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Capture of CO_2 from Medium-scale Emission Sources

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Abstract

Until now, the work done on capture and storage of CO_2 has mainly focused on capture and storage of CO_2 from fossil fuel fired power plants and other large point sources. Although medium-scale sources of CO_2 account for a smaller proportion, their contribution to global CO_2 emissions is still substantial and in the range of 10 – 15% of total global energy related CO_2 emissions. The study identifies possible combinations of capture technologies and medium scale combustion installations and assesses these in terms of potential and costs. Although medium-scale capture of CO_2 is expected to be more expensive than large-scale capture, it may nevertheless be competitive with alternative methods of abating CO_2 from medium-scale sources in some circumstances.

Keywords: CO_2 capture, medium-scale combustion, coal boiler, oxygen conducting membranes

1. Introduction

The main focus of existing work on CO_2 capture has been on capture and storage of CO_2 from fossil fuel fired plants power plants and other large point sources. Usually, CO_2 capture from medium scale sources has not received much attention, because of expected high costs and concerns about the safety of CO_2 transportation from populated areas where medium scale sources are often located. Although these medium-scale sources of CO_2 account for a smaller contribution to global CO_2 emissions compared to large point sources their proportion is still substantial (about 10-15%). In order to comply with (inter)national targets, carbon capture and storage from these small and medium scale sources might be necessary in the future.

Ecofys and the Energy research Centre of the Netherlands (ECN) therefore carried out this study for the IEA Greenhouse Gas R&D Programme to identify suitable combinations of medium scale sources and capture

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technologies in terms of applicability, costs and emission reduction potential,. This conference paper is based on the content of the report 'CO_2 capture from medium scale combustion installations' [1]. The second part of the report covers the case study on oxyfuel coal boilers with oxygen conducting membranes and is included in another conference paper by Carbo et al. (2008) [2].

2. Scope

For the purpose of this study a medium-scale installation is defined as a combustion installation with size between 1 and 100 MW_{th}, which is at the scale of district heating plants, industrial installations and large commercial buildings. The corresponding amount of CO_2 produced depends on the size of the installation and the type of fuel used. Because of higher carbon content a 100 MWth coal-fired installation produces about 250 ktonne CO_2 per year whereas a 100 MW_{th} gas-fired installation produces only 150 ktonne CO_2 per year. This equals to 33 and 20 kg/h assuming a load factor of 7500 hours.

3. Methodology

The study starts with the characterization of typical medium-scale combustion installations and is followed by a market analysis of these technologies. The characterization focuses on aspects such as typical size, fuel use, efficiency and flue gas characteristics of the combustion installations. The market analysis gives an indication of the current and future market for carbon dioxide equipment and the emission reduction potential that can be obtained by applying the different capture technologies. It concentrates on the current most important medium-sized power and heat generating installations: reciprocating engines, gas turbines and boilers. The study reviews publicly available information on the market size of medium scale sources of CO_2, with emphasis on the USA, the Netherlands and China.

The second part of this study involves the technical characterization of capture technologies for medium-scale combustion plants. A long list is created with potential feasible combinations of combustion installation with capture technology. Six cases that represent a combination of technology, fuel and capture technology are selected for in-depth analysis on the technical aspects, the potential for application and an indication of the energy requirements and cost performance.

4. Characterization and market analysis of medium scale combustion installations

A commonly used categorization for power and heat production units, which is also used throughout this study, is furnaces (including boilers), steam turbines, reciprocating engines, large gas turbines, micro gas turbines and fuel cells. Typically, these medium-sized installations are placed close to the location where the energy is used (distributed), for example at industrial sites.

Devices that produce only heat are furnaces. They either supply heat to the processes directly or indirectly through the generation of hot water or steam (then called boilers). Furnaces which supply heat directly are used in the iron and steel industry, ceramic industry, cement and limestone industry and glass industry and furnaces which supply heat indirectly are used in a wide range of other applications. The scale of furnaces covers a wide range - from small domestic heaters (smaller than 30 kW_{th}) to large boilers for coal-fired plants (larger than 1000 MW_{th}). Steam from boilers is either used for industrial purposes or used in steam cycles to produce electricity and/or heat.

