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Full chain analysis and comparison of gas-fired power plants with CO_2 capture and storage with clean coal alternatives

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Abstract

This paper presents the new models developed for the natural gas fuelled power generation chain, involving various natural gas production methods, gas processing routes, gas transport options, and alternative gas based power generation with/without CO_2 capture. The comprehensive and quantitative Life Cycle Inventory (LCI) database developed models inputs/outputs of processes at high level of detail, allowing to account for technical and geographic differences in the power generation value chain scenarios analysed. With the advantage of LCI models developed at unit process level, this work successfully identified the key operational parameters for alternative gas-fuelled power plants and the key component processes that emit the majority of GHGs across the gas supply chains.

Keywords: Life cycle assessment, natural gas, LNG, power generation, CO_2 capture and storage

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1. Introduction

According to IEA [1] the share of fossil fuels in global primary energy consumption is predicted to fall slightly from 81% in 2010 to 75% in 2035; natural gas is the only fossil fuel to increase its share in the global mix over the period to 2035. The growth of energy demand has the potential to cause a significant increase in greenhouse gas (GHGs) emissions. The development of renewables, clean fossil fuel technology with carbon capture and storage (CCS), and nuclear energy is expected to make a low-carbon and oil-independent power generation mix a reality [1, 2]. However, the new power generation technologies involve new processes, which may cause GHGs emissions or other environmental burdens

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either from on-site operations or upstream processes involved [3-5]. Therefore, it is imperative to conduct a comprehensive environmental assessment of alternative CCS options in power generation, which is capable of tracking GHG releases throughout all stages of power generation life cycle and provide accurate information for decision makers.

The life cycle GHGs emissions of various gas fuelled power generation plant configurations with alternative CO_2 capture, transport, and storage scenarios have been investigated by few previous Life Cycle Assessment (LCA) studies [6-11]. These studies indicate that the average life-cycle GHGs emissions of gas fired power plants with alternative CCS are 133.49 kg CO_2-e per MWh electricity generated and conventional natural gas combined cycle (NGCC) plants with average life-cycle GHGs emissions of 413.96 kg CO_2-e per MWh. This indicates that CCS can reduce 68% of life-cycle GHGs emissions. However, all these studies are based on a low resolution analysis (plant level analysis or gate-to-gate data from generic databases or specific case studies), and they report wide ranging results for life cycle GHGs emissions from 91.90 to 177.84 kg CO_2-e per MWh. Furthermore, previous studies also show that gas production and supply chains account for more than 50 % of life-cycle GHGs emissions in most cases, ranging from 37.51 to 120.30 kg CO_2-e per MWh. This implies that it is necessary to investigate gas production and supply chains in detail when analysing life-cycle GHGs emissions of gas fuelled power plants with alternative CCS. Two previous studies analysed the natural gas domestically extracted from the US and natural gas supplied from overseas to the US [7, 9], and provided detailed GHGs emissions from gas production, gas processing and gas transportations for the US cases only.

This paper firstly presents the newly developed models for the natural gas based power generation chains, including conventional and unconventional gas production methods, gas processing routes, gas transport options, and alternative gas fuelled power generation systems with or without CO_2 capture and storage. The comprehensive and quantitative Life Cycle Inventory (LCI) database developed models inputs and outputs of processes at high level of detail, allowing to account for technical and geographic differences in the power generation value chain. Secondly, the models developed are applied to various gas supply scenarios and a full chain analysis covering the gas supply chain and alternative power generation systems with and without CCS are presented. Finally, the life cycle GHG emissions performance of gas based power plants are compared with the *clean coal* technology alternatives considering realistic fuel supply chain and power generation scenarios from around the world.

2. LCA model scope and boundaries

The boundaries of the LCA system developed are presented in Fig. 1, which illustrates all subsystems that are modeled individually.

The functional unit selected for the value chain is 1 MWh of electricity generated. The comparison between different conventional and unconventional natural gas production alternatives are presented using kg of natural gas produced as the reference unit. The subsystems shown in Fig. 1 were further broken down or modularised so they can be modelled accurately. Through modularisation, the LCI models quantify flows of materials, natural resources, energy, intermediate products or emissions at component or unit process level. This approach allows to account for the technical, spatial and temporal differences that exist between different industrial sites and operations by modifying the parameters of the component unit processes as necessary. Furthermore, modularisation allows plant operators and designers to model and compare different technical and engineering scenarios from a life cycle perspective, eliminating the limitations introduced by the linear input/output coefficients used by conventional LCI models. The following sections present four comparative analyses that illustrate the depth, flexibility and accuracy of the LCI models developed.

