recover both latent and sensible heat in the system.

Figure 2 shows the differences in heat rate that result from applying specific modifications to the baseline model. Each difference is found by subtracting the baseline oxy-fuel model heat rate from the modified model heat rate. An increase in the heat rate indicates greater fuel consumption for a unit of power generated and lower thermal efficiency. A decrease in heat rate indicates lower fuel consumption for a unit of power and higher thermal efficiency. The discussion below details each approach named in Figure 2.

Lower energy O_2 production: NETL has been involved with industry (Air Products, Praxair) to reduce the specific energy requirement for the separation of O_2 from air and continues to pursue gains in this area. Over the past five years the specific energy requirement in a standard cryogenic air separation unit (ASU) has been reduced, from approximately 270 kWh/ton O_2 to approximately 220 kWh/ton (at 99% O_2 purity). Present technology can produce 95% purity oxygen at a specific energy usage of approximately 210 kWh/ton. While the reduction from 270 kWh/ton to 220 kWh/ton for 99% purity O_2 is significant, and we use the 220 kWh/ton O_2 as our baseline specific energy consumption and 99% O_2 as our baseline purity, technologies are presently being demonstrated that can reduce the energy consumption to as low as 150 kWh/ton 99% O_2. Both Figure 1and Figure 2 show the significant gain that can be made if the target of 150 kWh/ton 99% O_2 can be met. It can be seen from the heat rate reduction of -775 BTU/kWh that this is the single most effective way to improve the performance of an oxy-fueled power plant.

Lower excess oxygen: By lowering excess oxygen the oxygen production rate for combusting a given amount of fuel is reduced. Lowering the excess oxygen from 3.5 to 1.0% O_2 in the wet flue gas can be seen to result in a significant improvement in heat rate (-151 BTU/kWh). Oxy-fuel combustion can burn much closer to a stoichiometric mixture of oxygen and fuel because it takes place under significantly different conditions from air firing. Burners can be designed with different characteristics from those using air. Experiments are continuing to determine how close an oxy-fuel flame can come to stoichiometric. The closer the flame can be maintained to stoichiometric, the less O_2 has to be separated from the air.

Low recirculation: One of the advantages of using oxygen as the oxidant is that recirculation allows the designer to change flame conditions significantly. The lower the recirculation rate the higher the mole fraction of oxygen. This can enable the approach to stoichiometric combustion as well as possible improvements in loss on ignition (LOI). Reduced recirculation also results in lower fan loads.

In this study, the International Flame Research Foundation definition of recycle ratio[4] is used:

$$R = \frac{FGrcrc}{FGtot}$$

where R = recirculation ratio; FGrcrc = mass of the recirculated flue gas being recirculated; FGtot = total mass of the flue gas including both the portion recirculated and the portion sent to the IPR™ system.

