Alternative Utilization of Waste Heat Streams in Pre-Combustion CCS IGCC Power Plants

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Abstract

Many processes in IGCC power plants produce waste heat streams which need to be utilized in order to keep economy and efficiency of the plant at high levels. Using of low rank coal and integration of pre-combustion CCS results in higher number and impact of these heat streams. Current trend where all heat is utilized within the cycle itself, especially by sophisticated systems of regeneration, is beneficial for the overall efficiency. This approach however complicates the system and causes issues and decrease of operational efficiency during start-up, shut-downs and non-steady-state operation. Alternative utilization of these heat streams by small modular power production units used typically for industrial waste heat recovery is investigated. These can be based on organic Rankine cycle (ORC), absorption power cycles or other systems. It is shown that using these units can substantially simplify plant control, flexibility and improves not only operation efficiency of IGCC plants; especially when low rank coal is utilized and CCS system need to be implemented. Detailed technical and economical results are presented for a case scenario of power plant output of 250 MWe. Plant is using a pre-combustion CCS system and utilizing a low rank brown coal as a fuel and modular absorption power cycle units for utilizing waste heat streams.

Keywords: IGCC, Waste Heat Recovery, pre-combustion CCS

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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 CO2 emissions control. Among the considered and in current technology available options stand out Integrated Gasification Combined Cycle (IGCC) plants as they have potential for lowest efficiency penalty. These plants are the most efficient way of coal to energy conversion. The efficiency penalty, together with the additional costs, is limiting the economy of the plant even in environment of emission trading schemes. Therefore novel ways to improve these aspects are in active research.

The process of fuel preparation within IGCC plants results in substantial streams of waste heat. At high temperature this is usually utilized by the power cycle for steam preparation, however there are still large amounts of left out heat streams typically below 200°C where the heat is rejected by the cooling systems. These waste heat streams are more significant and in larger extent when CCS technology is considered. Low rank coal as fuel also affects these heat streams to grow in volume. Temperature of these streams is often too low for reasonable utilization within steam cycle; however it is well fit for typical Waste Heat Recovery (WHR) applications with Organic Rankine Cycle (ORC). Along with ORC a novel promising technology of Absorption Power Cycle (APC) is proposed for waste heat streams at very low temperatures where ORC efficiency is decreasing significantly. If waste heat stream are integrated into the steam cycle, theoretically high system efficiency can be achieved, but the system would become very complicated and inflexible. On the other hand individual independent units located adjacent to each waste heat stream do not pose complications. Plant operation isn’t dependent on their function and during non-steady operation they can flexibly provide output dependent only on the adjacent system but not the entire plant. Regardless of small unit output power, many WHR systems are at low temperature significantly more efficient than steam cycle. Therefore the overall efficiency can be also improved.

The idea of utilization of waste heat streams in CCS IGCC plant has been previously considered for district heating.[1] This application is however dependent on the district heating system which isn’t very much widespread nor it is in hot regions of the world needed. Recovery of waste heat from CO2 compression has been also separately investigated [2] and it was found that with typical compression system of CO2 for transport and storage can be by ORC recovered around 17% of the energy input. Independently ORC WHR unit for Air

Separation Unit (ASU) [3] has been also considered for 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, although rather optimistic assumptions were taken.

This work however presents a comprehensive view on various waste heat streams throughout the IGCC plant with and without CCS. In the first part of the work are briefly described basic case IGCC plants with and without CCS. In following section is given closer look at particular waste heat streams throughout the plant and their potential for utilization is discussed. Next chapter describes the WHR systems considered in the focus of this work, ORC and APC. Finally results show and discuss these systems application, showing important efficiency increase and presenting technical and economic aspects.

2. BASE CASE IGCC

Base case IGCC plant is considered for plant of net power output 250 MWe, utilizing rather low rank coal with LHV 16.5 MJ/kg, water content nearly 30% and ash content 18% (properties are in table 1).

Table 1: Coal specifications

LHV [MJ/kg]	Wr	Ad	S
15	27	18	1.7

Plant is considered to be with CO2 capture but for comparison are results given also for basic case without capture. The plant is based on dry coal fed oxygen entrained flow gasifier. ASU has zero air integration for flexibility and simplicity. Steam cycle is designed as triple pressure which is currently a standard in combined cycle plants. Summary of the main input and assumptions is given in table 2.

Table 2: Model input and technical assumptions

Net Output	ASU integration	Gasifier	Steam cycle	CO2 capture	Ambient
250 MW	None	Dry, Oxygen, Entrained flow	Triple pressure	90%	25°C, 70% RH

Generalized process flow diagram of the IGCC plant with CCS is on figure 1. Plant uses fluidized bed drying process with internal waste heat utilization by compression of vapours from coal (WTA process [5]). After that coal is milled and pneumatically conveyed by inert nitrogen from ASU into the operation silos and then into the gasifier. Alongside coal, other inputs into gasification process are s oxygen supplied by ASU and steam. Feed water is supplied to provide radiant cooler of syngas within the gasifier where it turns into high pressure steam for use within the turbine. Syngas downstream is quenched by water and further cooled by feed water in convective coolers to allow syngas flow into filters of ash removal system. Following is the COS hydrolysis and Water Gas Shift (WGS) (only for CCS case), cooling down for desulphurisation by Rectisol wash and CCS CO2 separation, recuperative heating and further preheating before the combustion turbine. Exhaust gas is then used in Heat Recovery Steam Generator (HRSG) as in regular combined cycles where is bottoming steam cycle with triple pressure configuration. ASU is not air integrated into gas turbine. The system however has high integration into steam cycle for feed water heating and low pressure steam preparation. Only waste heat streams below approximately 140°C are not utilized within steam cycle. Detailed model of the plant is very similar to the one in [6].