The power generation technologies identified are steam turbines, reciprocating engines, gas turbines and fuel cells.

Table I summarizes the most important characteristics of the distributed power generation technologies. In general, steam turbines are optimized to heat production and generate electricity as a by-product. The capacity of steam turbines covers the largest range from 50 kW_e to several hundreds of MW_e for large utility power plants, followed by gas turbines that are found in the 0.5 to 50 MW_e class. Fuel cells are included because of their expected future importance in electricity generation and their anticipated potential for economically capturing CO_2.

Table I Characteristics of power generation technologies

	Steam turbine	Reciprocating engine	Gas turbine		Fuel cell
			Large gas turbine	Micro turbine	
Applicable market sectors	Institutional buildings, Industry, Waste fuels	Commercial buildings, Light industry, Grid, Waste fuels	Large commercial, Industry, Grid, Waste fuels	Commercial buildings, Light industry, Waste fuels	Residential, Commercial buildings, Light industry
Technology status	Commercial	Commercial	Commercial	Early entry	Early entry, development
Size (MW_e)	0.5 - 100	0.05- 20	0.5 - 50	0.03 – 0.25	0.005 – 2
Electrical efficiency	<10% - 40%	20% - 30%	40%	25%	25% - 35% (PEMFC) 35% - 43% (SOFC) > 40% (PAFC) 45% - 47% (MCFC)
Fuels	All	Natural gas, biogas, liquid fuels	Natural gas, biogas, distillate oil	Natural gas, biogas	Hydrogen, natural gas
Uses for heat recovery	LP and HP steam, district heating	Hot water, LP-steam, district heating	Direct heat, hot water, LP and HP steam, district heating	Direct heat, hot water, LP steam	Hot water, LP steam
Typical CO_2 flue gas concentration	8-15% (boiler) 3-4% (gas turbine HRSG)	9- 14%	3-4%	2-4%	8-10%

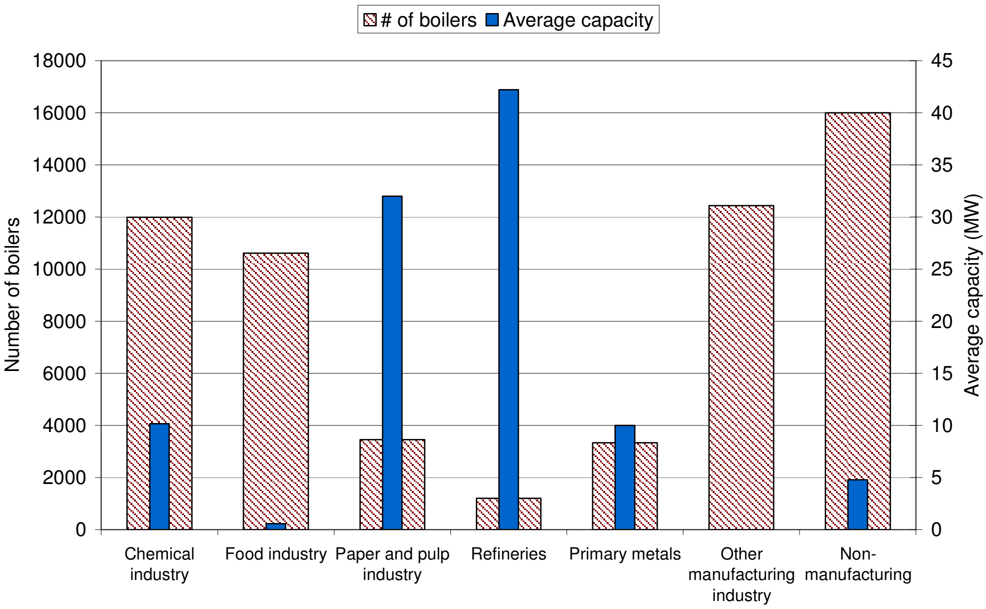

Figure I Number of boilers in industry (red bar) and average capacity of the boilers (blue bar) in the United States [3]

