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CCS on offshore oil and gas installation – Design of post-combustion capture system and steam cycle

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Abstract

Most of the released CO_2 on offshore oil and gas installation originates from the gas turbines that power the installations. For certain offshore installations, CO_2 capture and storage (CCS) could be an alternative to decrease the CO_2 emissions. When opting for a chemical absorption CO_2 capture system, a heat source for the stripper reboiler is needed. Since most offshore installations are powered by simple cycle GTs, there is typically no steam available that could be used for stripper reboiler heat. A compact steam bottoming cycle could, in addition to providing the reboiler steam, partly or fully provide power from a steam turbine generator to the equipment in the CCS system, including CO_2 compressors, pumps, and flue gas booster fan. Three different steam cycle configurations were designed, modeled, and simulated. The design of the post-combustion CO_2 capture system is also presented but the main focus in the paper is on the steam cycle design. In addition to the energy and mass balance results, a weight assessment of the major equipment was done with the objective to come up with a simplified weight relationship for changes in the oil and gas installation size in terms of changes in total mass flow from the gas turbines. A steam cycle with a back-pressure steam turbine was ultimately selected. The back-pressure option was able to provide all necessary steam *and* power (with some margin) to the CO_2 capture and compression system.

Keywords: Steam bottoming cycle; process simulation; weight assessment; back-pressure steam turbine; CO_2 capture; FPSO

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1. Introduction

Some of the largest CO_2 point sources in Norway are offshore oil and gas installations [1]. Most of the released CO_2 originates from the gas turbines (GTs) that powers the installations. Electrification, by providing power to the installations from the onshore electrical grid, has been politically promoted as a solution to alleviate the offshore CO_2 emissions. However, for fields far of the coast, for offshore installations that are wind-turned, and in areas with weak electrical grids, CO_2 capture and storage (CCS) could be an alternative.

When opting for a chemical absorption CO_2 capture system, a heat source for the stripper reboiler is needed. Since most offshore installations are powered by simple cycle GTs, there is typically no steam available that could be used for stripper reboiler heat. On about a third of the GTs on the Norwegian continental shelf, waste heat recovery units (WHRUs) utilizing hot oil, water, or other media are installed downstream of the GTs [2]. One could envision a redesigned WHRU to allow for reboiler steam, however, a compact steam bottoming cycle could also be an attractive solution, especially since the requirement for reboiler steam mass flow is very high for a chemical absorption capture system. A steam bottoming cycle could, in addition to providing the reboiler steam, partly or fully provide power from a steam turbine (ST) generator to the equipment in the CCS system, including CO_2 compressors, pumps, and flue gas booster fan.

Compact steam bottoming cycles for offshore installations are, as of 2016, operating on three Norwegian offshore oil and gas installations, however, none were considered for CCS applications. Design considerations for offshore compact steam bottoming cycles are discussed in [3]. Different plant layouts and operating scenarios at both design and off-design conditions are analyzed in [4]. Single-objective optimization of the weight-to-power ratio is performed in [5]. Multi-objective optimization of weight and power is examined in [6] and combined heat and power layouts including extraction, condensing steam turbines and back-pressure steam turbines are evaluated in [2]. However, none of the cited works have considered CCS applications.

The research question for this work was formulated as: What is the best steam cycle design for an offshore oil and gas installation with post-combustion CO_2 capture? To answer this question, three different steam cycle configurations were designed, modeled, and simulated. The design of the post-combustion CO_2 capture system will also be presented but the main focus in the paper will be on the steam cycle design. In addition to the energy and mass balance results, a weight assessment of the major equipment was done. Subsequent to the design screening and selection, the most favorable steam cycle configuration was further analyzed with the objective to come up with a simplified weight relationship for changes in the oil and gas installation size in terms of changes in total mass flow from the gas turbines. This mathematical relationship could be used for early estimates of weight of major components in a steam bottoming cycle when evaluating a CO_2 capture system on an offshore oil and gas installation.

Nomenclature

Aux	Auxiliaries
CCS	CO_2 Capture and Storage
FPSO	Floating Production, Storage and Offloading
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator
HX	Heat Exchanger
MEA	Monoethanolamine
ST	Steam Turbine
WHRU	Waste Heat Recovery Unit
m	Mass flow rate (kg/s)
p	Pressure (bar)
T	Temperature (°C)
η	Efficiency (-)

2. Methodology

The work was focused on a case study based on a floating production, storage and offloading installation (FPSO). The case study involved CO_2 capture from the exhaust originating from six 20 MW gas turbines on the FPSO installation. MEA was used as solvent for post-combustion capture and the process was simulated in CO2SIM, an in-house process simulator developed at SINTEF Materials and Chemistry. GT PRO was used for the steam cycle process design and the energy and mass balance calculations, whereas PEACE was used for the steam cycle weight assessment. Both GT PRO and PEACE are provided by Thermoflow [7]. The water and steam properties within GT PRO were IAPWS-IF97. Reference conditions for enthalpy were 0 °C, with H_2O as liquid.