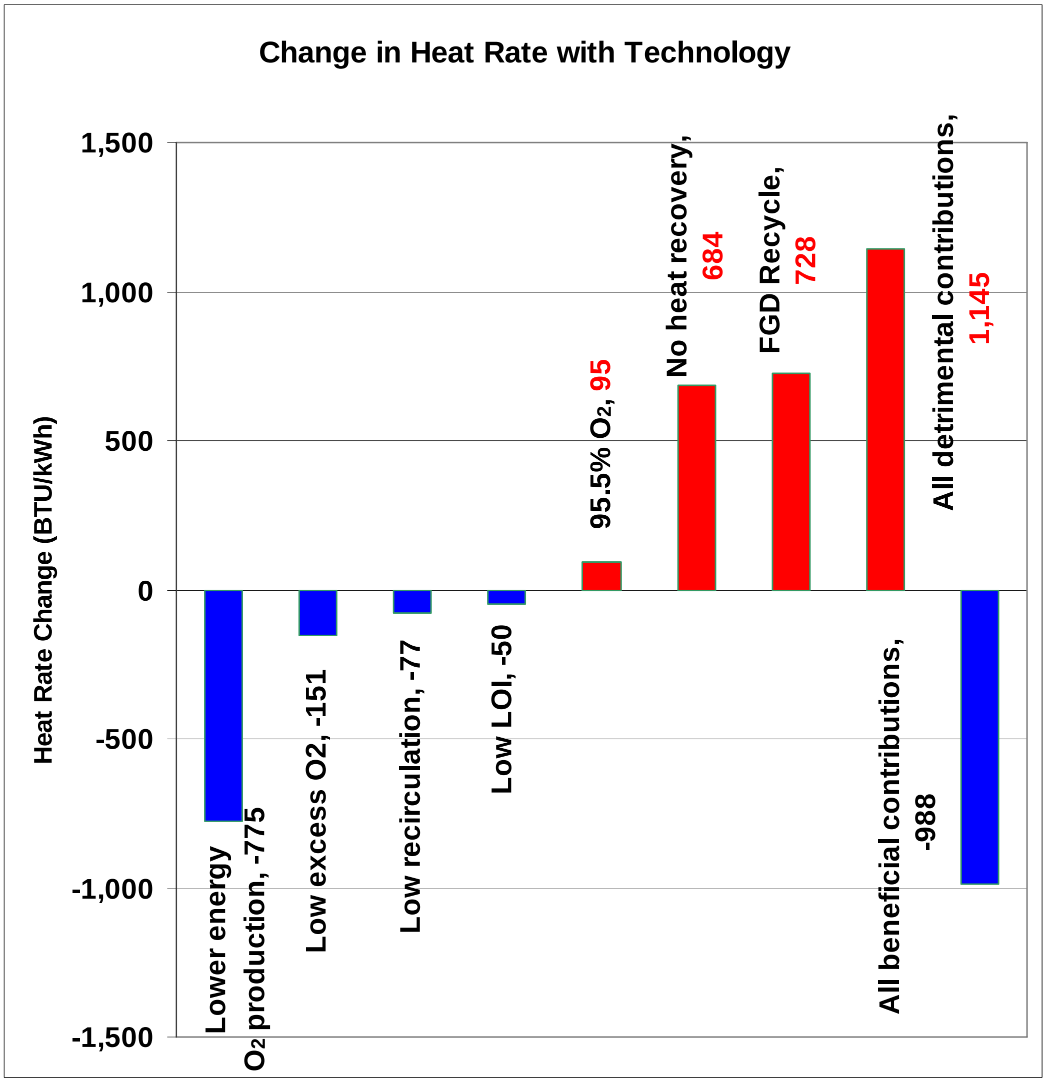

Figure 2: Change in heat rate with technology compared with the oxy-fuel base case. Positive numbers (shown in red) indicate more fuel used for each kWh produced. Negative numbers (shown in blue) indicate a reduction in fuel usage for each kWh produced.

The recirculation rate was varied from as high as approximately 0.58 (37% O_2) to as low as approximately 0.34 (61% O_2). Even holding the recycle rate constant can result in a change in O_2 content due to changes in other parameters such as the H_2O content, purity of the O_2, air in-leakage, excess O_2, fuel load, LOI, and others. This presents a challenge to burner designers since the O_2 fraction can change with differing conditions more readily than when using air as the comburent. The reduction of -77 BTU/kWh shown in Figure 2 is mostly due to reduced fan loads. It is difficult to model the rest of the interactions that take place without good operating data for oxy-fuel boiler systems. This is probably the lower limit of the potential improvement that can be expected by reducing recirculation rate.

Low unburned carbon: Unburned carbon is a loss to overall power plant's bottom line. Since the burner designer using oxy-fuel is working with different flame characteristics compared to air, there are new parameters that can be investigated such as: excess oxygen, recirculation, particle size, radiant heat transfer, and LOI. There is on-going research in this area and the potential reduction in heat rate, by -50 BTU/kWh for a reduction from 1% unburned carbon to 0.5% unburned carbon, is significant.

Use of 95.5% purity O_2: Energy consumption changes if the purity of O_2 can be relaxed from 99% pure to 95% pure. The specific energy requirement for O_2 production is approximately 220 kWh/ton for 99% O_2 and approximately 210 kWh/ton O_2 for 95.5% O_2 using current technologies. However, the increase in tramp gases (predominantly Ar and N_2) results in the use of more energy during the recirculation, capture, and compression processes, because the tramp gases will also have to be moved by fans and compressed along with the CO_2 for carbon capture. In this case, the results of the modeling indicate an increase in heat rate of approximately 95 BTU/kWh (increased fuel input for a specific output power). This is probably a lower limit on the actual penalty; power usage is dependent on the purity of the CO_2 required for pipeline delivery, and this set of models works with a relaxed CO_2 purity that allows contamination with inert gases. The added separation penalty, in both energy and lost CO_2, which would occur if EOR purity were required is not assessed. The penalty is also sensitive to the method for production of O_2. In these models it was assumed that a typical cryogenic denitrification plant would be used. If, instead, an advanced design denitrification facility produces 99%+ pure oxygen during standard operation, there is no reason to consider a lesser purity.