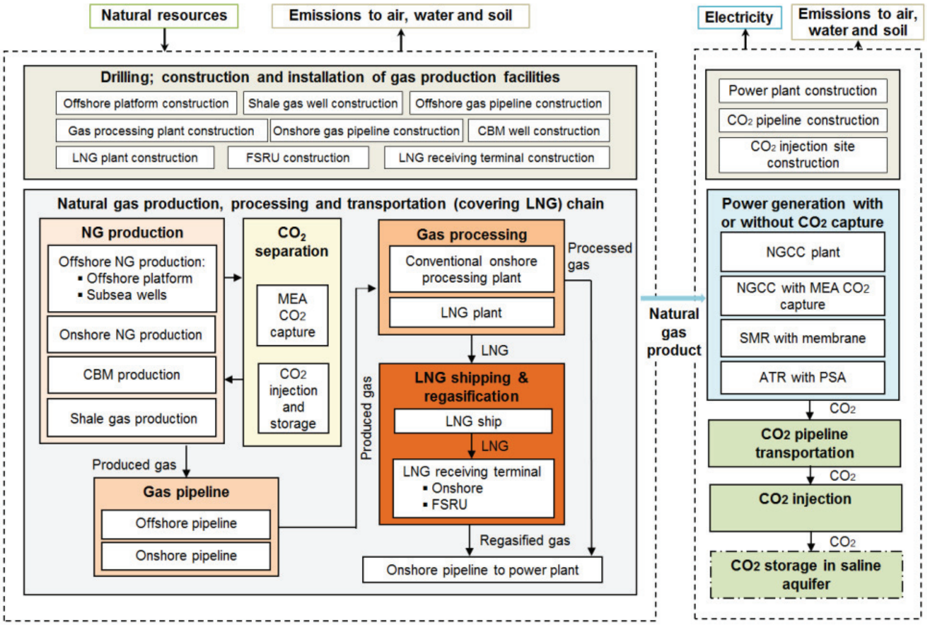

Fig. 1. Generalised natural gas based power generation routes with CCS LCA system and boundaries.

3. Comparative assessment of different natural gas supply chain options

3.1. GHGs emissions from different gas production operations

The models developed were applied to different gas reservoirs and alternative gas production operations as described in Table 1. Given the operational parameters shown in Table 1, the GHG emission results in Fig. 2 illustrate that the gas production method used, which is specific to the type of gas reservoir in question, is the main factor which determines the amount of GHG emitted. For instance, GHG emissions from onshore gas production, CBM production and shale gas production are significantly higher than offshore gas production processes, which have the lowest GHG emissions with 0.018 kg CO_2-e per kg natural gas produced. The majority of the GHG emissions from offshore gas production are from drilling and well completion. The GHG emissions from shale gas (0.119 kg CO_2-e per kg natural gas produced) are slightly higher than that of onshore gas production and CBM production. In shale gas production, the use of compressors to increase the pressure of natural gas for pipeline transport creates significantly high rates of GHG emissions. Shale gas well completion activities include hydraulic fracturing and a flowback period to clean the well from flowback water (which contains methane) and any excess sand (fracturing proppant). In this study, it is assumed that the flowback water is routed through a separation equipment to separate water, gas, and sand. The separated gas is then routed to the flare stack.

3.2. Comparison of different gas supply chains

The models developed were also applied to various gas supply chains, with natural gas sourced and transported to the UK from geographically different reservoirs. Two example supply chains and the data used in modelling these options are presented in Tables 2 and 3. As some gas reservoirs produce natural

Table 1. Assumptions for different gas reservoirs and alternative natural gas production operations.

On shore	Natural gas production rate	800	MMscf/day
	Reservoir life span	30	years
	Production rate per well	0.384	MMscf/day
	Onshore well number	2,083	
Offshore	Natural gas platform production rate	200	MMscf/day
	Reservoir life span	20	years
	Platform drilling	no	
	Number of wells in whole life span	12	wells
	CO_2 content in raw gas	3.50%	in volume
	20 MW gas driven compression is installed 6 years after the first gas production to maintain peak production		
Shale gas	Field production rate	800	MMscf/day
	Single vertical well production rate	11	MMscf/day
	Well numbers in total	73	-
	Reservoir life span	30	years
CBM	Coal bed methane gas production rate	1,360	MMscf/day
	CBM reservoir life span	30	years
	CBM per well production rate	0.8	MMscf/day
	CBM well number	1,700	wells
	Life cycle CBM well number	6,000	wells

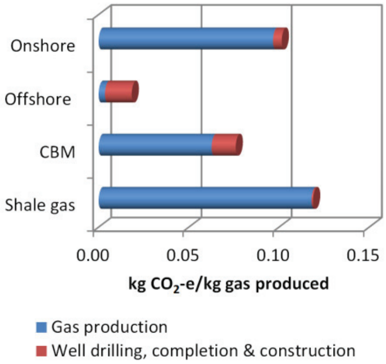

Fig. 2. GHG emissions from alternative gas production methods.