2.1. Boundary conditions and computational assumptions

The boundary conditions for the work are listed in Table 1. The computational assumptions are listed in Table 2.

Table 1: Boundary conditions.

Gas turbine exhaust	
T (°C)	466
m (kg/s)	404.2
CO_2 (vol%)	2.98
H_2O (vol%)	6.67
O_2 (vol%)	14.36
Ar (vol%)	0.90
N_2 (vol%)	75.09
Ambient conditions	
T (°C)	15
p (bar)	1.013
Rel. hum. (%)	60
Cooling water system	
Type	Direct sea water cooling
T (°C)	9
ΔT (K)	14

Table 2: Simulation parameters used for CO_2 capture and compression power and heat demand.

Absorber	
Amine MEA (wt%)	30
CO_2 capture rate (%)	90
Stripper	
Pressure (bar)	1.8
Reboiler steam	
T_{sat} (°C)	152
Lean/Rich heat exchanger	
Approach temperature (°C)	6.5

Flue gas booster fan	
η_{isen} (%)	85
$T_{gas,inlet}$ (°C)	33.7
Pumps	
η_{isen} (%)	75
CO_2 compressors	
η_{isen} (%)	85
p_{outlet} (bar)	150

2.2. CO_2 capture system design

Figure 1 shows the CO2SIM flow sheet used in the study. A direct contact cooler was employed to reduce the exhaust gas temperature from the HRSG down to 33.7 °C. This is not shown in the flowsheet.

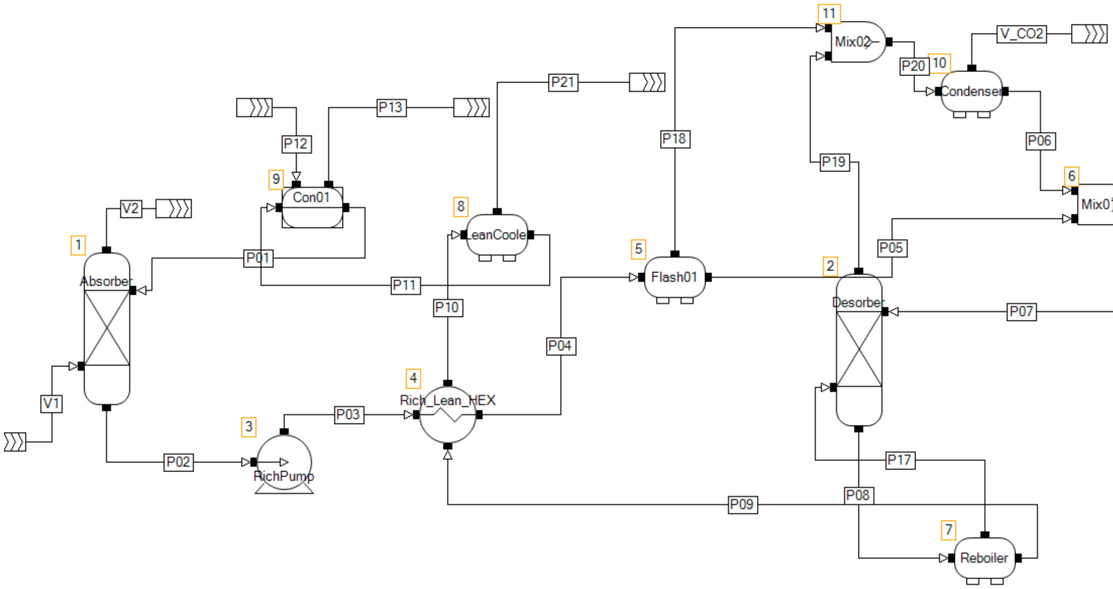

Figure 1: CO2SIM flow sheet for the CO_2 capture simulation

Simulation of a closed loop absorber-desorber process requires the definition of a lot of process parameters like dimensions of the towers, liquid circulation rates, the amount of steam into the reboiler, temperatures, etc. Ideally, one should optimize the process for all these parameters. The focus of this work has been to find “close to optimal values,” and the procedure that was used will first be outlined.