Of the above discussed technologies, boilers, reciprocating engines and gas turbines are represented well in the medium-scale segment. A 2005 US market survey on industrial and commercial boilers shows that 97% of the industrial boilers has capacities below 73 MW_{th} (250 MMBtu/h) [3]. The highest number of both industrial and commercial boilers is found in the capacity range below 3 MW_{th}. The most important steam-intensive industries are pulp and paper, chemical industry, refineries and primary metals. These industries have installed 82% of the total industrial boiler capacity in the United States. The average capacity of the boilers in industry is highest in refineries (42 MW_{th}) and the paper and pulp industry (32 MW_{th}), smaller capacities are found in primary metals (10 MW_{th}) and the chemical industry (10 MW_{th}) [3]. Figure I shows the average capacity in the major steam intensive industries in the United States.

Diesel and gas-fired reciprocating engines are dominant in the segment of capacities below 3.5 MW_e. Gas turbines are the dominant technology above 20 MW_e. The mid-range is equally shared between the technologies, although we see a trend that smaller gas turbines become more available in the low capacity ranges. The market for reciprocating engines expands rapidly. Most reciprocating engines are found in the 1.0–2.0 MW_e class, representing 22% of the total sales of gas engine and turbines in 2004 (see Figure II). Over 50% of the total gas turbine and engine capacity ordered in 2004 (26 GW_e) is to be found in the capacity range 120 MW_e and above [4]. Medium-scale gas turbines from 1 to 40 MW_e are 15% of the total ordered gas turbine capacity in 2004. An example from the United States shows that the largest capacity of gas turbines with sizes below 40 MW_e is installed in the oil recovery and chemical industry [5].

Fuel cells, currently in the pilot phase, are potentially well suited for distributed power generation and CHP markets in the future.

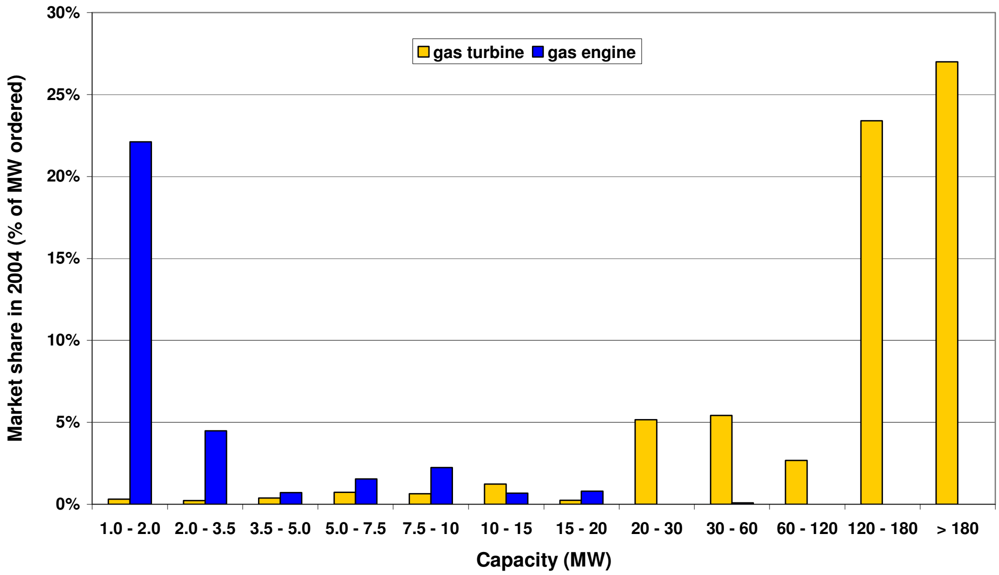

Figure II Share of ordered gas engines and turbines in 2004 [4]

5. Medium scale capture technologies

Among the CO_2 capture methods for medium-scale combustion installations are post-combustion, pre-combustion and oxy-fuel conversion technologies. The capture processes are further classified according to the separation technology used – liquid phase absorption, solid absorption, membranes and cryogenic absorption (see Table II).