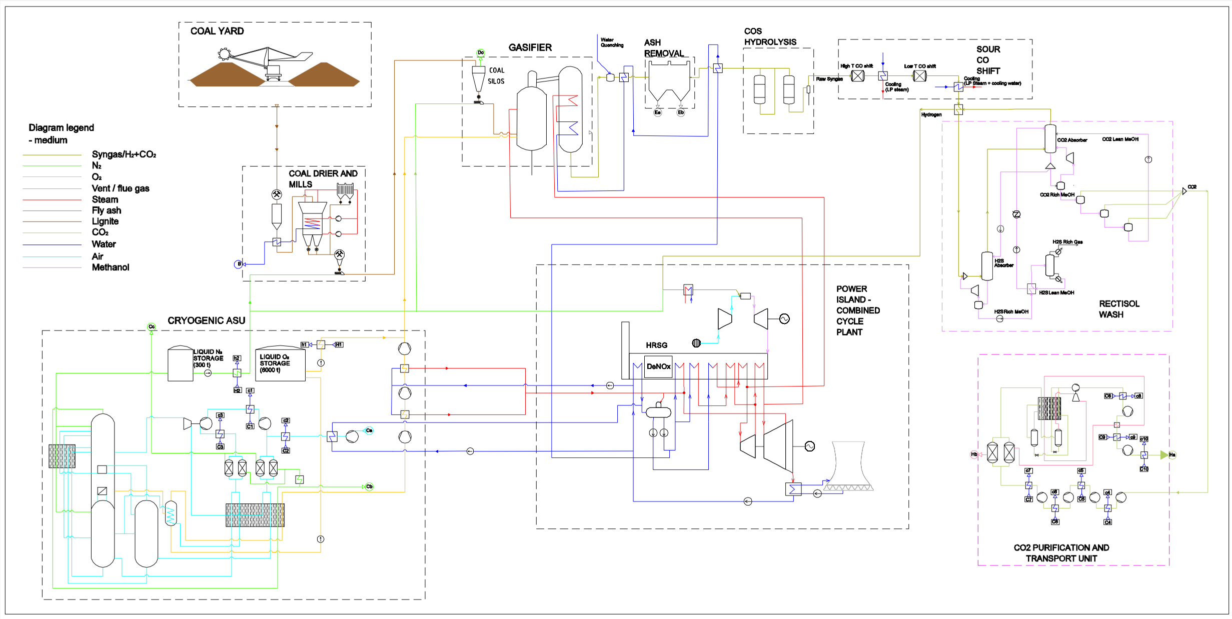

Figure 1: Process flow diagram of the base IGCC CCS plant

3. POTENTIAL WASTE HEAT STREAMS

Most of the waste heat streams in the process are utilized by the steam cycle to preheat feed water or prepare steam. This high integration helps in achieving good efficiency, however results in complicated process with largely decreased plant flexibility. Large distances between sources and utilization of recovered heat streams also impose heat losses. Furthermore the left out heat streams, although mostly at temperatures around 100°C which generally are not considered to be utilized in the plant still contains significant working potential. Utilization of these streams by separate modular WHR units however should pose no negative effect on plant complexity or operation flexibility. At moderate temperatures can be achieved even higher efficiency than in the original highly integrated scheme. These waste heat streams are from compressor intercooling and from aftercooling (air compressor for

ASU, compressor of oxygen and CO2 compression for transport and storage). Further there is syngas cooling before Rectisol wash (desulphurisation and CO2 separation) and vapours from coal dryer that also still bear significant heat content. As the flue gases especially after CO2 capture are virtually free of sulphur and dew point is thus fairly low, it may be beneficial to further utilize flue exhaust gas to temperatures below 100°C. This is however problematic by combined cycle itself and therefore separate bottoming unit will be considered.

3.1. Air Separation Unit

Air separation unit is shown on fig. 2 with highlighted important waste heat streams. It provides oxygen for gasification and nitrogen for coal transport and turbine diluent. It is based on cryogenic distillation for which air needs to be compressed to approximately 6 bar. In three stage compression waste heat emerges from intercooling and aftercooling as hot water at temperature around 100°C. For most efficient operation about half of the oxygen is recovered in liquid state and the rest in gas state. Gas oxygen is compressed for gasification to pressure over 40 bar in three stage compressor where cooling medium (oil or pressurized water) reaches temperature 200°C. In original design this heat is recovered in steam cycle. Parameters of the heat streams are given in table 3.

In the proposed concept these streams of cooling medium serve as a heat input for WHR units. Higher efficiency would be achieved by direct connection without the intermediate loop. Operational reliability, availability and also intercooler design however dictate this configuration. When the WHR unit is offline it doesn't practically affect the plant operation at all.

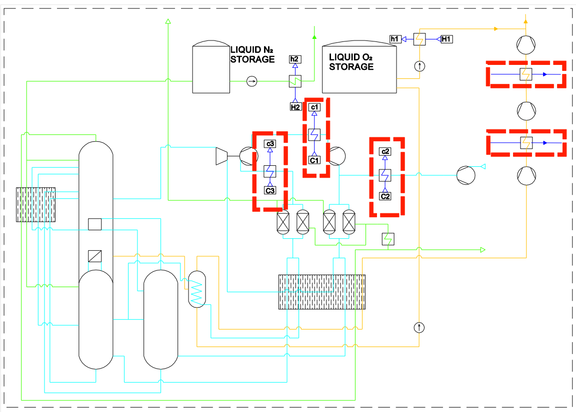

Figure 2: Scheme of Air Separation Unit with highlighted potential for WHR

Table 3: Parameters of ASU related waste heat streams

Decription	Gas Temperature [°C]	Medium	Mass flow [kg/s]	Temperature [°C]	Note
Air compressor IC and AC	107-114	Water	66.6	100.3	
O_2 compressor IC	~210	Water (27 bar)	46.7	199.5	in base case heats up feedwater

3.2. Coal fluidized bed dryer

Due to high water content of the coal there is a coal dryer. For high efficiency and performance the WTA principle is employed, where vapours from the coal with a portion of air are compressed and its heat is utilized in heat exchanger within the fluid bed to heat up and dry the coal as the vapours are condensing. Outlet is further used in coal preheating however the air-vapour mixture at dryer outlet has still temperature over 100°C. Figure of the dryer is on figure 3 and properties of the outlet stream are in table 4.