Table 2 lists the variables chosen to be constant for all simulations. The amine blend was restricted to be 30w%t MEA because this is a state of the art amine for systems with low partial pressures of CO2. The parameter for the rich-lean heat exchanger is important for overall energy requirement.

The value we wanted to minimize was the specific reboiler duty, the amount of energy (MJ) per kg CO_2 captured. During the minimizing procedure, the solvent circulation rate was varied to arrive at the minimum reboiler duty.

This was done assuming very tall absorbers and stripper. The heights of the absorber and stripper were then reduced to a point where it did not affect the reboiler duty.

2.3. Steam cycle design

Three different configurations were designed, modeled, and simulated within this work. The selected configurations were:

a) A steam cycle based on an extraction, condensing steam turbine producing enough steam for the reboiler and maximum power while keeping a low weight-to-power ratio.
b) A steam cycle based on a back-pressure steam turbine producing sufficient steam for the CO_2 capture system while keeping a low weight.
c) A steam cycle with a stand-alone HRSG (no steam turbine) producing maximum process heat while keeping a low weight-to-heat ratio.

The selected material selection for the HRSG heat transfer tubing and the steam parameters for the different configurations are listed in Table 3.

Table 3: Selection of heat transfer tubing material and steam cycle parameters.

	a) Extraction ST	**b) Back-pressure ST**	**c) HRSG only**
Material HRSG tubing	Incoloy	Incoloy	Incoloy
Material HRSG fins	SS TP409	SS TP409	SS TP409
Live steam p (bar)	25.0	25.0	5.5
Live steam T (°C)	440	440	155
Pinch-point ΔT (K)	30	30	30
Condenser p (bar)	0.06	-	-
HRSG Δp_{gas} (bar)	25	25	25

2.4. Weight assessment

The weight assessment included the weight of the major components in the capture system and the steam cycle. In the steam cycle the following major components were evaluated: steam turbine, HRSG, and condenser. The weight assessment did not include weight of piping, skid structure, water treatment system, and water tanks. In the capture system the following major components were evaluated: absorber, desorber, reboiler, condenser, and other heat exchange equipment (rich-lean HX, coolers, etc.).

3. Results and discussion

3.1. Process design and simulation

For the capture system, the specific reboiler duty for the process was evaluated to be 3.6 MJ/kg CO2 corresponding to a steam flow of 28.9 kg/s. The absorber and desorber were sized to be 18.6 m packing height with a 13.6 m diameter and 7 m packing height with a 3 m diameter respectively.

Figure 2 displays the three selected steam cycle configurations including process parameters p, T, m, and h, at selected stream locations. A summary of the results is shown in Table 4.

