Analysis of sCO_2 Cycles for District Heating Applications

Mathias Penkuhn, George Tsatsaronis
Technische Universität Berlin

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Introduction

Carbon dioxide is a natural, alternative working fluid with favorable properties. Its application in supercritical (sCO_2) power generation cycles:

- offers the potential to realize high-efficiency designs,
- with low emissions, and
- favorable economics because of smaller equipment and higher operational flexibility compared to conventional water-steam-based power cycles.

Significant, worldwide effort in research and development is directed at future implementation and commercialization of sCO_2 technology for power generation.

mathias.penkuhn@tu-berlin.de

Introduction

Previous research has identified two thermodynamically efficient cycle designs for standalone power generation:

- the recompression cycle for standalone sCO_2 cycles, and
- the split-flow expansion cycle for waste heat recovery sCO_2 bottoming cycles.

Potential applications will feature designs that provide

- either substantial economical,
- or operational advantages.

Cogeneration processes are generally considered advantageous. In particular, sCO_2 power cycles have waste heat that:

- is available as high-temperature thermal energy above 70 °C, and
- is suitable for desalination, or district heating.

mathias.penkuhn@tu-berlin.de

Scope of the Study

As heat extraction for district heating is a beneficial, potential application in cold and temperate climates, the study:

- investigates the possibility of combined heat and power (CHP),
- using an sCO_2 bottoming cycle,
- in a gas turbine combined cycle application.

System designs are chosen according to the following design considerations:

- sCO_2 power cycles are high-temperature, high-pressure, but low-pressure ratio, and highly-recuperative designs.
- Cogeneration system design options are derived from conventional water-steam-based designs [1].

System Description

The sCO_2 cycle is integrated in a gas turbine combined cycle, with:

- the gas turbine model GE 9E.04 representing the topping cycle at ISO conditions* with backpressure adjustments,
- using different sCO_2 cycle designs as the bottoming cycle.

sCO_2 cycle design options for heat extraction for district heating include:

- recooling,
- split-flow, and
- turbine extraction.

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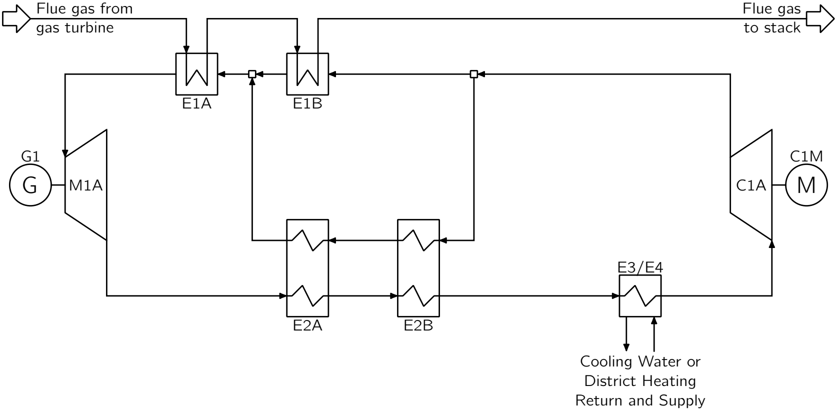
*Allows for comparison with catalogue data of the conventional CCGT with 1 gas turbine and 1 steam turbine

mathias.penkuhn@tu-berlin.de

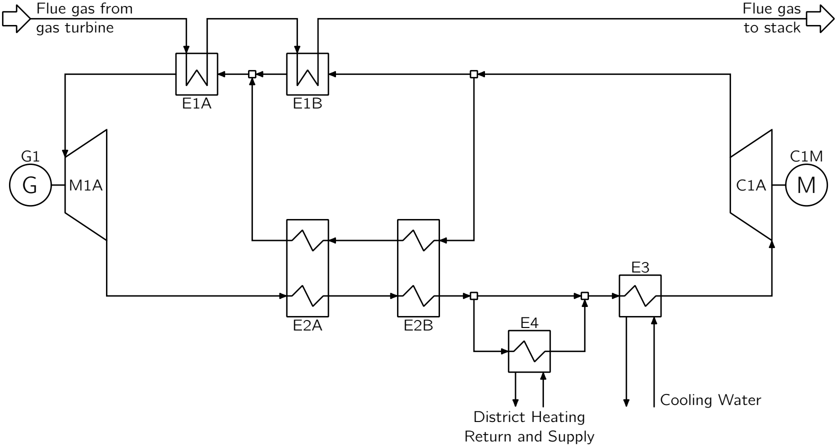
Recooling or Backpressure sCO_2 Cycle (Design 1)

Recuperated, recooling or backpressure sCO_2 cycle design:



