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Maximization of Net Output for Boundary Dam Unit 3 Carbon Dioxide Capture Demonstration Project

Background

- Boundary Dam Unit 3 Carbon Dioxide Capture Demonstration Project (BD3 ICCS) is known as the first utility scale commercial CO_2 capture and storage facility fully integrated to a coal-fired power plant.
- Without CO_2 capture, pre-upgraded BD3 produced a 150 MW gross output and a net output of 139 MW.
- Initial models incorporating CCS calculated a net power output of 80.95 MW which indicated a reduction in net output of approximately 42%.
- The CCS facility requires steam for solvent generation and electricity for CO_2 compression as well as other additional auxiliary loads therefore the net output is decreased with the integration of CCS.
- Several factors have been taken into consideration including:
  - Technology for CO_2 Compression
  - Turbine Refurbishment
  - Steam Extraction and Optimization
  - Flue Gas Cooler (FGC) Installation for Heat Recovery
  - Main Steam Temperature
  - Boiler Refurbishment and Others

Engineering Design Process

Various cases were evaluated in the design process for BD3. Using an iterative process, the net output was maximized while losses were minimized. Electricity outputs for each model are depicted in Fig. 1. The improvements in gross output, auxiliary load losses, and net output from the initial model to the final model are also compared. Initial models incorporating CCS produced a 124.13 MW gross output and a net power output of 85.95 MW with losses attributed to steam extraction. However, it was noted that for this initial model some auxiliary loads had not been considered. Consideration of these inputs further reduced the net output to 80.95 MW. The resulting energy penalty, approximately 42%, was most concerning when considering the business case for BD3. Improvements were made through subsequent models. This included steam cycle components, and decreasing auxiliary loads. Power production increased; the final integrated model produced a net output of 110.88 MW – a 29.93 MW increase when compared to the initial cases. The optimizations that led to this 29.93 MW gain are explained below.

