POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

A Novel Externally Fired sCO2 Oxy-Combustion Power Cycle for Offshore CCS

Process Modelling and Off-Design Analysis

Laurea Magistrale in Energy Engineering - Ingegneria Energetica

Author: Davide Tonetto

Advisor: Prof. Emanuele Martelli

Co-advisor: Lars O. Nord, Elettra Vantaggiato, Marcin Pilarczyk

Academic year: 2025-2026

1. Introduction

Carbon Capture and Storage (*CCS*) is widely regarded as an indispensable mitigation pathway for sectors that are structurally difficult to decarbonise, including offshore oil and gas operations. A particularly relevant opportunity arises from offshore natural gas fields with high CO_2 content, where the produced gas is often unsuitable for conventional combustion and the associated CO_2 must be separated and vented or reinjected at considerable energetic cost.

The ZEUS cycle addresses this challenge through an indirect, condensing sCO_2 power cycle coupled to a high-pressure oxy-fuel combustor [1]. ZEUS architecture schamatics is reported in fig. 1. Fuel and high-purity oxygen are premixed and burned in a high-pressure combustor initially developed for rocket propulsion, with a recirculated CO_2 stream acting as thermal diluent to maintain the flame temperature at 1100°C. The resulting flue gas is composed by 86% CO_2, 13% O_2, and 1% O_2. The condensed CO_2 working fluid is compressed by a multistage pump and then split into two parallel branches: one passes through the recuperator (*HXrec*), recovering heat from the turbine exhaust, while the other passes through the secondary heat exchanger *HX2*, recovering heat from the lower-temperature region of the exhaust gas stream. The split ratio *sp* between the two branches is regulated by the splitter model, so that it imposes matched outlet temperatures on both streams, avoiding entropy generation upon remixing. The two branches then recombine and proceed together through the primary heat exchanger *HX1*, where the merged stream receives final heating from the high temperature section of the exhaust gas before reaching the turbine inlet. After expansion, the working fluid is cooled in the recuperator and condenser and pumped back to operating pressure. The exhaust stream, after sequential heat recovery in *HX1* and *HX2*, is cooled to condensing condition at 99.8°C and its water content is removed, yielding a CO_2-rich stream suitable for direct geological reinjection.

In any oxy-fuel combustion cycle, the pure oxygen must be used as oxidiser rather than air, as it is essential to avoid diluting the flue gas with atmospheric nitrogen. The consequent nitrogen-free exhaust stream is what enables the high