Table 2 Parameterisation of the LCA model for North Sea offshore natural gas production and supply to the UK.

North Sea offshore platform natural gas production	Production rate	200	MMscf/day
	Reservoir life span	20	years
	Platform drilling	-	no of wells
	CO_2 content in raw gas	Low case: 3.5	% volume
		High case: 9.0	
	CO_2 capture rate	Low case: 0 (no capture)	% volume
		High case: 74	
	Final CO_2 content in produced gas	Low case:3.5	% volume
		High case: 2.5	
	CO_2 storage in saline aquifer	Low case: no storage	
		High case: no storage	
		100	%
Pipeline to onshore processing plant	Distance	125	Km
Processing plant	Plant throughput	200	MMscf/day
	CO_2 content in produced gas	2.5	% volume
Pipeline to distribution system	Distance	5	km

Table 3 Parameterisation of the LCA model for Middle East offshore natural gas production and LNG transport to the UK.

Middle East offshore platform natural gas production	Production rate	1,730	MMscf/day
	Reservoir life span	20	years
	Platform drilling duration	3.5	years
	Number of wells predrilled	10	wells
	CO_2 content in raw gas	0.50	% volume
Pipeline to NG processing plant	Distance	80	Km
Onshore NG processing plant	Plant throughput	1,730	MMscf/day
Onshore LNG plant	Plant capacity	0.0	MTPA
	Number of trains	2	
LNG shipping	Distance	11,300	Km
	Velocity	36.12	Km/hour
	Carrier volume	266,000	m^3
UK Onshore LNG receiving terminal	Capacity	1,730	MMscf/day

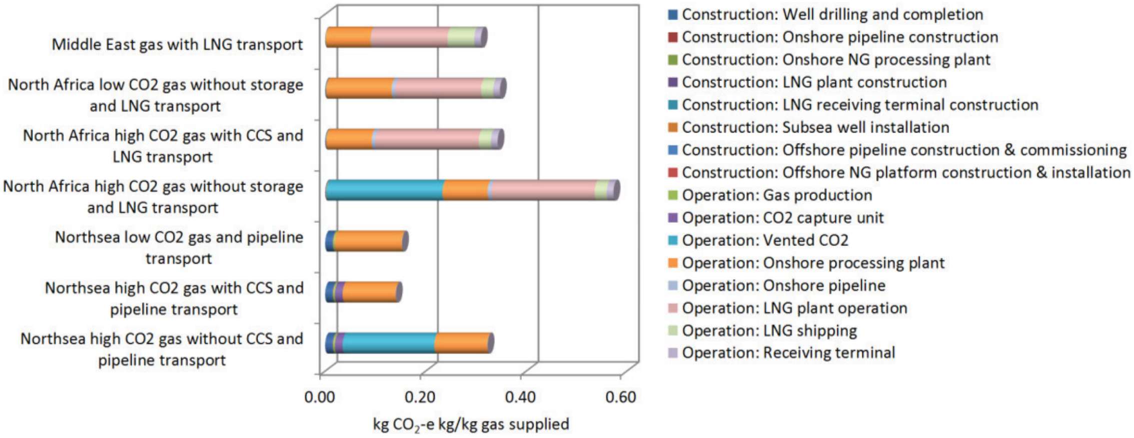

Fig. 3. Comparison of various gas based supply chains.

gas with high CO_2 content (such as gas production from the Sleipner field in the North sea), the gas supply scenarios included both low CO_2 concentration produced gas and high CO_2 concentration produced gas with CO_2 capture and saline aquifer storage, or venting options.

Fig 3 presents the life cycle GHG emissions per kg gas produced and delivered to the UK customer from geographically different sources. The life cycle GHG emissions for different supply chains studied vary significantly from 0.1406 to 0.5734 kg CO_2-e/kg natural gas supplied, with emissions due mainly to the CO_2 capture unit (if implemented), the gas processing plant, the LNG plant and/or LNG shipping.