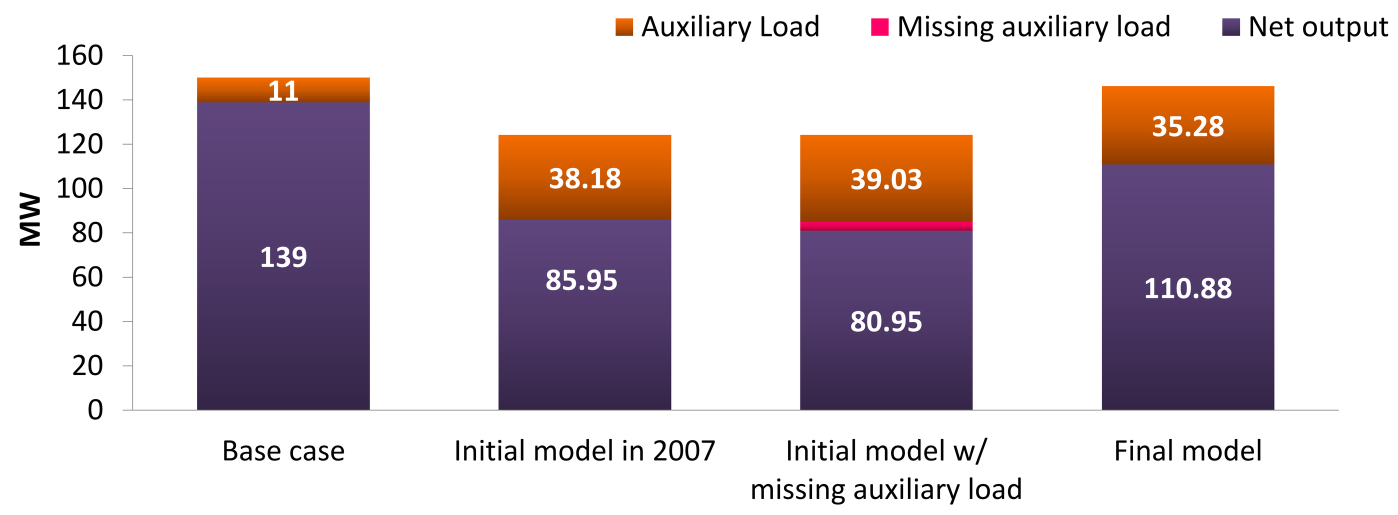

Figure 1. Improvement of net output during the ICCS design process

Steam Extraction and Optimization

Four scenarios were investigated as steam extraction locations. The controlled extraction by incorporating a Pressure Maintaining Valve (PMV) at the IP-LP crossover between the extraction point and the LP turbine inlet will lead to the loss in power generation. Therefore, all scenarios assumed the use of an uncontrolled extraction. Since, at this time a wet limestone flue gas desulfurization (FGD) system was assumed for SO_2 removal there was no requirement of steam for the SO_2 capture process.

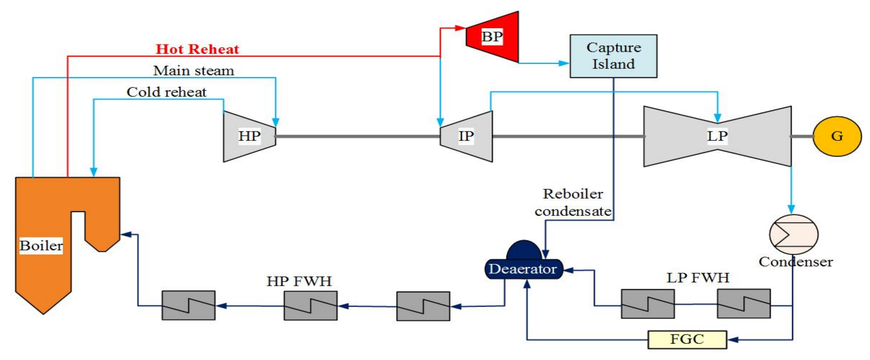

Figure 2. Simplified diagram for steam extraction from hot reheat/ backpressure turbine

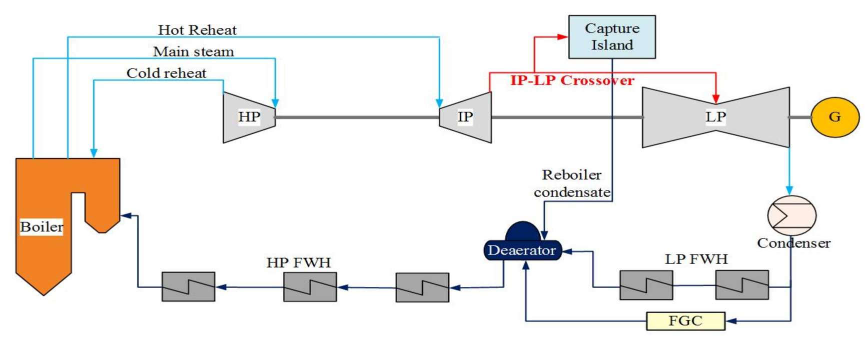

Figure 3. Simplified diagram for steam extraction from IP-LP crossover

Scenario 1: Hot reheat / backpressure turbine

The use of a backpressure turbine generates additional electricity before sending the steam to the capture process; this can help to minimize losses in gross output for the power plant.

Scenario 2: IP-LP crossover

This option is the most reasonable as this steam is low quality and is easily accessible. The extraction from this location has no impact on LP operation other than reducing the flow.

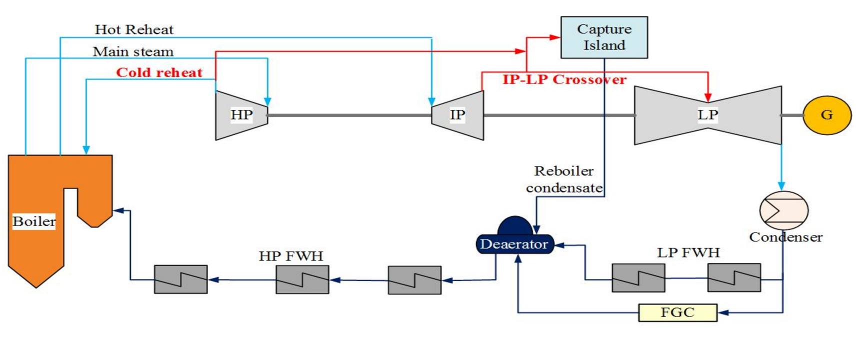

Figure 4. Simplified diagram for steam extraction from mixed cold reheat and IP-LP crossover