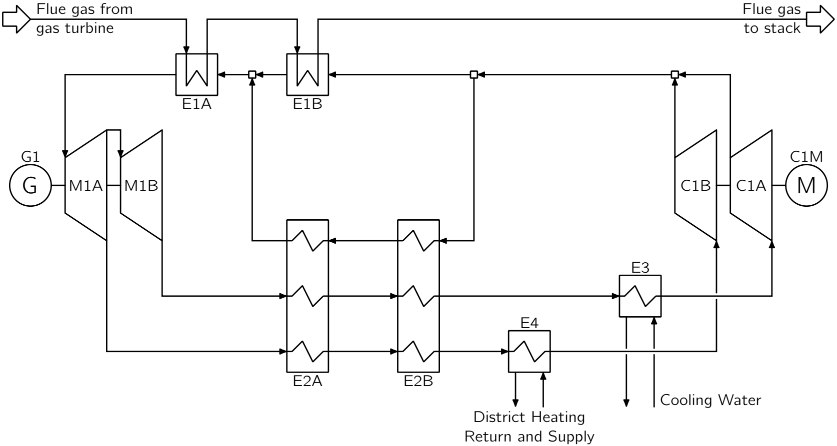
Split-flow, Recooling sCO_2 Cycle (Design 2)

Recuperated, split-flow sCO_2 cycle design:



Turbine Extraction, Recooling sCO_2 cycle (Design 3)

Recuperated, turbine extraction sCO_2 cycle design:



Methodology I

In this study, universally applied energy-based metrics are used for system analysis and evaluation:

- Electric efficiency:

$$\eta_{\mathrm{w}} = \frac{\dot{W}_{\mathrm{net}}}{\dot{m}_{\mathrm{fuel}} \cdot LHV_{\mathrm{fuel}}}$$

- Energy utilization factor for CHP processes:

$$\eta_{\mathrm{ov}} = \frac{\dot{W}_{\mathrm{net}} + \dot{Q}}{\dot{m}_{\mathrm{fuel}} \cdot LHV_{\mathrm{fuel}}} = \eta_{\mathrm{w}} + \eta_{\mathrm{q}}$$

Methodology II

For CHP processes, the following metrics are used for system analysis and evaluation:

- Electric power to heat ratio:

$$\sigma = \frac{\dot{W}_{\text{net}}}{\dot{Q}}$$

- Power loss coefficient at constant fuel energy supply:

$$\beta = \left. \frac{\Delta \dot{W}_{\text{net}}}{\dot{Q}} \right|_{\dot{m}_{\text{fuel}} \cdot LHV_{\text{fuel}} = \text{const.}}$$

Simulation Parameters

Simulations are conducted using the following parameters*:

- Turbine inlet conditions: 240 bar and 390 °C to 450 °C
- Compressor inlet pressure: 80 bar
- Recuperator minimum temperature difference: 10 K
- Recuperator maximum effectiveness: 0.9
- Cooler outlet temperature: 32 °C
- Heat extraction minimum temperature difference: 5 K
- District heating supply and return temperatures: 90/50 °C

Simulation constraints:

- Off-design and part-load effects, e.g., compressor surge, are neglected, no parameter optimization runs are conducted.

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* Best-practice assumptions [2, 3]

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Main Results I: Standalone Power Generation

ID	$\dot{W}_{\mathrm{net}}$ (MW)	$\dot{Q}_{\mathrm{dh}}$ (MW)	η_{w} (%)	η_{ov} (%)	σ (–)	β (–)
Conv. CCGT*	216.0	–	54.9	–	–	–
Recooling	206.0	–	52.7	–	–	–
Split-flow	200.5	–	51.2	–	–	–
Turbine extraction	206.0	–	52.7	–	–	–

Slightly lower, but comparable standalone electric efficiency for sCO_2 power cycles compared to conventional combined cycles because of non-optimized cycle parameters.

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*Based on gas turbine catalogue data [4]

Main Results II: Combined Heat and Power Generation

ID	$\dot{W}_{\mathrm{net}}$ (MW)	$\dot{Q}_{\mathrm{dh}}$ (MW)	η_{w} (%)	η_{ov} (%)	σ (–)	β (–)
Conv. CCGT*	182.3	168.1	46.3	89.0	1.08	0.20
Backpressure	186.6	162.4	47.7	89.2	1.15	0.12
Split-flow	200.5	53.4	51.2	64.9	3.76	0
Turbine extraction	186.6	162.4	47.7	89.2	1.15	0.12

Similar energy utilization factor, better behavior concerning heat extraction for sCO_2 power cycles compared to conventional combined cycles.

