A qualitative comparison of gas turbine cycles with CO_2 capture

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Abstract
Nine different concepts for natural gas fired power plants with CO_2 capture have been investigated, and a qualitative comparison is made based on technological maturity and operational challenges. This analysis is a follow-up of a quantitative analysis of the same concepts presented in previous papers. The cycles constitute one post-combustion, six oxy-fuel and two pre-combustion concepts. A methodology is developed enabling comparison based on the two qualitative criteria. The results show a similar trend with respect to increasing immaturity level and increasing operational challenges. However, the trend is slightly opposite when it comes to net plant efficiency meaning that the concepts facing high operational challenges and require technological breakthroughs to be realized, exhibit the best plant efficiencies.

Key words: CO_2 capture, concept comparison, qualitative analysis

Introduction

Over the past few years a multitude of different power cycles with CO_2 capture have been presented in the literature. In this context SINTEF and NTNU are collaborating to present evaluations and comparisons of concepts for gas turbine cycles with CO_2 capture. The results of a quantitative analysis of nine different concepts for natural gas fired power plants with CO_2 capture were presented in two previous papers ([1], [2]). The various concepts studied in these papers, as well as all other power cycles with CO_2 capture, differ in technological maturity and operational challenges and a general observation is that concept comparisons based on plant efficiency and the level of CO_2 capture alone, miss important aspects. It is highly relevant to consider other criteria for comparison as e.g. technological maturity, operational challenges, cost, technology development risks, emission of NOx and/or chemical wastes, and time scale for any realization of the concepts.

In the present paper a transparent methodology for qualitative evaluation of various concepts with focus on technological maturity and operational challenges, is presented. The methodology is applied to the concepts studied in [1] and [2]. These concepts constitute six variations of the oxy-fuel type of concepts: 1) The Oxy-fuel Combined Cycle (Oxy-fuel CC), 2) the Water Cycle (WC), 3) the Graz Cycle (Graz), 4) the Advanced Zero Emissions Power Plant (AZEP), 5) Solid Oxide Fuel Cell integrated with a gas turbine (SOFC+GT), and 6) Chemical Looping Combustion (CLC). Furthermore, there are two variations of the pre-combustion de-carbonization method involving natural gas reforming with: 7) an auto thermal reformer (ATR) and 8) a hydrogen membrane reformer (MSR-H2). Finally, there is one post-combustion concept based on a conventional combined cycle (CC) with CO_2 separation from the exhaust gas by chemical absorption in a MEA solvent (Amine). All concepts including flowsheet diagrams are described in [1].

Methodology

When comparing the various concepts, a consistent methodology should be applied. An example of a methodology and tool for an overall assessment of different concepts was presented in. [3]. In the present work, a similar approach has been used. It is also based on a numeric classification system, but the presentation is different from the weighting approach in [3]. The present work uses a

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breakdown into main blocks, and each block is characterized according to a maturity level system with a numeric classification.

The various concepts have reached different levels of technological maturity. For a systematic description of maturity, each of the main process operation units or block for each of the concepts are classified in accordance to the 5 maturity levels described in Table 1. A block is here defined as a distinct unit operation or an integrated unit consisting of two or more unit operations, which can be developed independently of surrounding blocks.

Table 1: Description of the defined maturity levels (based on IPPC, 2005, [4])

Maturity level	**Description**
0	Mature technology with multiple commercial replications for this application and scale of operation; considerable operating experience and data under a variety of conditions.
1	Commercially deployed in applications similar to the system under study, but at a smaller scale and/or with limited operating experience; no major problems or issues anticipated in this application; commercial guarantees available
2	No commercial application for the system and/or scale of interest, but technology is commercially deployed in other applications; issues of scale-up, operability and reliability remain to be demonstrated for this application.
3	Experience and data based on pilot plant or proof-of-concept scale; no commercial applications or full-scale demonstrations; technical issues or cost-related questions still to be resolved for this application.
4	Component or sub-system not yet tested, or with operational data limited to the laboratory or bench-scale level; significant issues of operability, effectiveness, reliability and manufacturability remain to be demonstrated.

The number of occurrences of the maturity levels one to four (level 0 is omitted) for each of the concepts are summed and presented together with the net plant efficiency. By such, the graph will show the number of immature blocks thereby indicating the required effort to realize the different concepts. The efficiency dimension contributes further to the characterization.