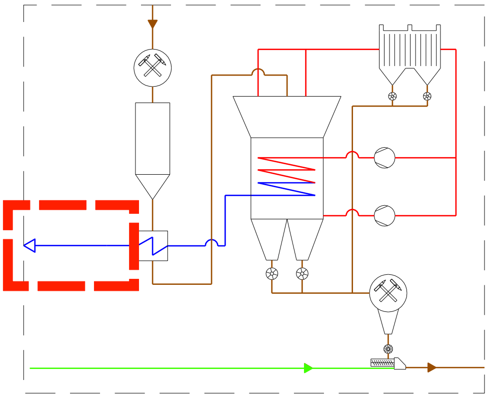

Figure 3: WTA fluidized bed dryer with highlighted waste heat stream

Table 4: Parameters of the coal dryer waste heat stream

H2O (%)	Air (%)	Pressure [bar]	Mass flow [kg/s]	Temperature [°C]
80	20	2	10.4	104

3.3. Syngas cooling

Syngas processing requires its temperature to be in certain levels within certain phases of the process, ranging from around 1400°C right at the top of gasifier down to -20°C in Rectisol washing for desulphurisation and CO2 capture. At high temperatures this heat is used to prepare steam from steam cycle feed water. At low temperature approximately below 200-150°C however this heat becomes harder to recover and its large part is rejected to environment as part of plant cooling systems. In the designed scheme is large part of the heat from syngas cooling utilized by steam cycle. Last stage of cooling after second stage of CO shift and before desulphurisation and eventually CO2 capture unit (figure 4) is here proposed to be recovered by separate unit. From properties of syngas stream shown in table 5 can be seen large content of water which is in syngas from quenching and increased by amount suitable for CO shift. As most of the water is in saturated vapour form which then condenses the amount of transferred heat is rather large.

Heat of the syngas in case without CCS is usually used within recuperative heat exchanger back to syngas after desulphurisation. Here the raw syngas contains significant amounts of water and CO2 whereas clean hydrogen rich gas has much smaller heat capacity. Recuperation is therefore used only to lesser extent, heat potential is mainly used for waste heat recovery either to steam cycle or separate unit and main syngas preheating is done by hot water from HRSG with very well matched temperature profiles and low loss of potential.

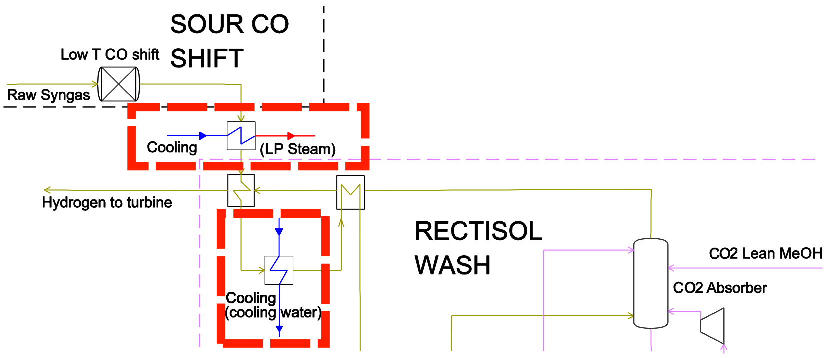

Figure 4: Syngas node between CO Shift, Rectisol wash and turbine

Table 5: Parameters of syngas after CO shift, before last stage of cooling

H2 (vol. %)	H2O (vol. %)	CO2 (vol. %)	other (vol. %)	Mass Flow [kg/s]	Temperature [°C]	Pressure [bar]
27.0	45.7	24.1	3.2	126.7	159	27

3.4. CO2 Compression

CO2 compression station compresses the CO2 to pressure high enough for transport and purifies it (especially drains excess of water and/or other condensable substances). Pressure high enough to transport and storage is typically considered approximately 110 bar. Compression takes place in multi-stage compression, typically as well as here here seven stages. Similarly as for the ASU the heat from intercooling and aftercooling in the compression can be used. Schematic diagram of the compression station with highlighted potential for WHR is given on figure 5.

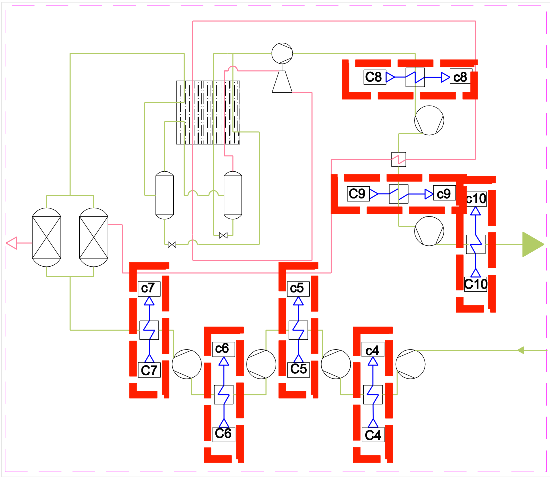

Figure 5: CO2 purification and compression unit with highlighted waste heat streams

Temperature of CO2 after first stage is 58°C, after another stages 92-96°C. Using of the first intercooling stream is not considered as it would negatively affect the overall WHR unit performance. As the CO2 compression is rather complicated system on which power production is not dependent and as the waste heat stream temperature is rather low, no integration of this waste heat into steam cycle is considered for the reference case. Higher efficiency of WHR unit could be obtained with cooling directly by the working fluid however for same reasons as in the case of ASU an intermediate water loop is considered. Properties of the water stream after mixing streams from second to sixth intercooler and aftercooler are in table 6.