No heat recovery: The core technology in the IPR™ process is heat recovery in the exhaust stream. Heat recovery is standard in the models in this paper. In the model that examines the effect of removing heat recovery we changed the cooling process in the exhaust stream to use cooling water with no energy recovery. The result is a large increase (684 BTU/kWh) in heat rate (approximately 1.5% change in thermal efficiency). It is important to take whatever opportunities are available to recover energy from the waste streams in the system.

FGD during recycle: There is a concern about the ability of standard boiler materials to withstand prolonged exposure to a denitrified environment with a high SOx content (>1%). Little is known about the performance of materials in the oxy-combustion environment; thus many studies add an FGD process in the recycle loop to remove sulfur from the recycled flue gas. Inclusion of the FGD step during recycle reduces the enthalpy of the recirculated flue gas and impacts the boiler performance. The model shows a penalty of approximately 728 BTU/kWh in heat rate over the baseline oxy-fuel system. This is a very steep penalty, and a strong argument for evaluating the materials issues thoroughly to determine the need for FGD.

Combined technologies with detrimental effects on heat rate: A model was built that combined of all of the detrimental contributions to thermal efficiency in order to see how poorly a system without advanced approaches could be expected to perform. The result is a 27.3% HHV thermal efficiency with an increase in heat rate of approximately 1,145 BTU/kWh (a 23% decrease in thermal efficiency).

Combined technologies with beneficial effects on heat rate: All of the beneficial technologies (those decreasing heat rate) were combined in a model to determine what the thermal efficiency might be for an advanced retrofit system. The result is a HHV thermal efficiency of approximately 32.9%.

Figure 3 shows the impact of the various technologies on the net power plant electrical output. Any drop in output means that additional capacity will be required to make up for the lost power. The greatest loss of capacity in the models examined is the loss of heat recovery – 99MW from a nominal 432 MW unit – a 23% reduction in power. Employing all of the potentially beneficial technologies, the loss in capacity is approximately 50MW – a reduction of 12% from the air fired case. When examining net power output, the energy cost of oxygen is clearly the most important technology. Both power and thermal efficiency can be impacted by design choices, and those choices result in significant changes to the cost of electricity.

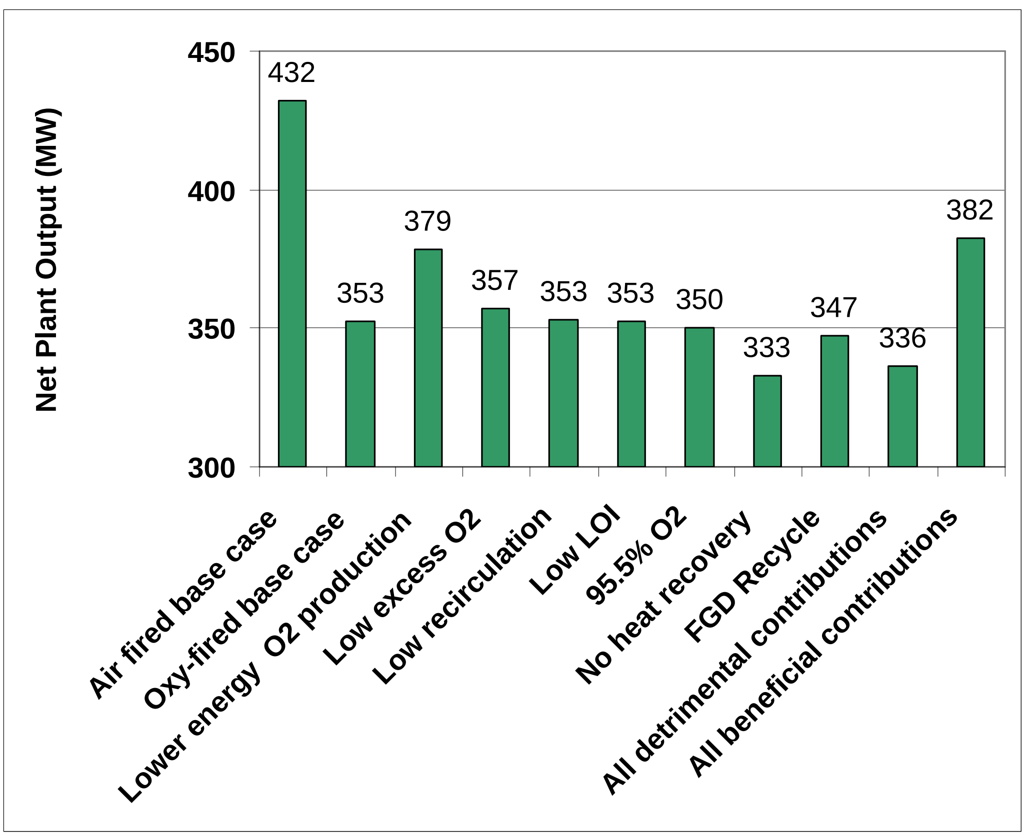

Figure 3: Net power plant output with potential technologies.