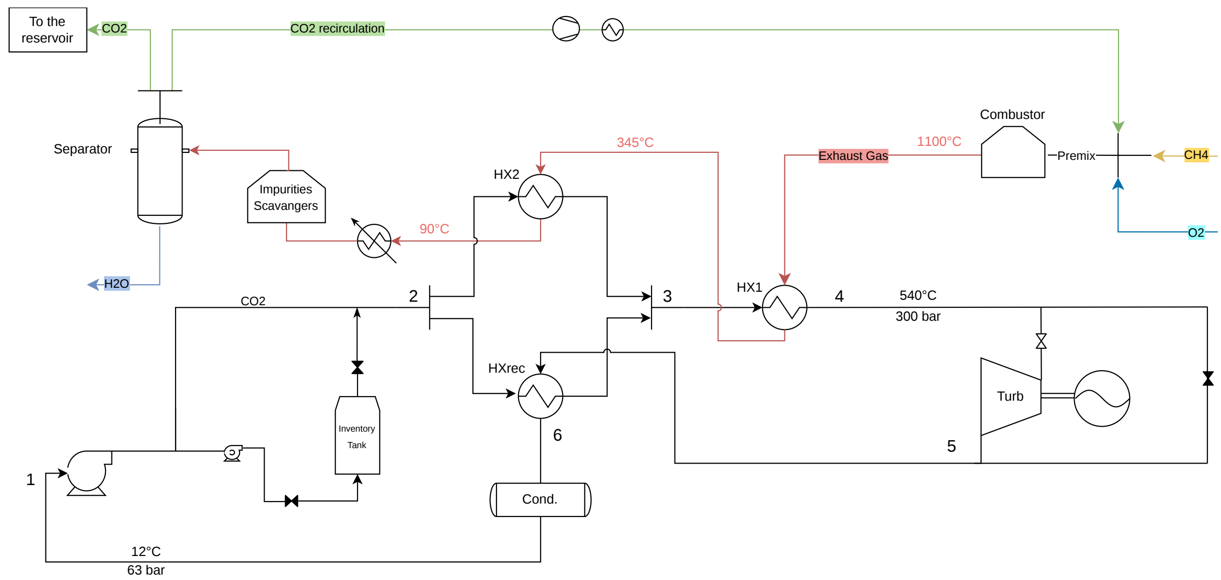

Figure 1: Zeus model schematic

CO_2 concentration required for capture without extensive downstream purification. Producing oxygen at the purity required for this purpose, however, is not energetically free: industrial oxygen is obtained through cryogenic air separation, a process that demands substantial electrical input to compress, cool, and fractionate air into its constituent gases. This electrical demand constitutes the Air Separation Unit (ASU) parasitic load, an auxiliary consumption that must be subtracted from the gross power output of the cycle and represents one of the principal efficiency penalties intrinsic to oxy-fuel power generation, alongside auxiliary losses associated with flue-gas recirculation and CO_2 compression and purification.

A central thermodynamic feature motivating this architecture is the behaviour of CO_2 during expansion. Relative to steam, CO_2 exhibits a comparatively low ratio of temperature change to pressure change (dT/dp) along the expansion path. As a consequence, for a given pressure ratio across the turbine, the temperature drop experienced by sCO_2 is markedly smaller than that experienced by steam undergoing an equivalent expansion. This results in a Turbine Outlet Temperature (TOT) that remains comparatively high, which, if not addressed, would impose a substantial heat-rejection loss at the condenser and severely penalise cycle efficiency. It is precisely this characteristic that necessitates the introduction of a recuperator: by transferring the residual sensible heat of the turbine exhaust stream back to the high-pressure working fluid upstream of the heat exchangers, the recuperator recovers a heat duty that would otherwise be rejected to the environment, and is therefore indispensable to achieving a thermodynamically competitive cycle efficiency.

This indirect architecture provides broad fuel flexibility, enabling the valorisation of impurity-rich gas streams that would otherwise be flared or reinjected without energy recovery, while the oxy-fuel combustion configuration ensures 100% carbon capture at the system boundary. The cycle additionally benefits from its offshore deployment location in the Norwegian Sea, where the low seawater temperature enables favourable CO_2 condensation and compression behaviour relative to warmer climates, where proximity to CO_2 critical point (30.98°C and 73.8 bar) greatly decreases condensed CO_2 cycle performance [5].

2. Methodology

The cycle was modelled as a steady-state flowsheet in *Thermoflex33*, with the *refProp* equation of state selected for its accuracy near the CO_2 critical region, consistent with the approach validated for the Allam cycle [4]. The model was first validated against the design conditions reported by Pedersen and Pilarczyk [2], then refined into an improved baseline through a parametric sensitivity analysis, and finally extended to a modified configuration incorporating pre-compression stages prior to condensation, inspired by Angelino's condensing cycle studies [5]. The fuel mass flow rate $\dot{m}_f$ was fixed at 1 kg/s for normalisation, allowing all other quantities to be reported on a unitary basis. The working fluid mass flow rate $\dot{m}_{wf}$ was treated as a controlled variable, regulated by an inventory-management control loop to maintain the *TIT* set point. The principal modelling assumptions, largely derived from the dataset of Pilarczyk [6], are summarised in Table 1.

The off-design behaviour of the cycle was characterised once the design-point simulation had fully converged. At this stage, all major components, including the heat exchangers and the turbine, were switched from Thermodynamic Design (*TD*) mode to Off-Design (*OD*) mode within *Thermoflex33*. Critically, the geometric and performance quantities computed during the design-point simulation, namely the heat exchanger conductance *UA*, the flow resistance coefficients, and the turbine stage-group flow functions and dry-stage efficiencies became the input parameters of the off-design model, which subsequently solves for the resulting outlet temperatures, pressure drops, and turbine performance as functions of the actual off-design flow conditions. This sequential dependency means that the off-design analysis is only meaningful once a physically consistent and converged design-point solution has been established, since any error in the design-point geometry would propagate directly into the off-design predictions. Turbine off-design behaviour was further computed using the *GT Master* module, with a Nozzle Control (*VAN*) strategy applied at the turbine inlet, while part-load operation was governed by variating the fuel mass flow rate $\dot{m}_f$, while the inventory-management control loop acted on $\dot{m}_{wf}$ to maintain the *TIT* set point.