Table 6: Properties of mixed stream of CO2 intercooling and aftercooling coolant

Original gas Temperature [°C]	Medium	Mass flow [kg/s]	Temperature [°C]
92-96	Water	203.9	84.0

3.5. Combined Cycle "Super-bottoming" unit

The flue gas in CCS plant is virtually free of any sulphur as nearly all remaining H2S after desulphurisation stage of Rectisol is further cleaned up by next CO2 capture stage. Dew point of the flue gas is thus very low and condensation shouldn't occur until very low temperatures (<50°C). Therefore there is opportunity to cool down flue gas further, below typical values lying above 100°C. In steam cycle design regardless of triple pressure design it is however nearly impossible to cool down flue gas further due to limited feed water heat capacity. Therefore an additional bottoming unit is considered to be placed in HRSG extension after the end of steam cycle. Schematically this is shown on figure 6 and flue gas properties are given in table 7. Note that considering this option for base case plant without carbon capture care must be taken to sufficiently decrease the H2S (and COS) content in syngas to values similar as obtained in CCS schemes. For this option should also be taken care of minimization of HRSG pressure drop increase as it would lower gas turbine power output.

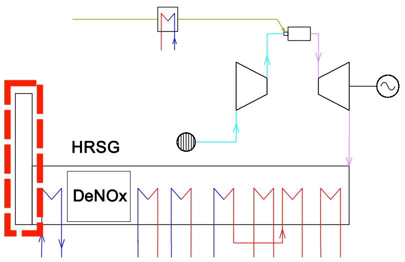

Figure 6: Schematic representation of opportunity for “super-bottoming” cycle

Table 7: Properties of flue gas at HRSG exit

Temperature [°C]	Flow [Nm3/s]	composition [vol. %]				
		CO2	Ar	N2	H2O	O2
~100	605	0,68	1,00	74,60	10,12	13,59

3.6. Summary of waste heat streams

A large number of potentially attractive waste heat streams for heat recovery are identified. The ones considered further (all except for heat in Rectisol washing) are along with their main properties summarized in table 8 which possess relatively large potential.

Table 8: Waste heat streams properties.

Decription	Medium	Mass flow [kg/s]	Temperature [°C]
ASU Air Compression	Water	66.6	100
ASU O2 Compression	Water	46.7	200
Coal Dryer Vapours	Air+Vapour	10.4	104
Syngas Cooling	Syngas	126.7	159
CO2 Compression	Water	203.9	84
“Super-bottoming”	Flue Gas	750.6	100

4. ORC AND ABSORPTION POWER CYCLE UNITS

Organic Rankine Cycle units are regularly supplied as nearly plug and play modular units for waste heat recovery applications. It became basically a standard for low temperature waste heat recovery applications. At very low temperature heat source are however even ORCs inefficient and expensive. For this reason is in this work considered a rather novel Absorption Power Cycle (APC) working with Lithium Bromide aqueous solution as a working fluid. In previous works this cycle has been identified as a perspective method for utilizing heat sources at very low temperatures. Especially when whole system (with cooling tower or air cooled condenser) is considered, the cycle outperforms ORCs. To show potential of heat recovery in electricity form, please refer to figure 7. Figure shows net electrical output of the WHR system with ambient conditions 25°C and 70% relative humidity and cooling tower (detailed assumptions shown in [7]). Below 120°C is assumed APC, above ORC.

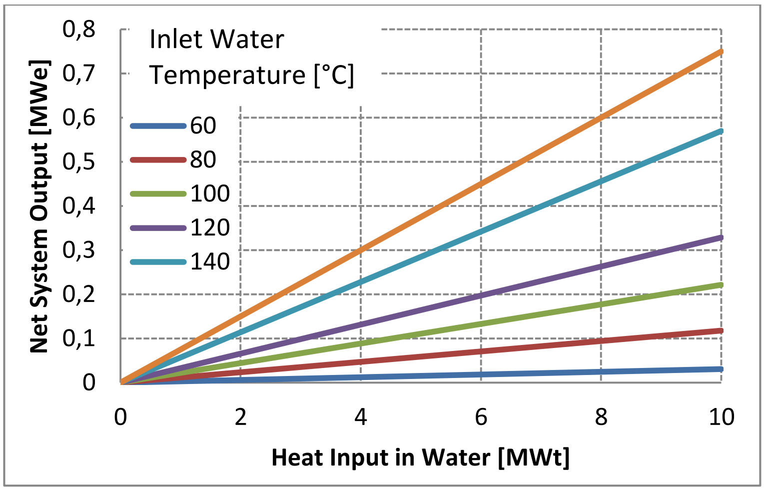

Figure 7: Net power output of potential WHR units

4.1. ORC

Organic Rankine Cycle is utilizing working fluid on organic base which has generally lower evaporation temperature, lower heat of vaporization and different shape of vapour liquid equilibrium curve than water. This allows for several benefits compared to steam cycle such as higher cycle efficiency at low temperatures, better utilization and cooling down of the heat source or higher volumetric flow allowing design of expansion machine with lower loses compared to design of steam turbine. These benefits made ORC a standard technology for utilization of heat sources at temperatures 200-400°C [8].