Discussion of Infiltration:

An issue under consideration for oxy-fired CO_2 capture is the extent to which infiltration can be avoided in the power plant gas path. Part of the discussion focuses on how much impact the increased nitrogen from the infiltrating air has on combustion and gas processing.

If the infiltration rate is low and nitrogen can be tolerated in the CO_2 product, then the impact depends on NOx production in the higher nitrogen flame (where nitrogen content is raised by air infiltration) and the required processing of the NOx. Since there is limited information on thermal NOx production in oxy-fuel flames under varying conditions it is difficult to predict the NOx levels in oxy-fuel flames as infiltration increases the N_2 content. If the NOx can be co-sequestered with the CO_2, there is not much of a problem since the quantity of NOx is small. However, if it cannot be co-sequestered it has to be removed, which requires some NOx treatment (which is not generally a part of CO_2 processing systems and would require additional equipment). If there is no infiltration, the NOx is limited to fuel NOx and is at a concentration that does not require further processing.

One potential problem with infiltration is the dilution of the captured CO_2 with tramp gases. If the minor constituents can be tolerated in the sequestration scheme then there is no problem compressing the entire mixture to supercritical pressure and sending the entire dry mixture through a pipeline to the sequestration site. Initial experiments have even indicated that geological sequestration should be tolerant of minor constituents including SOx[5]. However, there should be further research to determine if the transport and co-sequestration of SOx can be tolerated.

If significant amounts of air are brought into the system through infiltration and if high-purity CO_2 is required, distillation may be used to meet the requirement for pure CO_2. This additional distillation step will have an associated detrimental impact by reducing the total CO_2 captured and increasing energy usage. The higher the amount of infiltration, the greater the fraction of contaminants, and the smaller the fraction of CO_2 that can be economically captured. If the sequestration method is tolerant of a gas mixture, and if air infiltration can be minimized, then there is no reason to not capture 100% of the CO_2 (and all other gases) during steady state operation.

One way to avoid air infiltration is to run boilers at a slight positive pressure. However, there are safety issues involved in operating at positive pressure as well as an uncertainty as to how much CO_2 is lost to the atmosphere through the same leaks that allow air in when the boiler is running under negative pressure.