In the present study, the *ASU* was not explicitly modelled within the flowsheet, in order to preserve a simplified and computationally efficient representation, and because detailed operational data on *ASU* performance were not available from the primary reference source. This simplification does not compromise the consistency of the results, since the *ASU* power demand depends primarily on the oxygen mass flow rate and the required purity level, both of which remain fixed under constant fuel flow conditions.

Table 1: Summary of modelling assumptions

Component	Assumption
EoS	*refProp*
Working fluid	sCO_2
Fuel	Pure CH_4
Oxidant	100% O_2
Flue gas y_{O_2}	1 % mol
T_{flame}	1100°C
Combution pressure	115 bar
HX1, HX2, HX_{rec} ΔT_{pp}	15 K
Condenser pressure	58 bar
η_{turb}	85 %
η_{pump}	75 %
ASU power demand	1000 kJ/kg_{O_2}
TIT	640°C
$p_{\text{turb,in}}$	300 bar

3. Results and Discussion

The model was validated against the reference data of Pedersen and Pilarczyk [2], reproducing a net efficiency of 28.3% (including *ASU* parasitic load), in close agreement with the reported 29%. A first sensitivity analysis identified an efficiency maximum at a *TIT* of approximately 640°C, motivating the definition of an improved baseline. At this design point, the cycle achieves a gross power output of 27.0 MW_e, a thermodynamic efficiency η_I of 43.1%, a net efficiency of 41.0% after auxiliary consumption (20.5 MW_e net power), and 32.4% when the *ASU* parasitic load is included (16.2 MW_e).

The oxygen mass flow rate $\dot{m}_{O2}$ was determined by the combustor's 1% mol residual oxygen constraint, yielding a value of 4.305 kg/s at the reference unitary fuel flow $\dot{m}_f = 1$ kg/s. Following Luberti et al. [7], who report an average specific electricity consumption of approximately 1000 kJ/kg_{O_2} for producing oxygen at purity exceeding 99.5%, the *ASU* parasitic load was computed in post-processing as $\dot{W}_{ASU} = 1000 \cdot \dot{m}_{O2}$, yielding a 4.3 MW_e load at the baseline condition. This corresponds to an efficiency penalty of 8.6 percentage points relative to the cycle efficiency excluding *ASU* consumption, a value comparable to the 7.2–9.1 percentage-point penalties reported for post-combustion *CCS* configurations by Kvamsdal et al. [3], while the ZEUS cycle achieves a substantially higher CO_2 capture rate, exceeding 99%, than conventional post-combustion alternatives. The sensitivity analysis performed on the baseline model showed that condensing pressure p_{cond} exerts the largest influence on efficiency, decreasing from 41.5% at 50 bar to 37.4% at 72.5 bar (without accounting the ASU load). In particular, efficiency drops for a condensing pressure above 70 bar, as the model cannot process the physical infeasibility of condensing CO2 at critical conditions. *TIT* exhibits a non-monotonic effect: although turbine specific work increases continuously with *TIT*, the working fluid mass flow rate $\dot{m}_{wf}$ is decreases to satisfy the *TIT* control loop set point, and the exhaust stack temperature rises substantially, together producing the observed efficiency maximum near 640°C. Turbine and pump isentropic efficiencies were found to influence η_I approximately linearly, while turbine inlet pressure exhibits a local optimum near 280 bar, in agreement with the designed pressure at 300 bar.