ORC is considered in this work only down to heat source temperatures of 120°C. Even though below this value it is sometimes considered [9], low efficiency and economy of application is becoming questionable. Another reason is better performance of proposed APC described in next section. Heat sources at temperatures above approximately 200°C are for this work mostly preferred heat utilization into the main power cycle. ORC is considered in basic scheme as on figure 8 as cooling and heat rejection is required for most cases in the system anyway, recuperator doesn't have effect on cycle achievable power output for given heat source and usually it is a large part of system cost. Even though first trials with supercritical ORCs are reported [10], only subcritical ones were considered in this work. Wide range of working fluids was considered including both wet and dry fluids to achieve maximal energy conversion. Best performance is however achieved with Isobutane and Isopentane, typical ORC working fluids.

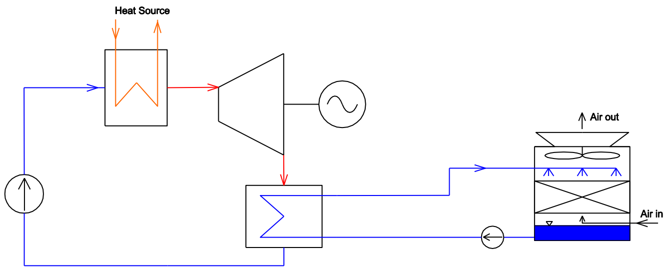

Figure 8: Basic scheme of the ORC WHR system

4.2. Absorption Power Cycle

Absorption power cycle is considered in this work for recovery of heat at source temperatures below 120°C. More known Kalina Cycle has been in the past thought to revolutionize field of power cycles. But it was met only with very limited commercial application less than 40 MW worldwide [11] and power plants were facing many problems and issues. This absorption cycle unlike Kalina cycle uses ionic solution of Lithium Bromide (LiBr) in water which brings over ammonia-water mixture many advantages.

LiBr cycles are fairly well known in absorption cooling. For power production this option has have been mentioned in few works in the past [12] but until recently has not received much attention. First detailed theoretical work regarding the cycle for low temperature WHR is brought by Hernando et al. [13], where the cycle is identified as potentially suitable with efficiency outperforming regular Rankine cycle. With first ideas independent of Hernando's work was the potential of the cycle in whole waste heat recovery system including heat rejection by fan wet cooling tower or air cooled condenser investigated in thesis [7], where it is compared against number of ORC cycles with the cycle having superior performance at heat source temperatures below 120°C in 25°C environment temperature. Exergo-economic study of this cycle confirmed also its ultimate thermodynamic performance over Kalina cycle [14].

Schematic diagram of the LiBr cycle is on figure 9. Heat input (stream 21) serves to heat up and partially evaporate the working fluid, LiBr solution. As the pure water vapour evaporates from the solution, LiBr concentration in remaining liquid is increasing which further increases its boiling temperature. At the end of the evaporator (stream 4) is then mixture of steam and absorbent solution at desired temperature and respective LiBr concentration in liquid phase. Liquid and vapour phase are split off in separator. Steam after separation (stream 5) consists of pure H2O and it is in a superheated state due to different liquid-vapour temperature of pure water and LiBr solution. Separated rich solution (stream 7) goes to recuperator where it is cooled down and gives away the heat to feed solution and then is throttled to low pressure level. Steam is routed to the turbine after which, at the beginning of absorber-condenser, is adiabatically mixed with the LiBr rich solution into which steam is partially absorbed. Absorption increases the mixture temperature while maintaining the same pressure. Mixture in established vapour-liquid equilibrium is further cooled which results in absorption-condensation of remaining vapour into liquid and gradual decrease in mixture temperature. Pressure of the liquid fluid after condensation is then increased by the pump as in most power cycles. Detailed model of the cycle model and calculations is given in [7] including results for various properties formulations and also more complex variant of the cycle.

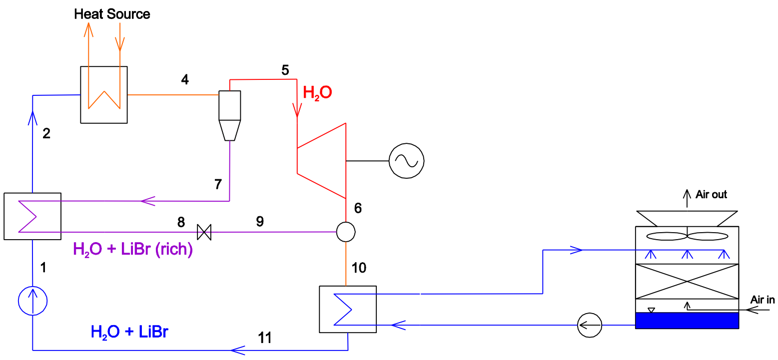

Figure 9: Schematic diagram of the LiBr Absorption Power Cycle

APC can achieve relatively high temperature match in evaporator and condenser by its variable boiling and condensation temperature (see fig. 10), which enables better heat source potential utilization as well as lower parasitic load by less amount of cooling water at higher temperature, especially in case of small units. LiBr APC provides also other benefits. Its working fluid is non-toxic and environmentally harmless. Expansion machine, usually very problematic element for both ORC and Kalina cycle shouldn’t pose a problem as LiBr is salt which doesn’t transfer into the steam during evaporation and low system pressures provides quite large volumes providing for simple design of high efficiency turbine.