Table II Overview of processes for power generation with CO_2 capture

Separation technology	**Capture method**		
	Post-combustion decarbonisation	Pre-combustion decarbonisation	Oxy-fuel conversion
	(O_2/N_2-separation)	(CO_2/H_2-separation)	(O_2/N_2-separation)
Liquid phase absorption	• Mono Ethanol Amine (MEA) absorber	• Selexol CO_2 absorber	
Solid sorption	• Flue gas CO_2 adsorption • Pressure Swing Absoprtion (PSA) or • Temperature Swing Adsorption (TSA)	• Sorption enhanced reforming • Sorption enhanced shift • In situ CO_2 separation • PSA for CO_2 separation	• Chemical Looping Combustion (CLC)
Membranes	• Membrane assisted absorption	• Membrane reformer • Shift membrane reactor	• OCM combustor (AZEP) • SOFC (GT) with afterburner • Boiler with integrated OCM • Membrane oxygen production
Cryogenic			• Oxyfuel conversion with CO_2 re-cycle • Oxy fuel boiler • Matiant cycle • Water cycle

5.1. Furnaces and boilers

For coal-fired furnaces and boilers oxyfuel combustion with cryogenic air separation is a suitable capture option. For natural gas and oil fired furnaces and boilers, post-combustion MEA, PSA or TSA seems to be the more appropriate technology. Pre-combustion and oxyfuel would require relatively high oxygen demand for the capture of one tonne of CO_2, because oil and natural gas contain relatively high ratios of the element hydrogen. This drawback might be partly circumvented by using an Oxygen Conducting Membrane (OCM) to supply the oxygen.

5.2. Reciprocating engines

Reciprocating engines can be equipped with post-combustion technologies without any major technical problems foreseen. It is assumed that sufficiently low concentrations of SO_x and NO_2 can be reached to avoid MEA degradation. Also all pre-combustion technologies presented in Table II are applicable to reciprocating engines. The fuel processor can be a natural gas reformer as well as a coal gasifier. However, the latter can suffer from economy of scale problems, especially concerning the cleaning of the fuel gas. Oxyfuel capture is applicable to reciprocating engines, but is less preferred in case of natural gas-fuelled applications. For solid fuels, gasifiers with pre-combustion or oxyfuel combustion, are the preferred options e.g. the combination of a coal gasifier with a reciprocating engine.

5.3. Gas turbines

In principle, all types of carbon capture technologies can be applied to gas turbines. From all studies published so far it can be concluded that SO_x and NO_x levels are sufficiently low for the application of MEA technology. Gas turbines can also easily be modified for the use of hydrogen as a fuel, which makes gas turbines suitable for pre-combustion technologies. In case of oxyfuel with oxygen from cryogenic distillation or membrane separation, a recycle of cooled flue gas is necessary, to prevent high turbine inlet temperatures. This flue gas has high CO_2 concentrations. The use of CO_2 instead of air as the working fluid for the gas turbine requires drastic modifications of the gas turbine. These modifications are necessary due to the difference in physical and chemical properties between air and CO_2 and require significant massive upfront R&D investments.

5.4. Solid Oxide Fuel Cells (SOFC)

In Solid Oxide Fuel Cells the fuel remains completely separated from the air. Only oxygen passes through the electrolyte, which makes the SOFC in principle an oxyfuel option. The maximum fuel utilisation however is about 85%. After-combustion will be necessary to avoid large energy losses. If some form of oxyfuel combustion is applied here, e.g. by supplying liquid oxygen from a storage facility, or through the use of an OCM, CO_2 can be captured by cooling with water knock-out.

