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Minimizing the Energy and Economic Penalty of CCS Power Plants Through Waste Heat Recovery Systems

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Abstract

Implementation of CCS technologies into fossil power plants brings inevitable technical, energy and economic penalty. This penalty increase when low rank coals as lignite are utilized. The efficiency loss results in larger amounts of waste heat rejected into the ambient as it cannot be reasonably utilized within the power cycle. The temperature of the waste heat in some cases is however still sufficient for conversion to electricity by small modular waste heat recovery (WHR) units based on technologies such as Organic Rankine Cycle and absorption power cycle.

Three generally considered CCS technologies were modelled – oxyfuel combustion and ammonia scrubbing based post-combustion (subcritical power plant with fuel drying) and pre-combustion (IGCC with Rectisol method for CO_2 separation), for which the WHR options have been analyzed. Systems with WHR improve plant efficiency, but also flexibility due to decoupling waste heat streams from the main steam cycle. Results are presented for scenarios of 250 MW_e coal fired power plants, applied to central European conditions. The efficiency increase in the case of an IGCC-CCS plant is up to 4.2 percentage points, followed by oxyfuel with 1.3 percentage points while effectiveness in post-combustion is minimal, 0.1 percentage points. The economic effect is positive in all CCS plants, allowing for improvements in the LCOE by up to 6.3%.

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1. Introduction

Growing electricity demands, abundant amounts of coal and at the same time adverse effects of anthropogenic greenhouse emissions related to climate change are the reasons why carbon capture and storage (CCS) technologies are expected to be necessary for CO_2 emissions control. The efficiency penalty, together with the additional costs, is

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limiting the economy of the plants that would employ CCS even those that might have a chance to participate in emission trading schemes. Therefore novel ways to improve these aspects are an area of active research.

CCS technologies generally reduce efficiency by consuming electricity and/or withdrawing steam that could otherwise be used to create electricity, while also generating significant waste heat. Integrating these heat streams into the steam cycle may, in some cases, provide theoretically high efficiency. On the other hand this heat is often at low temperature (below 200°C) and cannot be effectively applied to the power generation cycle. In addition, with integration the power plant could become complicated and inflexible. Independent power generation units located adjacent to each waste heat stream and tailored to specific temperatures do not pose the same complications, as plant operation isn't dependent on their function and during non-steady operation they can flexibly provide power output. For a low-temperature heat source and for small unit output many waste heat recovery (WHR) systems are significantly more efficient than using a steam cycle. Moreover, steam cycles may not be technically applicable. Therefore the overall efficiency can be also improved by adding a waste recovery system that can use heat at low temperatures.

The idea of utilization of waste heat streams in CCS plants has been previously considered for district heating.[1] This application is, however, dependent on the district heating systems which are not widespread. Recovery of waste heat from CO_2 compression has been separately investigated in [2] showing that ORC unit may be recover up to 17% of the energy input. Independently ORC WHR unit for air separation unit (ASU) [3] has been also considered as another application. Later in work focusing separately on ASU [4] was found that ASU power consumption can be decreased by 11% from incorporation of ORC cycle, albeit with some rather optimistic assumptions. Preliminary results of WHR options have been reported for an IGCC plant with water quench [5], where the potential of such system applications can result in an efficiency increase by more than 2 percentage points and for a system with CCS and around 0.5 percentage points for an IGCC plant without CCS.

This work aims to give a comprehensive view on various waste heat streams throughout power plants with and without CCS for three basic CCS options (oxyfuel, post-combustion - ammonia scrubbing [6,7] and pre-combustion with Rectisol solvent system [8]). Compared to previous works, in this research there has been a concerted effort to use more realistic assumptions.

2. Review of WHR Technologies

In waste heat recovery for electricity production many technologies can be generally applied, but only a few are commercial and feasibly applicable. Prospective emerging technologies still in the research and development phase include indirectly heated Brayton cycle [9], inverted Brayton cycle [10], Stirling cycle [10,11], trilateral cycle [3], thermoelectricpiezoelectric, thermionic and other conversion methods [12]. In this work we have evaluated two options, an ORC and an absorption power cycle, described below. Fig 1 provides a schematic diagram of both.

WHR systems advantages include system flexibility, efficiency of small units and, when compared to a steam cycle, lacks superheaters, which would complicate the system. The assumed ambient conditions for the plants (WHR units and main power plants) are 15°C, 70% relative humidity, and 1 bar. The assumed efficiency of the WHR turbines is 70%, pumps were assumed to be 60% efficient and pinch points in heat exchangers were assumed at 10°C.

2.1. Rankine Cycle

The steam Rankine cycle is robust and well proven for power generation, with steam microturbines commercially available for smaller applications, including WHR (example of a compact microturbine with power output down to 75 kW has been described elsewhere [13]). However, for WHR from sources in the temperature range 200-400°C an Organic Rankine Cycle (ORC) is generally considered as a best option and it is considered a standard technology [14]. An ORC utilizes organic working fluid, which generally has a lower heat of vaporization and different vapor-liquid equilibrium curve shape than water. This allows for higher cycle efficiency, turbine efficiency, omitting of superheaters or better utilization of the heat source when compared to steam turbine. The advantage of ORCs is also their availability as modular units. ORC is considered in a basic scheme (i.e. no recuperator) in Fig. 1a. As cooling and heat rejection is required for most cases in the system, thus, the recuperator doesn't affect achievable cycle