Unless geologically stored, the original CO_2 concentration in the produced raw gas affects the life cycle GHG emissions to a great extent, since the CO_2 in the natural gas will eventually be released to atmosphere from the CO_2 capture plant (if implemented), the processing plant or the LNG plant. This is illustrated by the case of North African gas with high CO_2 content (12 % volume in the produced raw gas), platform CO_2 capture and venting followed by LNG transport to the UK (Fig.3). As the high CO_2 content North Sea natural gas example in Fig. 3 illustrates, the platform based CO_2 capture and saline aquifer storage case yielded the lowest GHG emissions in all the scenarios studied. After CCS, the CO_2 content of the produced gas was reduced to 2.5%, demonstrating the vital role of CO_2 storage in minimising the volume of CO_2 vented to the atmosphere. The distance between the gas production site and the customer also plays an important role, as LNG production, LNG shipping and LNG receiving processes also contribute to the GHG emissions. It was found that the GHG emissions from the natural gas processing activities are higher than the emissions generated from natural gas production processes in all cases. It is also shown (Fig. 3) that the LNG related processes introduce significant GHG emissions. In summary, the CO_2 content of the raw natural gas and the distance to the customer are important factors which determine the life cycle GHG emissions per kg natural gas supplied.

3.3. Full chain analysis of UK power generation with LNG sourced from the Middle East

A Middle East based LNG supply chain was integrated with different natural gas power generation, CO_2 capture and saline aquifer storage options using the LCA models developed. The operational parameters used for the scenarios considered are illustrated in Tables 4 and 5 and the results of the analysis are presented in Fig. 4.

Table 4. Operational parameters for gas fired power plants with and without alternative CO_2 capture routes.

CCGT power plant	Power plant capacity (MW)	500
	ψ is the atomic ratio of H/C	3.886
	fuel to air equivalence ratio ϕ	0.85
	Δp_c / p_c is the pressure drop rate in the combustor (%)	3.0
	P_c/P_{ref} is the combustor inlet pressure/reference pressure	15.8
	T_c/T_{ref} is the combustor inlet temperature / reference temperature	1.8
	p_c is the combustor inlet pressure (MPa)	1.6
	X is steam/fuel ratio	0
CCGT with MEA CO_2 capture power plant	Power plant capacity (MW)	500
	ψ is the atomic ratio of H/C	3.886
	fuel to air equivalence ratio ϕ	0.85
	p_c is the combustor inlet pressure (MPa)	1.6
	Flue gas bypass rate	0
	Gas turbine plant thermal efficiency (%)	55
ATR with PSA power plant	Power plant capacity (MW)	500
	NG Hydrogen/Carbon ratio(HC)	3.886
	Steam/Carbon ratio(SC)	2
	O_2/Carbon ratio(OC)	0.5
	H_2 recovery ratio(HR)	0.95
	H_2 to electricity efficiency (HE)	60%
Steam Methane Reforming with H_2 Membrane power plant	Power plant capacity (MW)	500
	Natural gas hydrogen to carbon H/C ratio	3.8862
	SMR + Membrane temperature (K)	1,000
	SMR + Membrane pressure (bar)	20
	Steam/carbon ratio	3
	H_2 to electricity efficiency (%)	60

Table 5. Operational parameters considered for the CO_2 transport, injection and storage processes.

CO_2 transport	
Mass flow rate of CO_2 product in pipeline (kg/s)	44.84
Length of the pipeline (km)	150
CO_2 velocity in pipeline (m/s)	2
CO_2 inlet pressures (MPa)	15
CO_2 outlet pressures (MPa)	15
CO_2 temperature (°C)	425

CO_2 injection and storage	
CO_2 injection rate (t/hr)	161.44
Depth of reservoir (m)	1239
Reservoir horizontal permeability (mD)	22
Reservoir vertical permeability (mD)	22
Reservoir pressure (MPa)	8.4
Reservoir Thickness (m)	171
Surface temperature (F)	68
Temperature increase in CO_2 heater (F)	5

In this example, natural gas is produced from an offshore platform and transported by an undersea pipeline to the onshore processing plant and is liquefied to LNG. The LNG is shipped to UK South Hook receiving terminal where it is re-gasified and transported to the power plant by pipeline. Four different options of power plant configurations were considered. These are conventional NGCC plant; NGCC plant with post-combustion CO_2 capture; steam reforming plant with membrane CO_2 capture; and an auto-thermal reforming (ATR) plant with pressure swing adsorption CO_2 capture. The captured CO_2 is transported by pipeline to a saline aquifer storage site, where CO_2 is injected into the reservoir.