6. Selection

Based on all possible combinations of combustion technologies with capture technologies a short list of six combinations has been composed for in-depth evaluation of potential carbon dioxide emission reductions and its costs. The cases cover a broad range of options, whilst complying with reasonable economic prospects and potential future markets. The six selected combinations of combustion installation and capture technology for the short list are:

- 1.5 MW_e diesel engine with membrane assisted liquid absorption
- 1.5 MW_e gas engine with membrane assisted liquid absorption
- 5 MW_e gas turbine with pre-combustion PSA capture
- 50 MW_{th} oxyfuel coal boiler with oxygen conducting membranes
- 5 MW_{th} oxyfuel natural gas boiler with oxygen conducting membranes
- 500 kW_e natural gas SOFC with oxygen conducting membrane afterburner

7. Results

For all selected options a first estimate has been made of the CO_2 avoidance costs (€/tCO_2) and the potential for application (Mt CO_2). In general, CO_2 capture from smaller combustion installations results in higher specific energy consumption and higher specific costs.

7.1. Cost

The estimated CO_2 avoidance cost including compression range between 27 and 112 € per tonne of CO_2 at typical operational hours for the six selected combinations (marked with red bullets in Figure III). The highest costs are estimated for post-combustion applied to relatively small reciprocating engines (both diesel and gas). Coal-fired boilers offer the cheapest option in terms of cost per tonne CO_2 avoided. Even if fuel prices would double or triple the economic advantage of the coal boiler is maintained. This option is currently not commercially applicable, because the OCM technology is still in an early stage of development. Pre-combustion capture in combination with industrial gas turbines is expected to be promising within the near future. The natural gas-fired SOFC offers an inexpensive option with respect to the costs per tonne of CO_2 avoided, namely 9 € per tonne CO_2 for typical load hours. Currently, there is no SOFC market and it is expected that a substantial market share can develop only within 10 to 20 years. If the SOFC market develops and fuel cell capital expenditures reduce it is very likely that this technology will offer an economically viable method to capture CO_2.

Under certain circumstances CO_2 does not need to be compressed directly after capture but might be collected from different medium and small scale capture plants in pipelines operating at low or even sub-atmospheric pressure. Compression will then take place at nodes in the collection grid. When compression is not included the CO_2 avoidance costs are 9 to 92 € per tonne of CO_2, with the lowest avoidance cost for natural gas-fuelled SOFC.

Table III Costs per tonne of CO_2 avoided at various fuel prices

Fuel price [€/GJ]	2	4	6	8	CO_2 emission [t/h]	Operation Time [h]
Diesel Engine 1.5 MW_e	106	108	110	112	0.9	4000
Gas Engine 1.5 MW_e	109	112	114	117	0.8	4000
Gas turbine 5 MW_e	42	47	53	58	3.4	6000
Coal-fired boiler @18bar, 50 MW_{th}	25	27	29	32	20.3	8000
NG boiler @1bar, 5 MW_{th}	107	108	110	111	1.1	2000
Natural Gas SOFC, 500 kW_e	33	34	36	37	0.2	6000

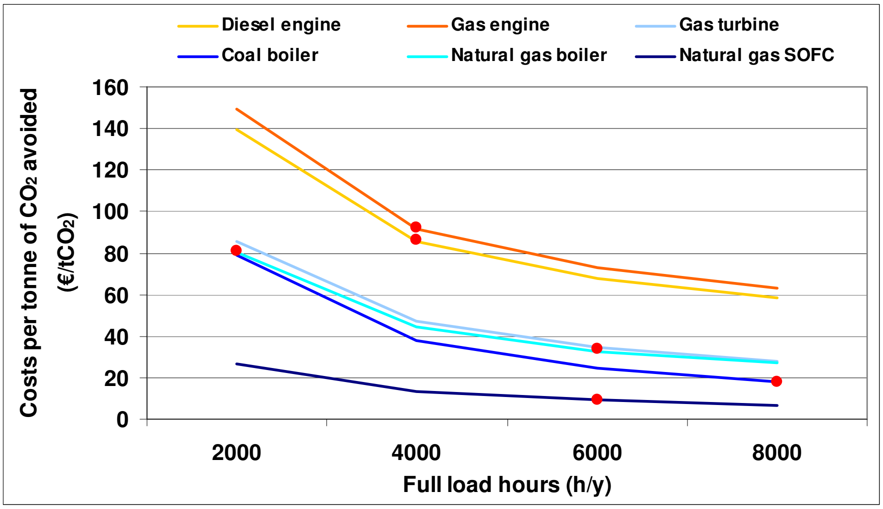

Figure III Costs per tonne of CO_2 avoided with compression (fuel price is set to 4 €/GJ). Avoidance costs for typical operation times of the technology are marked with a red bullet