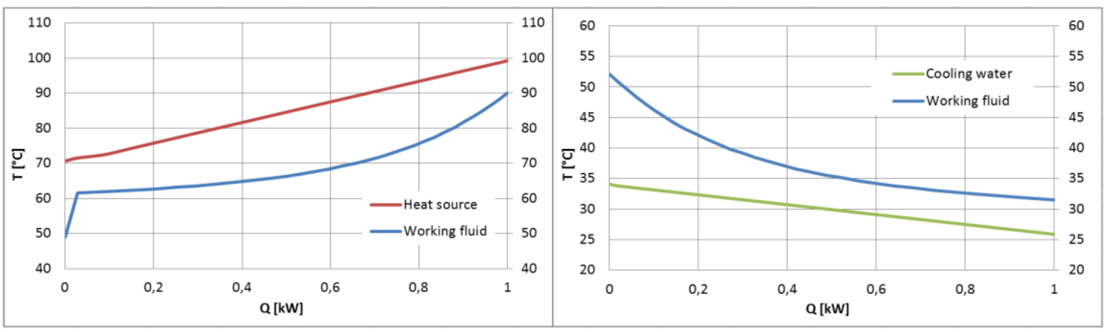

Figure 10: Q-T diagrams with temperature match of heat input and rejection for LiBr Absorption Power Cycle

Several issues will however need to be overcome and explored before considering commercial application. Due to below ambient pressure in evaporator the whole cycle will require airtight construction with vacuum inside. Another obstacle might be corrosivity of the solution. Potential issue is reaching crystallization barrier at low temperatures, this however hasn’t been experienced in previous modelling. Problems might arise in designing of the two-phase heat exchangers with changing temperature along the fluid flow which is planned to be explored soon in detailed modelling and experimental work. Experimental rig is planned to soon confirm real behaviour of critical parts of the system at the Faculty of Mechanical Engineering on CTU in Prague.

4.3. WHR Units Summary

ORC cycles are standard for waste heat recovery, especially for low heat source temperature and low unit output. Thanks to the modular approach in production they are also becoming a cost effective option. Even though applications of ORC are reported even below 100°C of heat source temperature their efficiency and effectiveness are quickly decreasing. To provide more effective heat recovery at these low temperatures is proposed absorption power cycle based on aqueous solution of LiBr. When the cycle is considered as an entire system with heat rejection system (Cooling Tower or Air Cooled Condenser), absorption power cycle outperforms ORC for temperatures below 110°C and 120°C respectively. Comparison of thermal and exergetic efficiency of optimized WHR systems and maximum output of ORC with wide range of working fluids is shown on figure 11.

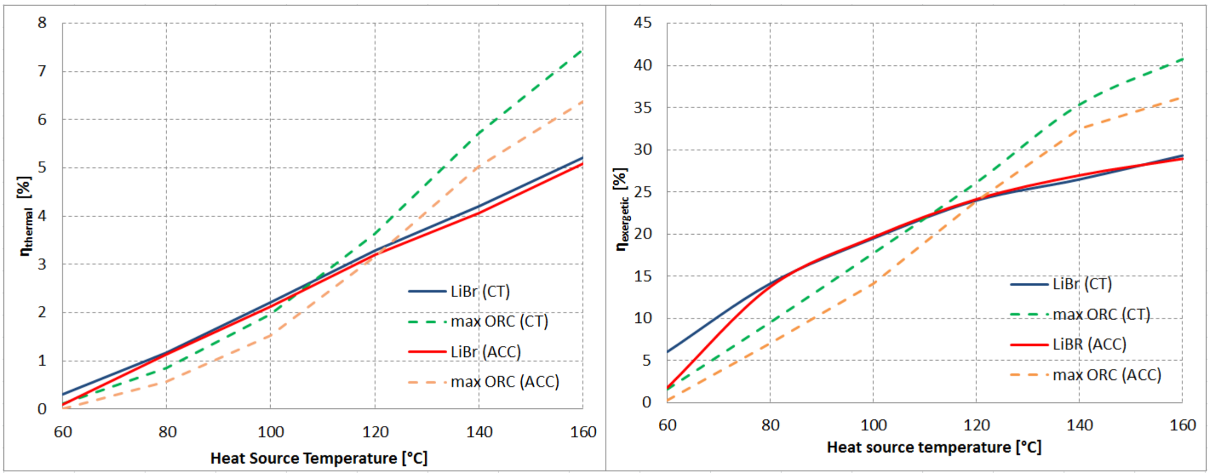

Figure 11: Thermal and exergetic efficiency WHR systems of maximum from range of ORCs and LiBr based absorption power cycle with cooling by wet fan cooling tower (CT) and Air Cooled Condenser (ACC)

5. RESULTS OF WHR SYSTEMS APPLICATION

Below are presented results of application of proposed WHR cycles onto identified waste heat streams. Net output of the single streams is presented in table in table 9 for the plant with CCS and for applicable waste heat streams in basic plant case without CCS in table 10. Largest power output is obtained from sources with highest temperature and heat content. For the two in CCS system these are syngas cooling with considerable amount of condensing water and cooling medium from oxygen compressor cooling. For these sources there is decrease in power production from steam cycle. It is however shown that using low temperature streams in more efficient ORC results not only in system simplification and flexibility improvement but also in higher power production. Different output for same systems are given by different efficiency of basic and CCS plant for 250 MW output at the starting point. Significant difference in "Super-bottoming" unit output is given by lower heat capacity and mass flow of flue gas when the CO2 is separated.