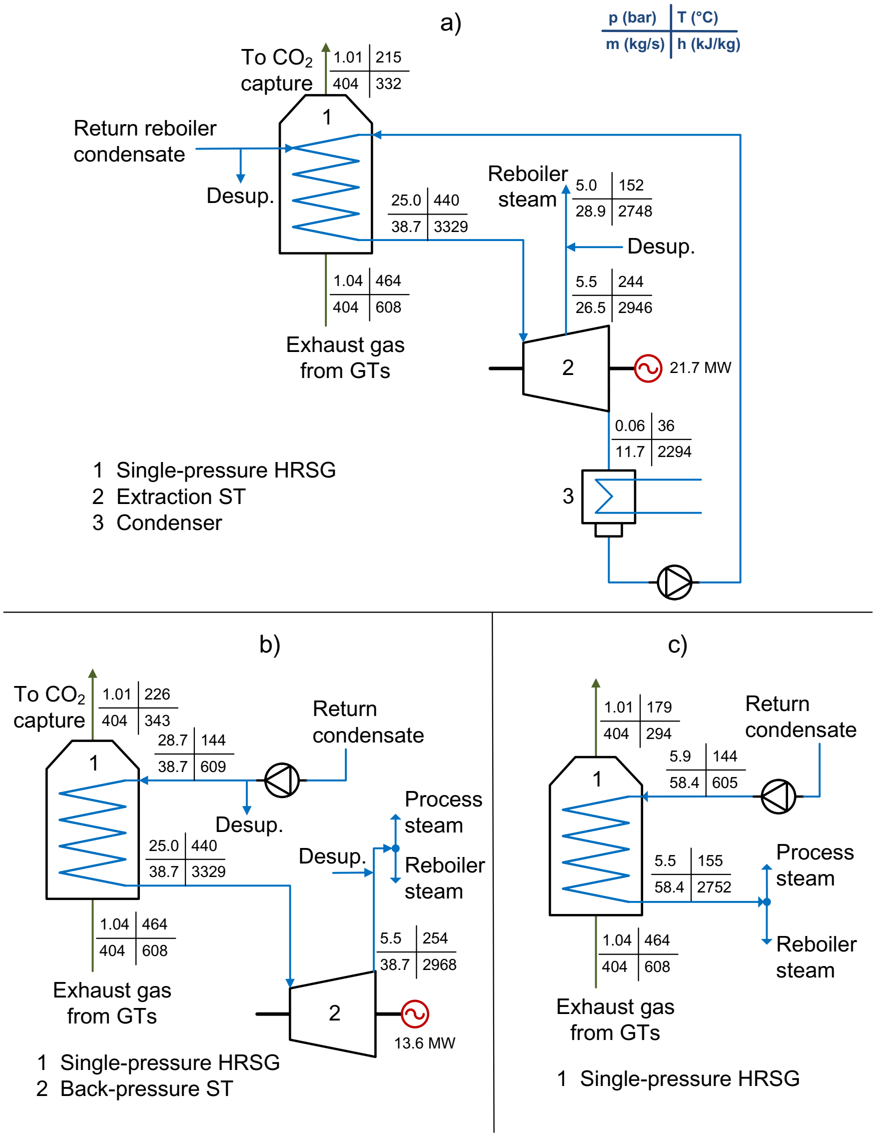

Figure 2: Process layouts for the steam cycles with: a) extraction, condensing steam turbine, b) back-pressure steam turbine, and c) HRSG only.

Table 4: Accounting of power and process steam for the three different configurations.

	a) Extraction ST	b) Back-pressure ST	c) HRSG only
ST power (kW)	21 700	13 600	-
- Steam cycle aux (kW)	400	300	0
- CO_2 capture aux (kW)	3 400	3 400	3 400
- CO_2 compression (kW)	5 500	5 500	5 500
Power available for other processes (kW)	12 400	4 400	- 8 900
Steam (latent heat) from steam cycle at 5 bar (kW)	79 400	114 100	152 800
- Reboiler steam (kW)	79 400	79 400	79 400
Process steam available for other processes (kW)	0	34 700	73 400

3.2. Weight assessment

The results of the weight assessment are shown in Table 5. It should be pointed out that the processes have not been optimized, e.g., with the objective of minimizing weight subject to the design constraints. Previous work on optimization of steam bottoming cycles for offshore oil and gas installations indicate that the decrease in weight-to-power-ratio when optimizing a knowledge-based design is around 4% [6].

Table 5: Results from weight assessment for the steam cycles with: a) extraction, condensing steam turbine, b) back-pressure steam turbine, and c) HRSG only.

	a) Extraction ST	b) Back-pressure ST	c) HRSG only
HRSG dry weight (kg)	385 000	367 000	362 000
ST weight (kg)	44 000	25 000	-
Generator weight (kg)	54 000	38 000	-
Condenser dry weight (kg)	14 000	-	-
Σ Component weights (kg)	497 000	430 000	362 000

The main components of the capture system had the following evaluated weights:

- Absorber: 1515 ton
- Desorber: 65 ton
- Reboiler: 50 ton
- Condenser: 10 ton
- Other heat exchange equipment (lean rich HX, coolers, etc.): 60 ton
- **Total weight of main components in capture system: 1700 ton**

3.3. Screening of technologies for the steam cycle

The pros and cons of the different steam cycle configurations are shown in Table 6. Ultimately, the back-pressure steam cycle was selected. The back-pressure option was able to provide all necessary steam *and* power (with some margin) to the CO_2 capture and compression system while being lighter than the extraction ST option. If spare GT power exists on site then the HRSG only option can be attractive. Else, the disadvantage of needing another power source for the CO_2 capture system was too great even with being the least complex and lowest weight system. Option a) was the most flexible option where the mass flow of extracted steam can be varied (i.e., the heat-to-power ratio can be varied) and can be an attractive option on an installation having the need for the additional power produced.