Since operational challenges are highly related to the interaction of subsystems, recycle streams and heat exchange, classification of the different concepts regarding operational challenges is mainly based on this type of information. Here, the number of subsystems and their interrelations and dependencies are quantified for each concept and the relative heat transferred (relative to LHV of the fuel) in some of the main heat exchangers is given. This will convey the impression of operational challenges and these are classified as either 1: low, 2: medium or 3: high. A subsystem is here defined as either a block or group of blocks, which constitute a distinct process. Examples are gas turbine, steam turbine cycle, synthesis gas production, air separation and CO_2 compression.

Comparison of concepts

Technological maturity

The maturity level of the blocks for each concept is given in Table 2, while the numbers of occurrences of the different maturity levels are presented together with the net cycle efficiencies in Figure 1. The basis for the result is briefly discussed in the following sections.

Table 2: Block maturity level for the various concepts. More than one occurrence of each block indicates the number of similar block types.

Block	Oxy-fuel CC	WC	Graz	AZEP	SOFC +GT	CLC	ATR	MSR-H2	Amine
Compressor	2		1		1	1			
Combustor	4	3	4				1	1	
Turbine	3	3, 3, 2[1]	3, 1[2]	2	1	2, 2		1, 2[3]	
HX (included HRSG)	1	2	1		2				
Exhaust/H_2O condenser	1	2	2	1		1		1	
CLC-reactors						4			
MCM reactor				4					
H2 Sep. membrane reactor								4	
Fuel Cell					3				
Fuel Cell Afterburner					4				
Absorber/stripper									1
CO_2 compression	1	2	2	1	1	1	1	1	1

[1] HPT, IPT, LPT, [2] HPT, LPT, [3] GT, CO_2/steam turbine

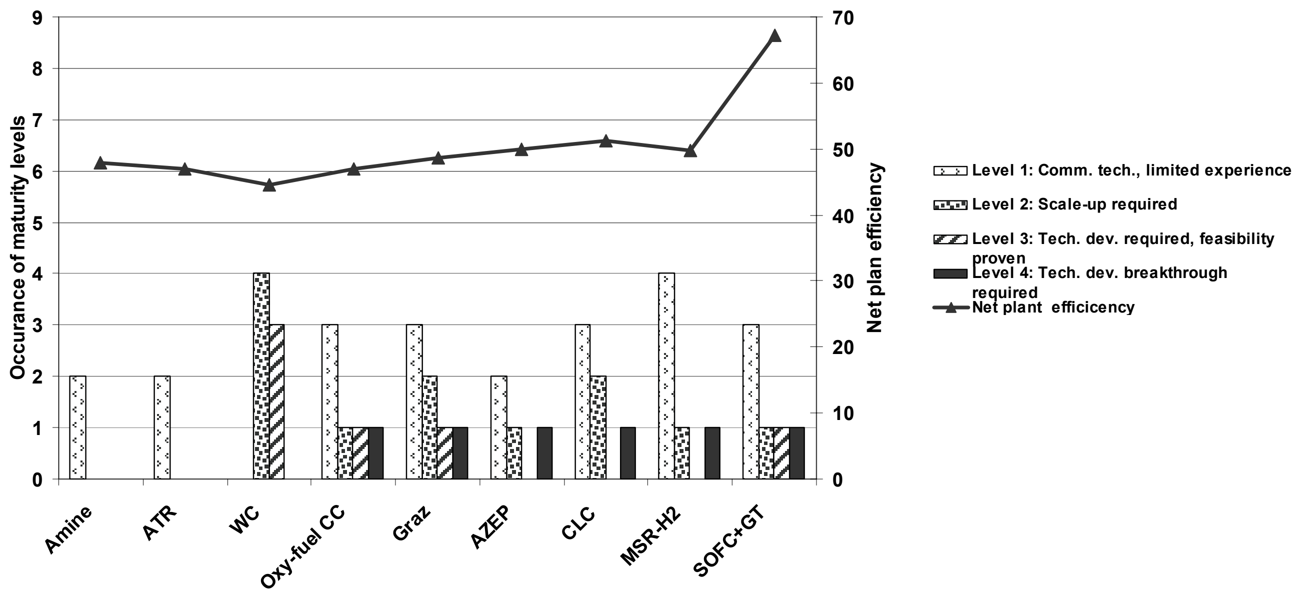

Figure 1: The number of occurrences of the different maturity levels and the net cycle efficiency for each concept.