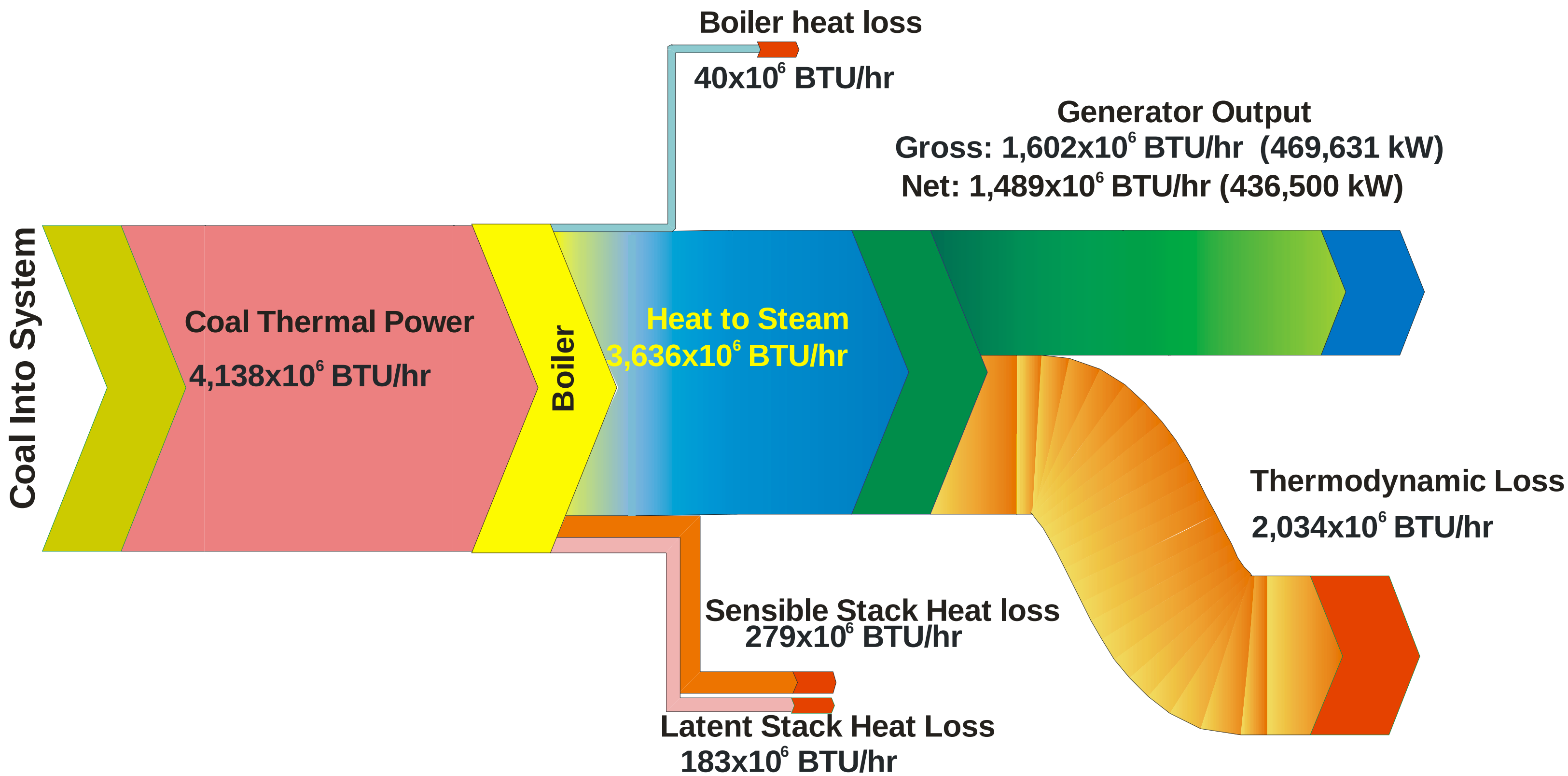

Figure 4: Sankey diagram of power flow in a PC coal air-fired power unit with no carbon capture. Power is shown in thermal energy equivalent per unit time. Only major power usage is shown for simplification. Numbers may not sum correctly due to rounding.