The modified configuration, incorporating precompression stages between the turbine outlet and the condenser, was found to offer no thermodynamic advantage over the baseline. Increasing the pre-compressor pressure ratio reduces the *TOT*, which constrains the achievable duty of *HX2* under the imposed split-ratio condition and increases the exhaust stack temperature, offsetting the gain in turbine specific work. A two-dimensional sensitivity analysis over *TIT* and pre-compressor pressure ratio confirmed that no improvement in η_I is achievable across the explored parameter space, indicating that the current split-ratio constraint and heat-recovery architecture are incompatible with the modified expansion topology.

Benchmarked against reference cycle technologies, the ZEUS baseline performs comparably to a recuperated steam Rankine cycle at the same *TIT*, consistent with its indirect, condensing architecture, which more closely resembles a Rankine configuration than a Brayton cycle. The performance gap relative to optimised indirect sCO_2 cycles reported in the literature is attributable to deliberate offshore design compromises, including limited heat-exchanger pinch points, the absence of reheating, and a reduced number of heat-recovery stages.

Off-design analysis revealed strong sensitivity to seawater temperature, with net efficiency declining from 43.5% at 1°C to 22.6% at 24.5°C, the degradation accelerating sharply as condensing conditions approach the CO_2 critical point. Under variable fuel flow, three operating regimes were identified: a sub-nominal regime (0.1–0.4 kg/s) with rapidly increasing efficiency as fixed auxiliary penalties become proportionally smaller relative to gross power output; a *TIT*-controlled regime (0.5–1.1 kg/s), representing the physically meaningful part-load operating range, with efficiency stable near 41%; and an over-fuelled, condenser-limited regime (above 1.2 kg/s) in which the heat sink becomes a binding constraint and net power collapses despite increasing fuel input. The *ASU* parasitic penalty of 8.6 percentage points remains invariant across all part-load operating points, since the oxygen-to-fuel ratio is held constant by the combustor model.

4. Conclusions

This work provides the first validated, systematic thermodynamic characterisation of the ZEUS cycle, establishing a baseline configuration achieving 41.0% net efficiency (32.4% including *ASU*), identifying condensing pressure and *TIT* as the dominant performance drivers, and quantifying the strong dependence of cycle performance on ambient seawater temperature and part-load operation. The recuperator was shown to play a structurally necessary role in offsetting the heat-rejection penalty arising from CO_2's comparatively flat expansion temperature profile, while the *ASU* parasitic load was shown to constitute a systematic but well-characterised efficiency penalty, broadly comparable to that of conventional post-combustion *CCS* alternatives. While the proposed pre-compression configuration did not yield efficiency gains under the current modelling constraints, the validated framework establishes a basis for future optimisation, control-strategy development, and integration studies, including potential synergies with decarbonised *LNG* production.

References

[1] K. Pedersen et al., "Development of ZEUS – Zero-Emission Unmanned Power Station," in *Proc. 8th Int. Supercritical CO_2 Power Cycles Symp.*, Paper No. 115, San Antonio, TX, USA, Feb. 2024.

[2] K. Pedersen and M. Pilarczyk, "Comparative study between offshore zero-emission unmanned power station and gas turbine combined cycle with carbon capture," Technical paper, GasTech 2024. Available: https://www.gastechevent.com/media/pirbgljv/kjartan-pedersen_aker-solutions_2165.pdf

[3] H. M. Kvamsdal et al., "Energetic evaluation of a power plant integrated with a piperazine-based CO_2 capture process," *International Journal of Greenhouse Gas Control*, vol. 28, pp. 343–355, 2014. doi:10.1016/j.ijggc.2014.07.004

[4] R. Scaccabarozzi, "Thermodynamic optimization of the Allam cycle and thermo-fluid dynamic design of the cooled CO_2 turbine," 2020.

[5] G. Angelino, "Carbon Dioxide Condensation Cycles For Power Production," *Journal of Engineering for Gas Turbines and Power*, vol. 90, p. 287, July 2011. doi:10.1115/1.3609190

[6] M. Pilarczyk, "Inventory system and recuperator for sCO_2 cycle in ZEUS," Melkøya Sprint Study Update, 2024.

[7] M. Luberti, M. Capocelli and G. Santori, "On the energetics of oxygen separation from air," *Chemical Engineering Science*, vol. 320, p. 122660, 2026. doi:10.1016/j.ces.2025.122660