The gas turbine technology needed for the Oxy-fuel CC, the Water Cycle and the Graz Cycle is not developed. However, the turbo machinery of the Graz Cycle has a preliminary design and there is a plan for building a prototype ([5]). Furthermore, for the last ten years a gas generator (i.e. an oxy-fuel combustion chamber) has been in progress of development for use in the Water Cycle. This gas generator has been tested in a 5 MW plant with existing turbine technology. However, the inlet temperatures are lower than given in the basis for the present analysis ([1]) and further development is required ([6]).

All the concepts involving membrane based unit operations (i.e., the AZEP, the SOFC/GT, and the MSR-H2) need further development. Based on the complexity of these blocks it is anticipated that several technological breakthroughs are required before it can prove to be feasible technologies. The key components that must be developed in case of the AZEP concept are an oxygen conducting membrane and a high temperature heat exchanger. In addition, a new combustion chamber for stoichiometric combustion must be developed. The main challenge related to the MSR-H2 concept is the development of the hydrogen membrane and to integrate this in large-scale reformers. Even though a 220 kW SOFC+GT plant without CO_2 capture has been demonstrated the development of a novel afterburner technology is the most challenging part and of crucial importance for application of the SOFC+GT concept studied here.

In case of the CLC concept, the most challenging part is related to the system around the two reactors, which in itself, however, are regarded as mature technology. Especially, this concerns the development of a Metal/Metal oxide system for application in high temperature environments. The turbines in the CLC concept must also be modified by replacing the combustion chamber with the reactor system. This is a similar modification to what is needed in the AZEP technology.

In the context of the 9 different concepts analyzed in the present comparison, the technologies involved in both the Amine and the ATR concepts are regarded as mature.

<u>Operational challenges</u>

The subsystems for each concept are defined as shown in Table 3 together with the number of subsystems, which interacts in an operational challenging manner. The latter comprises high degree of process- and heat integration and fast dynamic interactions. In Table 4, the number of recycle streams (both gas and liquid) and the relative heat transferred in the main heat exchangers are shown.

Table 3: Definition of subsystem and number of integrated subsystems associated with high degree of operational challenges (numbers in parenthesis)

Concept	Subsystems (number of)	Integrated subsystems (number of)
Amine	gas turbine, steam turbine cycle, absorber/stripper, CO_2 compression (4)	
Oxy-fuel CC	Air Separation Unit (ASU), gas turbine, steam turbine cycle, CO_2 compression (4)	
WC	ASU, gas/steam turbine, CO_2 compression (3)	gas/steam turbine and CO_2 compression (1)
ATR	reformer/shift, absorption/stripper, gas turbine, steam turbine cycle, CO_2 compression (5)	reformer/shift and gas turbine (1)
Graz	ASU, gas/steam turbine, CO_2 recycle compression, CO_2 compression (4)	gas/steam turbine and CO_2 compression (1)
AZEP	MCM reactor, gas turbine, steam turbine cycle, CO_2/steam turbine, CO_2 compression (5)	MCM reactor and gas turbine, MCM reactor and CO_2/steam turbine, CO_2/steam turbine and CO_2 compression (3)
MSR-H2	reformer, gas turbine, steam turbine cycle, CO_2/steam turbine, CO_2 compression (5)	reformer and gas turbine, reformer and CO_2/steam turbine, CO_2/steam turbine and CO_2 compression (3)
CLC	reactors, gas turbine, steam turbine cycle, CO_2/steam turbine, CO_2 compression (5)	reactors and gas turbine, reactors and CO_2/steam turbine, CO_2/steam turbine and CO_2 compression (3)
SOFC+GT	gas turbine, external reformer, SOFC unit, afterburner, CO_2/steam turbine, CO_2 compression (5)	gas turbine and SOFC, SOFC and afterburner, afterburner and CO_2/steam turbine, CO_2/steam turbine and CO_2 compression (4)

Table 4: The number of recycle streams and relative heat transfer in main heat exchangers