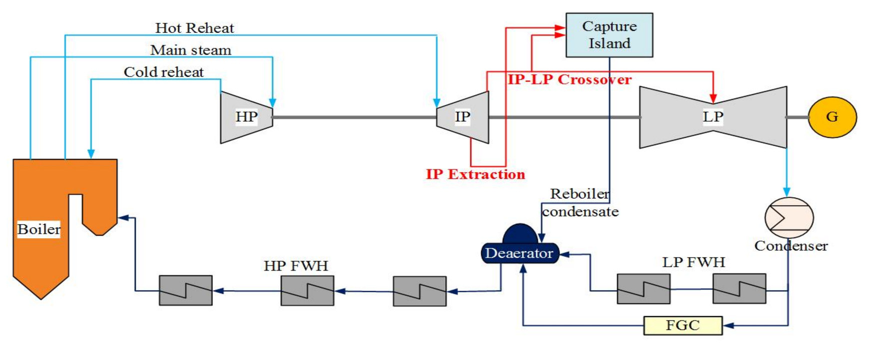

Figure 5. Simplified diagram for steam extraction from mixed IP and IP-LP crossover

Scenario 3: Cold reheat and IP-LP crossover

The steam was withdrawn from two positions including cold reheat and the IP-LP crossover. As adding a single large extraction flow can have impacts on pressure ratios, thrust loads, and stresses in the steam turbine sections upstream of the extraction point.

Scenario 4: IP and IP-LP crossover

Instead of withdrawing steam with higher thermal energy, such as from the cold reheat, Scenario 4 extracted steam with a lower pressure from IP and mixed it with steam extracted from the IP-LP crossover.

Effects of Turbine Optimization

Effects of the steam extraction flow rate were investigated as part of turbine optimization. Higher steam extraction flow rates lead to higher losses of gross output. The model associated with the original turbine design gave the highest loss due to the requirement for throttling and the installation of a backpressure valve to provide steam to the capture process at the suitable pressure.

The combined results from the optimizing steam extraction location, turbine design, and heat recovery through flue gas cooling paired with condensate preheating are illustrated in Fig. 6. To reiterate, steam extraction from the IP-LP crossover not only yields the highest gross output (136.6 MW) but also provides increased steam accessibility. Paired with the customized LP turbine, the net output can be increased to 138.8 MW - a significant 2.2 MW gain.

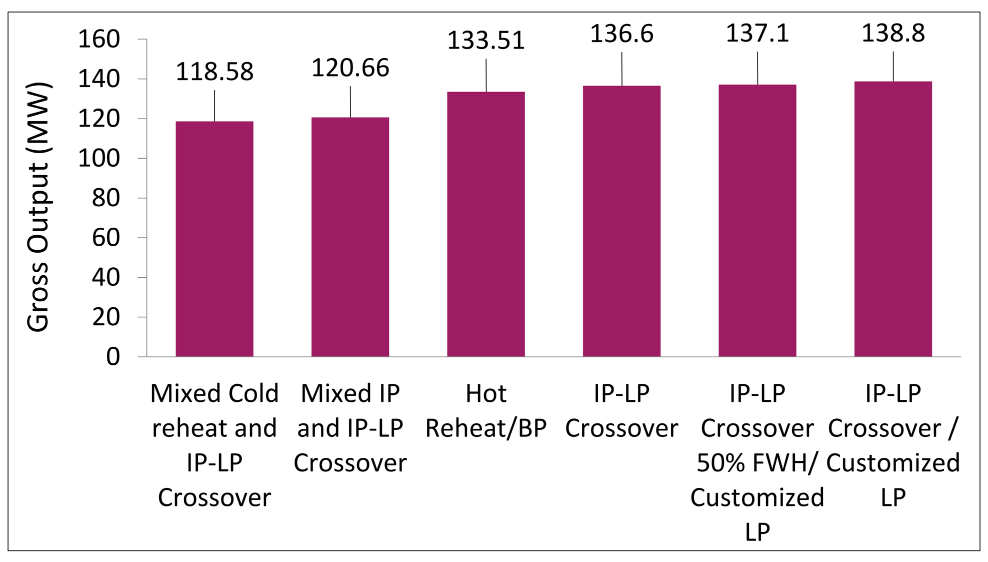

Figure 6. The results from the effect of steam extraction location and the turbine optimization