Table 9: Power output obtainable from waste heat streams for IGCC with CCS

System	Stream	Net output [kW]	WHR unit type	Output of steam integration [kW]
ASU	Air Compressors	500	APC	
	Oxygen compressors	3 381	ORC (Isopentane)	2 316
Coal dryer	Waste vapours stream	627	APC	
Syngas cooling	Hot syngas	10 044	ORC (Isobutane)	8 467
CO2 compression	Stage 2-7	771	APC	
"Super-bottoming" unit	Flue gas	1 324	APC	
Total change in plant net output		**5 864**		

Table 10: Power output obtainable from waste heat streams for IGCC without CCS

System	Stream	Net output [kW]	WHR unit type	Output of steam integration [kW]
ASU	Air Compressors	359	APC	
	Oxygen compressors	2 428	ORC (Isopentane)	1 863
Coal dryer	Waste vapours stream	450	APC	
Syngas cooling	N.A. - Used for regenerative fuel preheating			
CO2 compression	N.A. -Capture not implemented			
"Super-bottoming" unit	Flue gas	1 685	APC	
Total change in plant net output		**3 059**		

Data for the entire plant are shown in table 11. Net power increase is the CCS plant (5.1 MW) is almost double of the basic case (3.1 MW). For CCS system this means 2.1

percentage points in efficiency increase whereas for regular IGCC it is only 0.5 percentage point increase. Even though this doesn't cover the efficiency penalty of CCS systems (in this case 12.6%), it returns at least its significant portion. Gain by application to regular IGCC plant is comparable to various current advanced methods of increasing plant efficiency (improved turbine design, small increase in allowed high temperatures, advanced coal dryers, etc.)

Table 11: Overview of plants performance with and without WHR units

	IGCC - CCS	IGCC
Original power output [MW]	250	250
Power output with WHR [MW]	255.9	253.1
Original efficiency [%]	32.1	44.7
Efficiency with WHR [%]	34.2	45.2
Efficiency increase [p.p.]	2.1	0.5

5.1. Technical Aspects

Application of ORC units shouldn't pose any significant technical difficulties as it is already well mature commercially available and highly modular technology. On the other hand APC is in relatively early research phase. Most of the identified properties however indicate potential for commercialization in near horizon.

In this work performance of the WHR units was evaluated with each of them having their own plant-adjacent fan wet cooling tower. There is potential gain in common cooling integration into a single cooling tower (or cooling tower battery for fan cooling tower cells). This can have significant effect on amount of energy recovered as in low temperature region small increase in available temperature difference has large effect in work potential. Partial further improvement of performance will be achieved by avoiding significant amount of cooling duty by "running the heat through heat engine". On the other hand there will be partial increase in pumping power on intermediate loops between heat source and WHR unit.

When "super-bottoming" unit is considered for the flue gas at the end of HRSG the overall effect on HRSG pressure drop must be taken into account. Pressure drop of HRSG in fact decreases turbine outlet pressure. For this case a more detailed techno-economic study including heat exchangers design should be undertaken. If such unit should be considered for regular IGCC plant it is necessary that sulphur is removed to sufficiently low level that there is not a risk of flue gas condensation.

5.2. Economical Aspects

5.2.1. Investment cost - CAPEX

APC is in rather early research phase however after reaching commercial phase its cost is expected to be at least on similar level with ORC systems or lower. Capital cost for IGCC systems is expected to be around 1800 $/kWe with range going most often from 1400 to 2200 $/kWe [15-18] (exception Tianjin stage 1, China 1200 $/kWe [19]). Cost of IGCC plant with CCS is estimated to be around 2200 $/kWe with range from 1500 to 3200 $/kWe [16-18]. The cost of ORC units of required size and heat source temperature is around 2000 $/kWe [9,20,21] which is comparable to the cost of the whole IGCC.

Integrace WHR jednotky zvýší CAPEX celého systému IGCC o cca 1,5%.

5.2.2. Operational cost - OPEX

Operating costs associated with WHR units are minimal, nearly 1-2% from Investment cost. This makes the economics for application of this system highly perspective.

5.2.3. Cost of electricity - COE

Výrobní cena elektřiny stanovená pro analyzovaný případ WHR unit a IGCC s a bez CCS je uvedena v tabulce 12. Vstupní podmínky pro ekonomickou analýzu vycházejí z [25].

Table 12: COE of IGCC w/o CCS and WHR unit

Power unit	COE [c$/kWh]
IGCC	6.5 [22]
IGCC with CCS	9.45 [22]
WHR unit	5.91 – Investment cost 2000 USD/kWe, annual operating time 5500 h/year

Pokud výrobní cena elektřiny ze systému WHR unit bude nižší než výrobní cena elektřiny z IGCC s I bez CCS pak integrace tohoto systému do elektrárny IGCC bude mít kladný ekonomický efekt, jež bude mít za následek snížení výrobní ceny elektřiny celého systému průměrně o 0,1%. Tento efekt je ovlivněn (závislý) zejména na výši investičních nákladů a době využití WHR jednotky, jak je znázorněno na obrázku 12 a 13.