	No of recycle streams (gas/liquid/solid)	Relative heat transfer main HX [$MW_{transferred}$ /MW_{fuel_LHV}]
Amine	1 (liquid)	0.56 (HRSG)
Oxy-fuel CC	1 (gas)	0.74 (HRSG)
WC	1 (liquid water)	0.13 (HRSG)
ATR	1 (liquid water/steam)	0.41 (HRSG), 0.21 (steam boilers)
Graz	2 (gas and liquid water/steam)	0.31 (HRSG), 0.15 (CO_2 recirculation)
AZEP	1 (gas)	0.54 (HRSG), 0.99 (MCM reactor)
CLC	1 (solid)	0.46 (HRSG)
MSR-H2	1 (gas)	0.6 (HRSG), 0.25 (MSR unit)
SOFC+GT	2 (gas)	0.18 (afterburner pre-heater)

All the tree oxy-fuel concepts; 1) Oxy-fuel CC, 2) WC, and 3) Graz, involve recirculation of exhaust gases. This gives a closed loop, i.e. a close integration of components and as system vulnerable to start-up, shut-down and load changes. Since the Graz cycle involves 2 recycle loops (Table 4), it is anticipated that the operational challenges are higher than in case of the other two.

Furthermore, as can be seen from Table 3 and 4 all the concepts involving new and emerging technologies (AZEP, SOFC+GT, CLC and MSR-H2) involve high degree of subsystem integration, complex recycling of streams and/or large amount of relative heat transfer. For example capture of CO_2 in the SOFC+GT concept involves additional complexity as two immature technologies (SOFC and afterburner) are connected in series. Furthermore, the rapid load changes in the gas turbine compared to the SOFC's requirement for stable temperature conditions are operational challenging.

Additionally, the emerging unit operations constitute in itself integrated process phenomena (AZEP: oxygen separation, combustion and heat exchange, SOFC+GT: oxygen separation, reforming + electrochemical reaction and heat exchange, CLC: 2 reactors coupled through recycling of solid materials, MSR-H2: heat exchange, reforming, and hydrogen separation), which contribute further to increased operational challenges.

Tight integration of turbine expansion and CO_2 compression is regarded as operational challenging. This type of integration concerns the following concepts; WC, Graz, AZEP, SOFC+GT, CLC, and MSR-H2.

The ATR concept involves a tight process- (air, steam and fuel) and heat integration between the reformer/shift section and the Combined Cycle section. Thus the control of any plants based on this concept will be challenging as indicated by the high number of subsystems, recirculation of streams and heat exchanging streams. However, due to the long experience with some of the subsystems and other similar tight integrated modern process plants (e.g. IGCC plants) it is anticipated that the operational challenges will be in the medium range.

It is assumed that the operation of the Amine system will not imply considerable problems and even though with steam withdrawal from the steam cycle, the system challenges are classified as low.

Conclusion

A methodology for qualitative evaluation of power cycles with CO_2 capture has been presented. This methodology evaluates technological maturity and operational challenges. It comprises mainly the use of Tables 2, 3, and 4 and the representation of the qualitative evaluations in combination with quantitative results in Figure 1.

As can be seen from Figure 1, the following concepts: Oxy-fuel CC, Graz, AZEP, CLC, MSR-H2, SOFC+GT, all involve a block with maturity level 4 and as such these concepts can be classified as immature with significant technology development challenges. However, the anticipated challenges related to development of new gas turbines are lower than for large scale membrane based units as the large scale turbine manufacturers have a lot of experiences with similar development. Thus the Oxy-fuel CC and the Graz concepts are less challenging than the others (AZEP, CLC, MSR-H2, and SOFC+GT). The ATR and Amine concepts imply only minor challenges (some scale-up issues) related to technology development.

Based on information in Table 3 and 4 and the subsequent evaluation, the operational challenges are classified as low for the Amine concept, medium for the Oxy-fuel CC, the WC, and the ATR concepts, and high for the AZEP, the CLC, the MSR-H2, and SOFC+GT concepts. A similar trend as for the maturity level can be observed, meaning that the concepts facing high degree of operational challenges also require technological breakthroughs to be realized and vice versa. However, as can be seen from Figure 1, the net plant efficiency for the concepts with high degree of immature technology and, which will face high degree of operational challenges (AZEP, CLC, MSR-H2, SOFC+GT) is higher than for the others (Amine, ATR, WC, Oxy-fuel CC, Graz) and the ranking with respect to net plant efficiency means almost the opposite trend. Thus in order to determine the most promising concept, it will be important to address further the potential of relative plant efficiency improvement as well as other important factors such as the risk of not succeeding in the technology development, relative cost reduction potential, and time to plant realization.

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