Compression Power

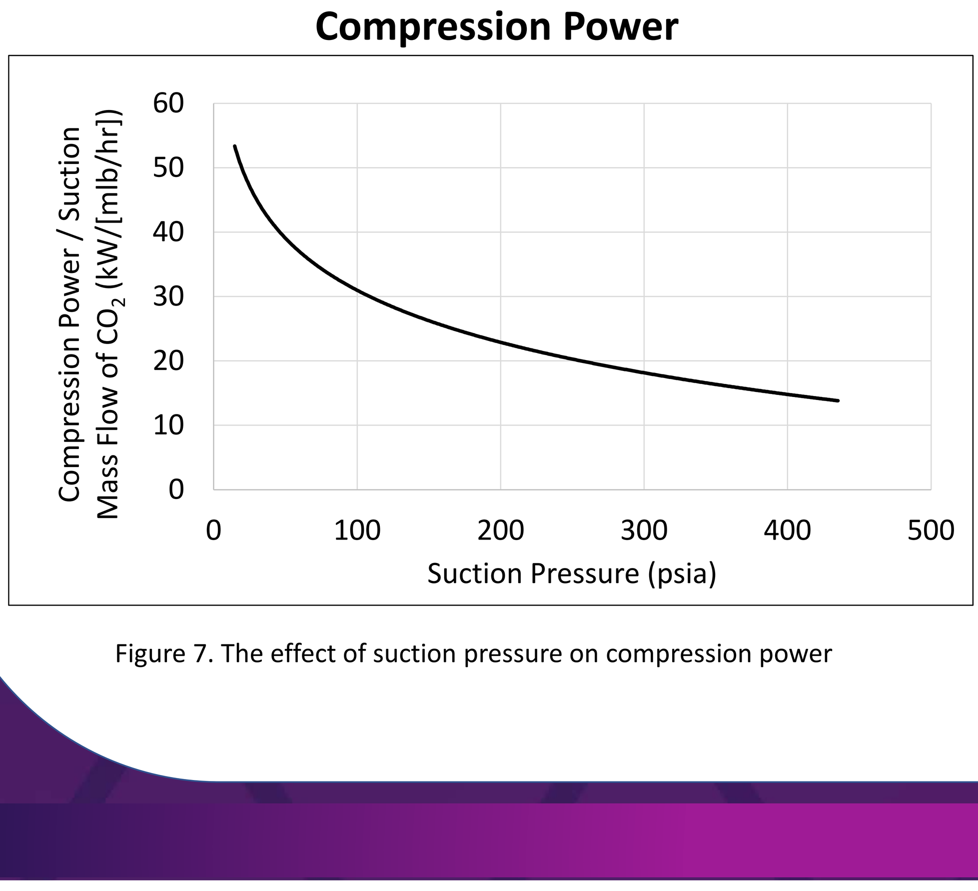

Figure 7. The effect of suction pressure on compression power

The effects of the CO_2 suction pressure from the capture plant on the compression power per mass flow of CO_2 is illustrated in Fig. 7. It can be noted that increased pressure of the incoming steam equates to lower energy requirements by the compressor. However, the higher suction pressure indicates higher steam extraction quality/quantity requirements. Suction pressure must be optimized to compensate between thermal energy supply to the capture process and the electricity supply to the compression process. The final model resulted in the compression power of 13.74 MW.

The Effect of Boiler Refurbishment

Figure 8. shows relative improvements in boiler efficiency and the cost of boiler upgrades for the different boiler upgrade options. Increased upgrades lead to higher relative improvement of boiler efficiency. However, the costs of the refurbishment are also increased through equipment and labor requirements.