Fig. 4 demonstrates that natural gas power plants with CO_2 capture and storage can reduce life cycle GHG emissions by 74 -85 %. In the case of gas power plants with CO_2 capture, the majority life cycle GHG emissions are from the gas processing plant, the LNG plant, LNG shipping and the power plant. Other processes or the plant construction activities account for insignificant GHG emissions in the life-cycle perspective.

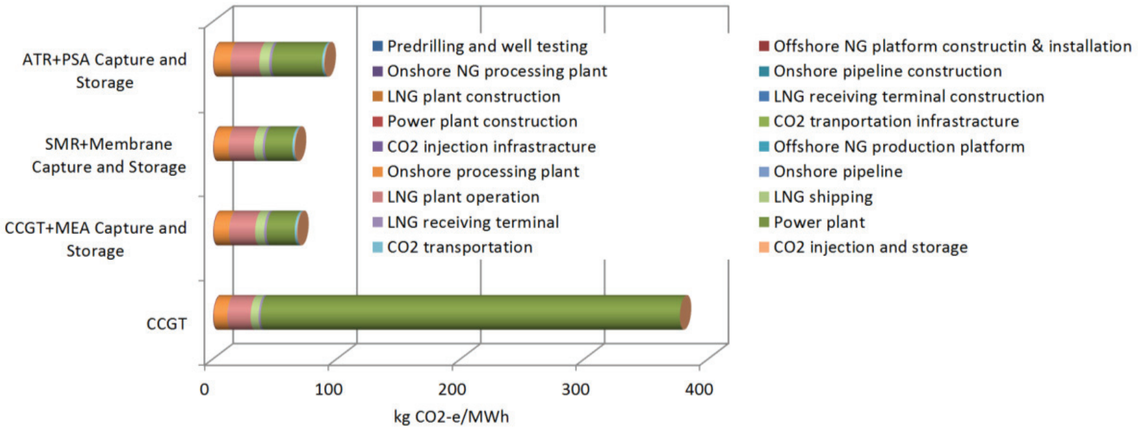

Fig 4. Life cycle GHG emissions for alternative natural gas fired power plant configurations with CO_2 capture, injection and storage using LNG supplied from the Middle East.

Fig. 5 compares the life cycle of GHG emissions for alternative coal and natural gas fired power plant configurations with coal and natural gas supplied to customers from various sources worldwide. This

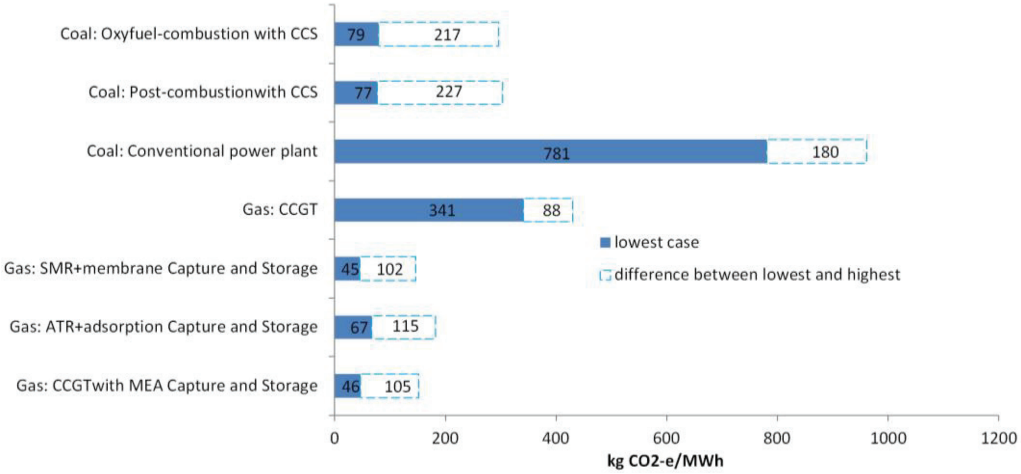

Fig 5. Life cycle of GHG emissions for alternative coal and natural gas fired power plant configurations with coal and natural gas supplied to customers from various sources worldwide.

study has shown that the life cycle GHG emissions from coal based CCS chains vary more significantly than the emissions from gas based CCS chains. This is due to different rates of uncontrolled methane emissions from different rank coal deposits when the coal is being mined. For the gas chain cases illustrated, the CO_2 content of the produced gas ranged from 0.5% to 35%. Although this is a very wide range, it nevertheless resulted in a relatively lower GHG emission range compared to that obtained for the coal chains. As shown in Fig. 5, the life cycle GHG emissions can be as low as 43 kg CO_2-e/MWh for gas based chains; while the life cycle GHG emissions for coal based chains with CCS can be as low as 77 kg CO_2-e/MWh.

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