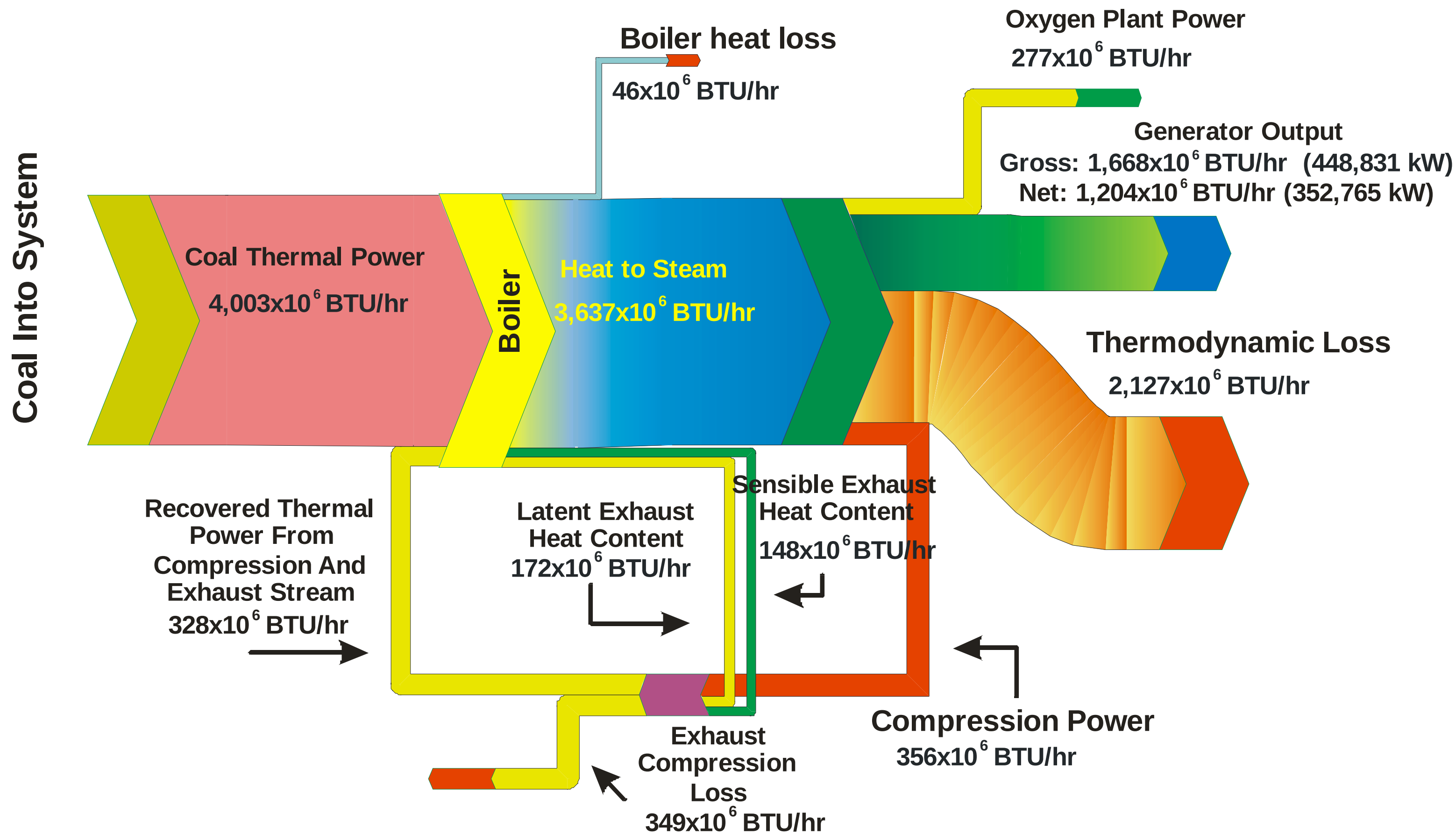

Figure 5: Sankey diagram of power flow in the same PC coal unit shown in Figure 4 after conversion to oxy-fuel with IPR™ CO_2 capture. Power is shown in thermal energy equivalent per unit time. Only major power usage is shown for simplification. Numbers may not sum correctly due to rounding.

Energy flow in power generation units:

Figure 4 and Figure 5 show the flow of thermal, shaft, and electrical power through both an air-fired unit without CO_2 capture and the same unit converted to oxy-firing with CO_2 capture. This is the equivalent of our base fired air case and our base oxy-fuel IPR™ model. In both figures only major power sources and sinks are shown. Both start with coal thermal power and show the transfer of heat into the system steam at the boiler node. Both figures show comparable boiler losses due to convection and radiation from the boiler.

In Figure 4, the stack losses are shown (both sensible and latent). However, in Figure 5 the exhaust thermal flow is shown but it is not considered a loss. The reason the IPR™ exhaust energy is not considered an immediate loss is that some of the latent and sensible heat in the exhaust is captured and some of the power used in processing the denitrified combustion products is captured and returned to the thermodynamic working fluid (the feedwater). Recirculation of flue gas is not shown because it is a thermal process internal to the heat transfer section. The loop shown in Figure 5 is an energy loop showing recovered energy from the non-recycled portion of the exhaust gas.

The major difference between the two configurations is the extra demands on the work produced from the steam cycle. The major demands of oxygen generation and exhaust gas processing produce a significant decrease in net electrical power in the oxy-fuel case (a loss of almost 100 MW in the base oxy-fuel case or about 54MW when comparing the better case with the air fired case). That is the reason that reducing the oxygen demand and recovering energy from the exhaust processing have such important impacts on the net unit generation (and overall thermal efficiency).

Summary:

The ranking of technological areas according to their impact on power plant performance (efficiency, capacity, and availability) has begun with an overview of the impact of specific technologies on capacity and efficiency. Those technologies showing the longer bars in Figure 2 (whether positive or negative) have the greatest impact on heat rate. In order, according to these modeling exercises, the greatest improvements in heat rate can be achieved through:

1. Lower energy O_2 production
2. Elimination of FGD during recycle
3. Improvement of heat recovery in exhaust gas processing
4. Reducing excess O_2
5. Using high purity O_2
6. Reducing recirculation
7. Reducing unburned carbon

A further parameter, which was not modeled in this study, is infiltration. This is, naturally, site specific and will be an important factor to consider in the engineering effort in preparing for retrofit CO_2 capture. Activities are underway to better quantify this variable. Initial indications are that this can have a significant impact on operation.

References:

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