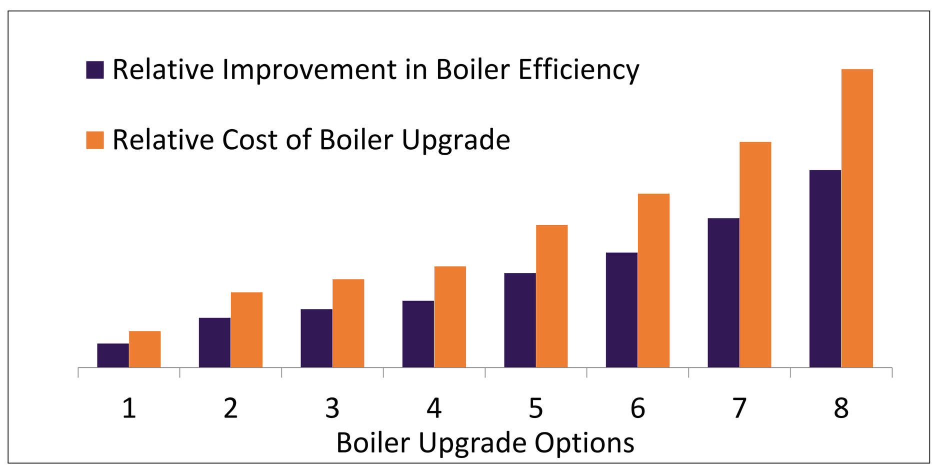

Figure 8. Relative improvement in boiler efficiency and cost of boiler upgrade at the different boiler upgrade options

Conclusions

Rigorous modelling and investigations improved the net output production of BD3 when integrated with CCS technology. The 29.93 MW net output increase from the initial process integration model was significant. The main contributors in the net output improvement were: selection of CO_2 compression technology (contributing to 24 % of the net output improvement), turbine refurbishment (contributing a 20 % improvement) due the elimination of turbine leakage and turbine degradation, and heat recovery and integration via flue gas cooling and condensate preheating (contributing a 13% improvement). Furthermore, increasing main steam temperature and the boiler efficiency as part of the refurbishment increased the net output 7% and 5% respectively.

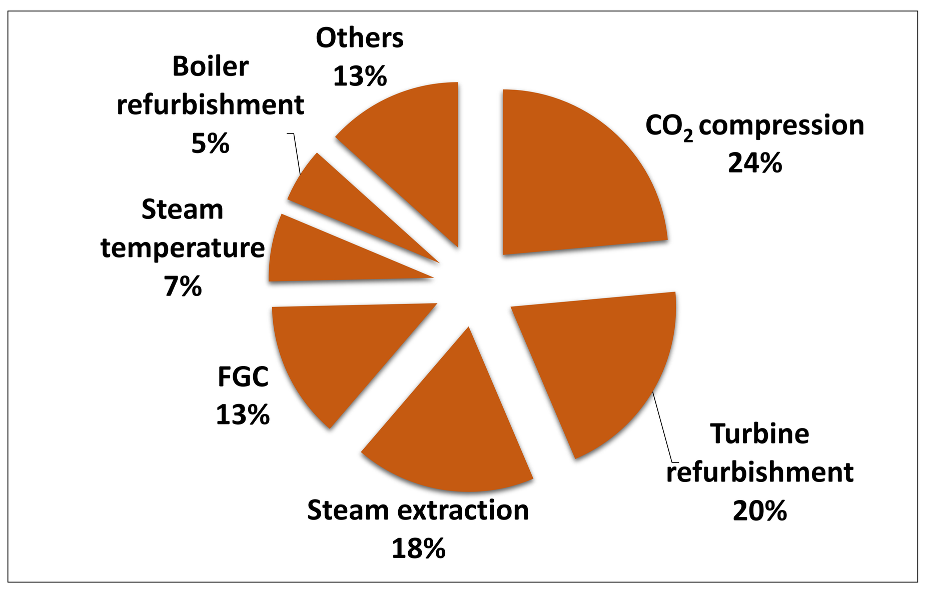

Figure 9. Net output percent increase corresponding to studied aspects

Currently, operating conditions at BD3 may differ from those described in this paper. Learnings from operational experience may have changed the way in which the capture island is run. The BD3 ICCS project continues to lead the evolution of CCS technology. The trail blazing nature of this "first of a kind" mega project has inspired the next generation of industrial scale carbon capture projects.

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