7.2. Potential for application

For all cases introduced we estimated the potential for application in terms of CO_2 emissions in Mt per year. Based on global market statistics of reciprocating engines sold in 2004 the total emissions of CO_2 for the 1-20 MW_e capacity class are estimated at 600 – 700 Mt per year. For gas turbines in the capacity range of 1 to 60 MW_e, the global CO_2 emissions are estimated at 350 – 400 Mt per year.

Estimation of global CO_2 emissions (excluding China) from medium scale coal-fired boilers (with capacities below 75 MW_{th}) is based on 2002 US data from [3]. Carbon dioxide emissions from US industrial and commercial medium scale coal boilers have been calculated at 80 Mt, which is only 1.5% of the total US energy related CO_2. When we assume the US situation as typical for the rest of the world (excluding China) global CO_2 emissions from medium scale coal fired boilers amount to 300 Mt. A rough estimate of global CO_2 emissions from medium scale coal fired boilers including China is about 1500 Mt. For China, it is estimated that 480,000 coal-fired boilers in the industrial and residential sector consume about 12 EJ annually and emit about 1200 Mt CO_2.

Summed, approximately between 10 and 15% of the worldwide energy related CO_2 emissions can be attributed to medium-size installations. A subdivision of emission and shares to the various distinguished types of combustion installations is presented in Figure IV.

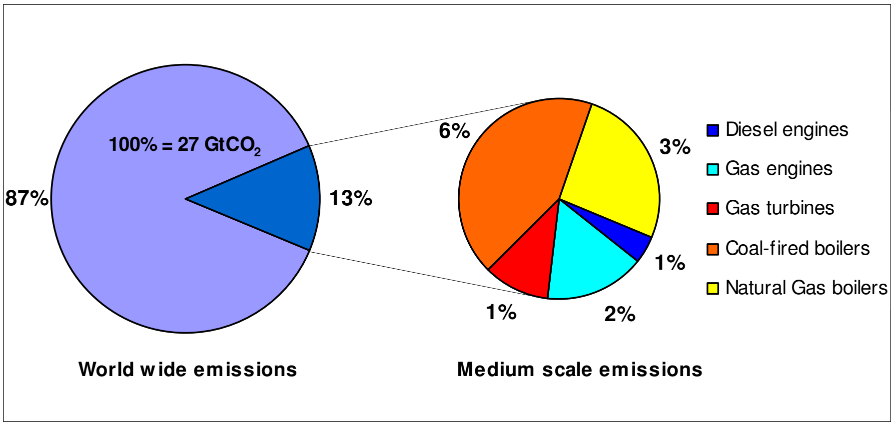

Figure IV Overview of CO_2 emission volumes of medium scale combustion installations

8. Discussion and conclusion

The main focus of capture of carbon dioxide has been on large combustion plants, notably fossil fuel power plants. However, to achieve reductions in CO_2 emissions that are expected to be necessary, substantial reductions in emissions from medium scale sources may be required. This study shows that a wide range of capture options is in principle applicable for medium scale combustion installations. Although not commercially available at the moment specific combinations of prime movers with capture equipment have good future prospects. For coal-fired boilers with integrated capture using oxygen conducting membranes for example CO_2 avoidance cost of between 25 and 32 €/tCO_2 are calculated. The proposed technology, however, still needs considerable development and full-scale application can not be expected within the next 10 to 15 years.

Comparable systems for natural gas fired boilers do not look favourable. This is mainly due to the higher hydrogen content of the natural gas compared to coal. Typical capture costs are estimated at above 100 €/tCO_2.

Solid oxide fuel cells offer also an attractive low-costs emission reduction. However, it is not expected that these SOFC will obtain a substantial market share within the next 20 years.

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