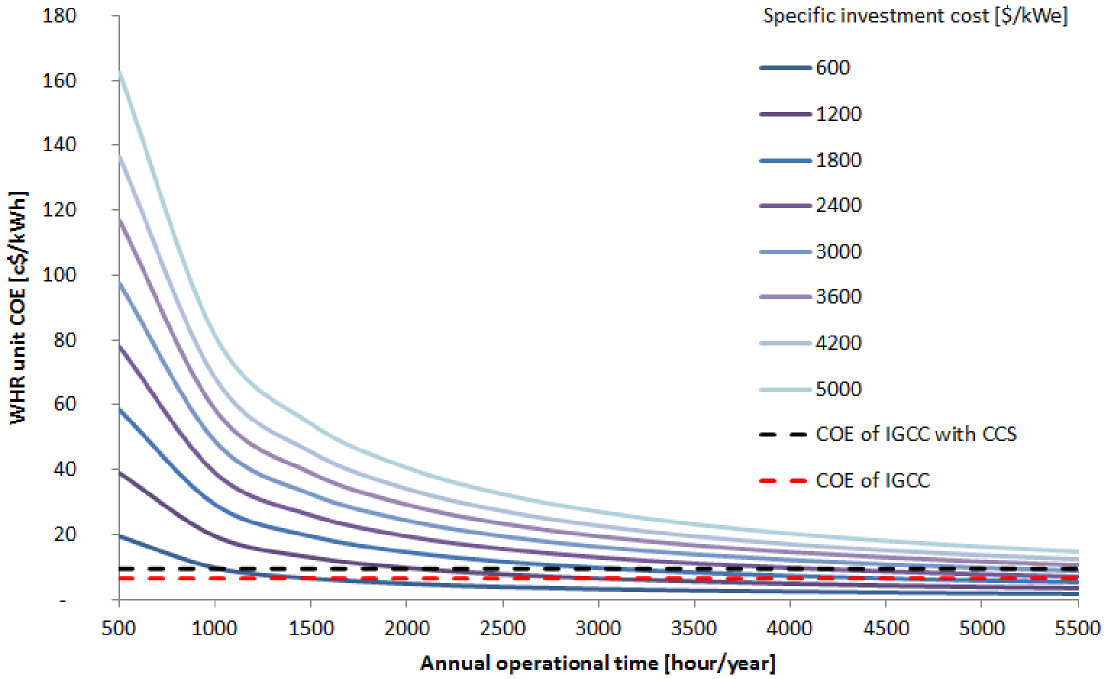

Figure 12: Thermal and exergetic efficiency WHR systems of maximum from range of ORCs and LiBr based absorption power cycle with cooling by wet fan cooling tower (CT) and Air Cooled Condenser (ACC)

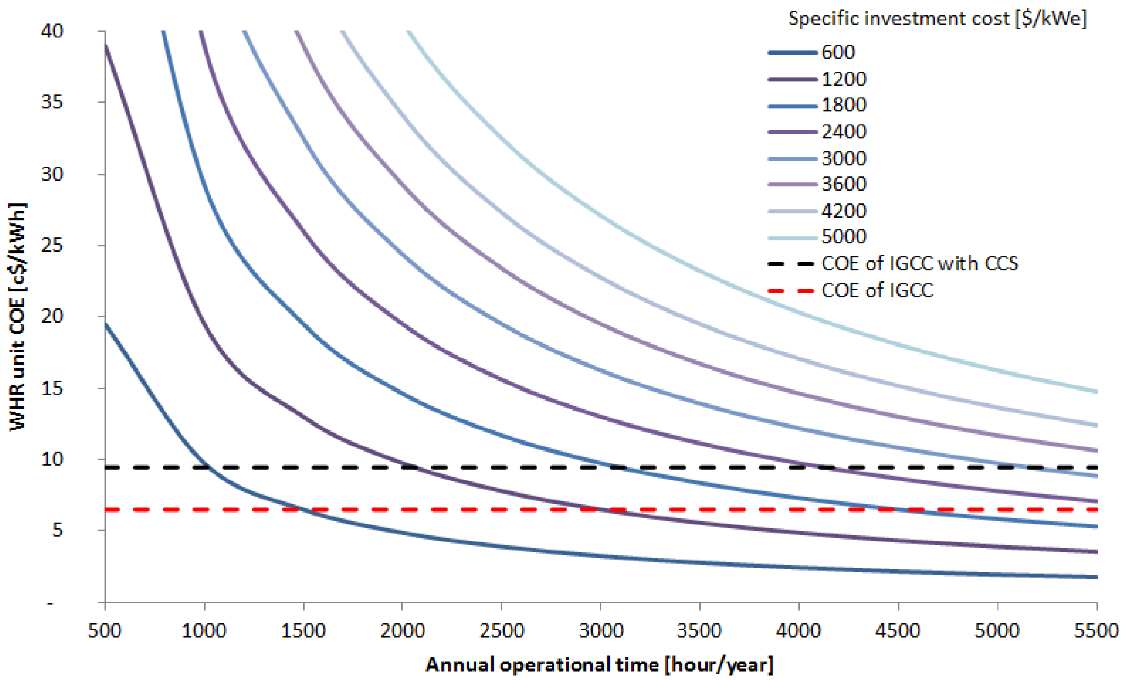

Figure 13: Thermal and exergetic efficiency WHR systems of maximum from range of ORCs and LiBr based absorption power cycle with cooling by wet fan cooling tower (CT) and Air Cooled Condenser (ACC)

Integrace WHR jednotky do systému IGCC s anebo bez CCS bude mít ekonomický přínos (díky snížení průměrné výrobní ceny elektřiny) pouze v případě, že výrobní cena elektřiny z této jednotky bude nižší než výrobní cena elektřiny ze systémy IGCC s anebo bez CCS technologie, tj. pro případ IGCC bez CCS s nižšími měrnými investičními náklady než 2200 USD/kWe a dobou proovzu vyšší než 1500 h/ročně, viz obr. 13.

6. CONCLUSION

Using separate WHR units for waste heat streams of IGCC plants is a perspective way how to improve their economy. It has main positive effect in two ways as it boosts power production and substitution of WHR units for its integration into main steam cycle improves plant flexibility. Two WHR systems are considered in this work, regular ORC and for temperatures below 120°C novel absorption power cycle with large potential for early and effective commercialization.

On a case of plant utilizing low rank coal it is shown, that this approach can bring 1.1 percentage point of plant efficiency and when CCS system is employed in the plant then efficiency is increased by 2.1 percentage points with room for further improvement. The cost per kW of WHR units is similar to cost of IGCC plants, especially with CCS. Combined with minimal operating costs a highly efficient and perspective system is achieved.

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