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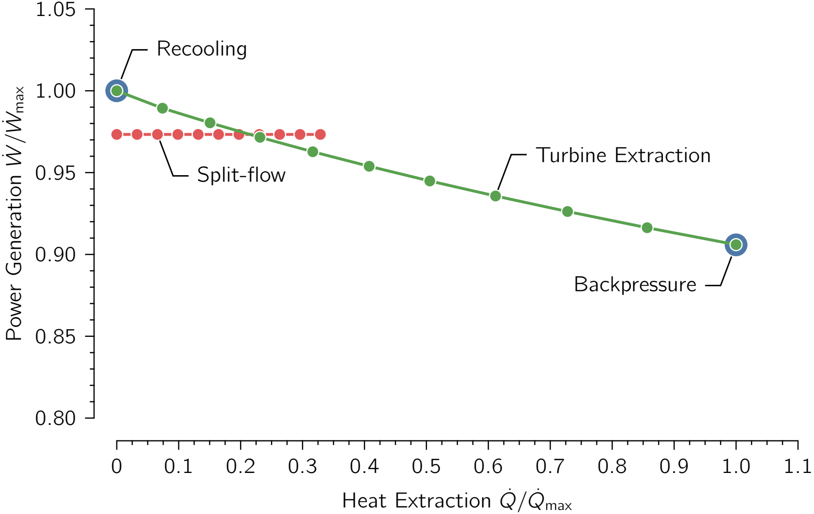
* Best-practice assumptions [5]

Design Space: Combined Heat and Power Generation



Sensitivity Analysis

District heating network designs are changing in the near future because of low-exergy considerations. Therefore, return and supply temperatures for future generations are lower than today:

- Set A: supply and return temperature 90/50 °C (Gen III*)
- Set B: supply and return temperature 70/40 °C (Gen IV*)
- Set C: supply and return temperature 110/60 °C (Gen II*)

Because of the recuperation effect in the sCO_2 cycle designs, the supply and return temperatures are expected to have a strong influence on cycle efficiency.

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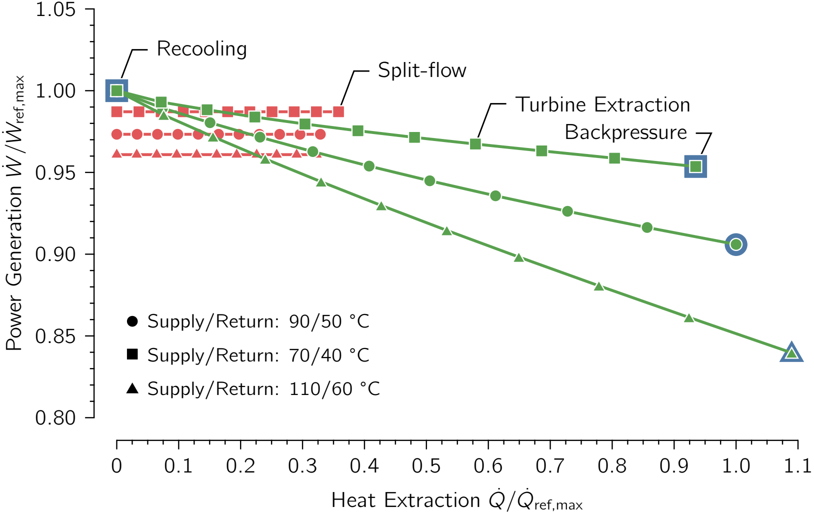
* Generations of district heating network designs. Nomenclature according to Lund et al. [6].

Sensitivity Analysis: Combined Heat and Power Generation



Sensitivity Analysis: Results

Compared to the reference case with a supply and return temperature of 90/50 °C, a reduction in supply and return temperature (Set B):

- allows for a higher power generation because of the increased potential to recover thermal energy, and
- thereby insignificantly reduces the amount of thermal energy available for heat extraction (lower ΔT_{dh}), but
- positively affects the split-flow design allowing for a higher heat extraction.

In contrast, higher supply and return temperatures (Set C):

- have a negative effect on power generation,
- allow for an increased heat extraction (higher ΔT_{dh}), and
- slightly reduce the amount of heat available in the split-flow design.

Conclusions

The present study successfully showed:

- the potential of using sCO_2 bottoming cycles for the cogeneration of heat and power,
- that a large amount of low temperature thermal energy can be effectively extracted, and
- that a certain amount is available without negatively affecting the power generation.

Future investigations should concentrate on:

- the sCO_2 cycle designs integrating the split-flow, and turbine extraction approaches,
- thereby reducing the impact of heat extraction on power generation, and
- analyzing the off-design and part-load behavior of the cycle designs.

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