Table 6: Pros and cons of the different process layouts.

a) HRSG and extraction, condensing steam turbine	
+ Can supply all heat *and* power to CCS system	– Large back-end of steam turbine
+ Flexible heat to power ratio	– Condenser
+ 60% more power than back-pressure ST case	– Large portion of steam flow extracted
	– 40% more weight than HRSG only case
b) HRSG and back-pressure steam turbine	
+ Can supply all heat *and* power to CCS system	– Locked heat to power ratio
+ Good margin on heat and power for changes in CCS system design or performance	– 20% more weight than HRSG only case
+ Compact steam turbine	
+ No condenser	
+ Particularly attractive if other heat consumers on installation	
c) HRSG only	
+ No steam turbine	– Needs additional gas turbine or other power source to supply power to CCS system
+ No condenser	
+ Lightweight	
+ Small footprint	
+ Particularly attractive if other heat consumers on installation	

3.4. Back-pressure steam turbine cycle – Scaling of weight

To generalize the weight assessment and to provide an early estimate of steam cycle weight during the design phase, 50 different steam cycle designs based on the back-pressure ST option were simulated. The results are displayed in Figure 3. The designs were generated based on changes in heat input to the HRSG, or more precisely, changes in mass flow rate from the gas turbines. In this way, a simple polynomial was generated that could be used for different oil and gas installation sizes (power demand).

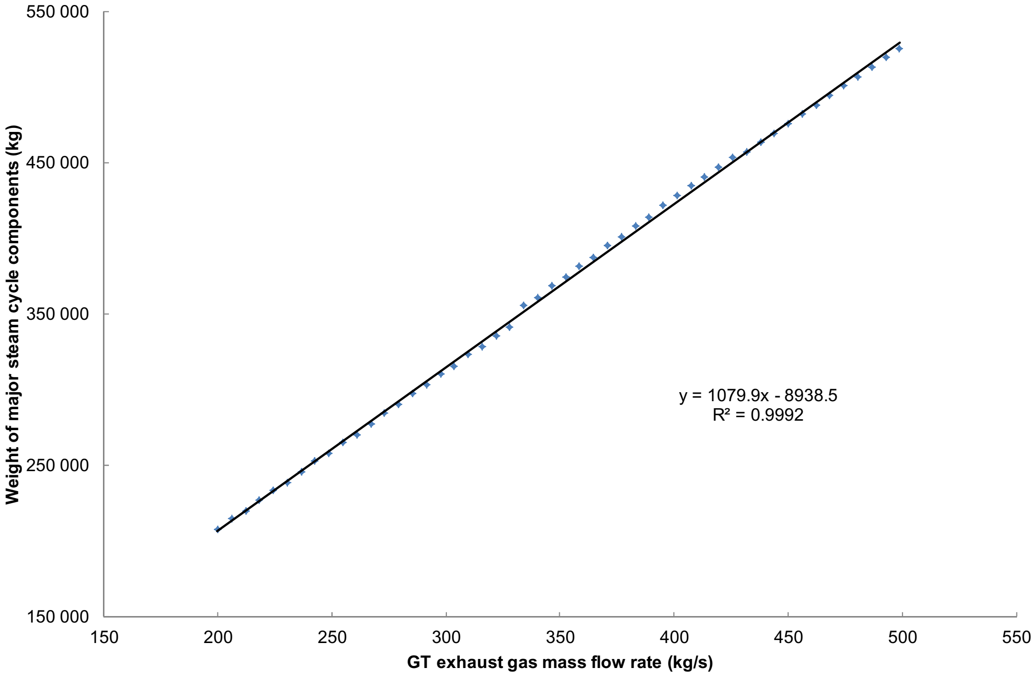

Figure 3: Sum of weight of major components as a function of gas turbine exhaust mass flow rate for configuration *b) steam cycle with back-pressure steam turbine*. Trendline based on polynomial with the resulting linear relation displayed on chart.

4. Conclusions

Based on three different steam bottoming cycle configurations designed for providing reboiler steam (and possibly power) to a CO_2 capture system on an offshore oil and gas installation, a cycle with a back-pressure steam turbine was ultimately selected. The back-pressure option was able to provide all necessary steam *and* power (with some margin) to the CO_2 capture and compression system while being lighter than the extraction ST option. If spare GT power exists on site then the HRSG only option can be attractive. Else, the disadvantage of needing another power source for the CO_2 capture system was too great even with being the least complex and lowest weight system. Option a) was the most flexible option where the mass flow of extracted steam can be varied (i.e., the heat-to-power ratio can be varied) and can be an attractive option on an installation having the need for the additional power produced. A linear relation between gas turbine exhaust mass flow rate and steam cycle weight was developed, which could serve as a first estimate of steam bottoming cycle weight (major components) for different installation sizes (GT power demand). A planned journal publication will further investigate and develop the steam cycle weight estimation methodology.

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