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Review article

Life Cycle Assessment of the natural gas supply chain and power generation options with CO_2 capture and storage: Assessment of Qatar natural gas production, LNG transport and power generation in the UK

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ABSTRACT

Fossil fuel-based power generation technologies with and without CO_2 capture offer a number of alternatives, which involve different fuel production and supply, power generation and capture routes with varied energy consumption rates and subsequent environmental impacts. The holistic perspective offered by Life Cycle Assessment (LCA) can help decision makers to quantify the trade-offs inherent in any change to the fuel supply and power production systems and ensure that a reduction in greenhouse gas (GHG) emissions does not result in increases in other environmental impacts. Beside energy and non-energy related GHG releases, LCA also tracks various other environmental emissions, such as solid wastes, toxic substances and common air pollutants, as well as the consumption of resources, such as water, minerals and land use. In this respect, the dynamic LCA model developed at Imperial College incorporates fossil fuel production, transportation, power generation, CO_2 capture, CO_2 conditioning, pipeline transportation and CO_2 injection and storage, and quantifies the environmental impacts at the highest level of detail, allowing for the assessment of technical and geographical differences between the alternative technologies considered. The life cycle inventory (LCI) databases that were developed, model the inputs and outputs of the processes at component or unit process level, rather than "gate-to-gate" level, and therefore generate reliable LCI data in a consistent and transparent manner, with a clearly arranged and flexible structure for long-term strategic energy system planning and decision-making.

The presentation discussed the principles of the LCA models developed and the newly extended models for the natural gas-fired power generation, with alternative CO_2 capture systems. Additionally, the natural gas supply chain LCA models, including offshore platform gas production, gas pipeline transportation, gas processing, liquefied natural gas (LNG) processes, LNG shipping and LNG receiving terminal developed are used to estimate the life cycle GHG emissions for an idealised case study of natural gas production in Qatar, LNG transportation to a UK natural gas terminal and use in a power plant. The scenario considers a conventional and three alternative CO_2 capture systems, transport and injection of the CO_2 offshore in the Irish Sea.

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INTRODUCTION

According to the recent World Energy Outlook report, the world energy demand will grow by 35% by 2035, assuming that recent government policy commitments will be implemented in a cautious manner [1]. Although the share of fossil fuels in the global primary energy consumption is expected 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 in the period up to 2035 [1]. Arguably, the growth of energy demand has the potential to cause a significant increase in greenhouse gas (GHG) emissions associated with climate change. It is widely accepted that, in terms of energy, the coming decades will be challenging for all nations in terms of developing energy-efficient, low carbon, energy-secure and competitive economy. Especially, the electricity industry in the industrialised world holds an important and pro-active role in providing solutions to both secure economic growth and prosperity, and to reduce greenhouse gas emissions in economically feasible ways [2]. Together, with the development of renewables and nuclear energy, clean fossil fuel technology with carbon capture and storage is an essential part of future energy portfolios in order to make a low-carbon power generation mix a reality [1,2].

The power generation technologies available today, and under development, introduce new processes which may release GHG emissions or other environmental burdens. These may either be directly, from the operations, or indirectly, through the upstream processes required in their implementation. For example, carbon dioxide capture processes can result in both direct and indirect GHG emissions and other environmental impacts [4–6]. This is also the case for renewable technologies; for example, considerable GHG emissions occur from the consumption of energy in manufacturing monocrystalline silicon for photovoltaic solar cells [3].

In order to make credible comparisons between alternative power generation options, it is imperative to conduct a comprehensive environmental assessment of the processes involved in power generation, tracking GHG releases throughout all stages of power generation life cycle (or value chain). It is then possible to provide accurate information for decision makers and ensure that a new power generation technology option would not result in upstream or downstream changes that will increase the overall release of GHGs. It is also important to ensure that the power generation systems considered do not aggravate other environmental concerns, such as solid and hazardous waste generation and the release of toxic substances which impact upon human health and ecological systems. This requires a holistic and system-wide environmental assessment.

Life cycle assessment (LCA) meets this criteria as it not only tracks energy and non-energy related GHG releases but also tracks various other environmental releases (e.g. solid wastes, toxic substances and common air pollutants) as well as the consumption of other resources (e.g. water, minerals and land use). This holistic perspective offered by LCA helps decision makers to quantify the trade-offs inherent in any change to the power production systems and helps to ensure that a reduction in GHG emissions does not result in increases in other environmental impacts. The other strength of LCA is that the International Organization for Standardization (ISO) has developed the ISO 14040 series of LCA standards, which provide guidance on setting appropriate system boundaries, reliable data collection, evaluating environmental impacts, interpreting results, and reporting in a transparent manner. This offers an excellent starting point for the development of measurement protocols for GHGs and other environmental impacts [7]. Considering the three flexible mechanisms developed to help emitters in developed countries to meet their GHG emission targets (Emissions Trading, Joint Implementation and the Clean Development Mechanism), LCA offers the means to include new power generation projects into the CDM framework and help the participants of flexible mechanisms to assess their proposed projects and verify their emission reductions from a value chain perspective using a credible and internationally accepted tool.

The life cycle performance of various power generation plant configurations without/with alternative CO_2 capture systems, transport and injection scenarios have been investigated by previous LCA studies [8–16]. However, since these studies are based on a low resolution analysis (plant level analysis or gate-to-gate data from generic databases), these studies report wide ranging results for climate change impacts and other impact categories such as abiotic resource depletion, acidification, human toxicity, etc. which cannot be adequately characterised in coarse resolution LCA studies. The use of gate-to-gate data implies that the electricity generation systems have been largely simplified to a single black box with constants and linear coefficients used to assign inputs and outputs, covering a broad range of technological and geographical differences, in which the actual variability of process parameters and operating conditions are implicitly neglected. In addition, plant level analysis limits the capacity of such studies to quantify the trade-offs inherent in any change to the power production systems and restrict the ability to identify design options that eliminate highly polluting emissions.

In this respect, the dynamic LCA model developed at Imperial College incorporates fossil fuel production, transportation, power generation, CO_2 capture, CO_2 conditioning, pipeline transportation and CO_2 injection and storage, and quantifies the environmental impacts at the highest level of detail. This allows for the assessment of technical and geographical differences between the alternative power generation, CO_2 capture, transport and storage technologies considered. Earlier publications by the authors [4,6] present the post-combustion life cycle model developed and a comparative assessment between the post-combustion and oxy-fuel capture options modelled for coal fired plants. This paper presents the principles of the LCA models developed and the newly extended models for the natural gas-fired power generation with alternative CO_2 capture system. Additionally, the natural gas supply chain LCA models, including offshore platform gas production, gas pipeline transportation, gas processing, liquefied natural gas (LNG) processes, LNG shipping and LNG receiving terminal developed are used to estimate the life cycle GHG emissions for an idealised case study of natural gas production in Qatar, LNG transportation to a UK natural gas terminal and use in a power plant. The scenario considers a conventional and three alternative CO_2 capture systems, transport and injection of the CO_2 off-shore in the Irish Sea.

LIFE CYCLE ASSESSMENT METHODOLOGY AND ITS APPLICATION IN POWER GENERATION WITH CO_2 CAPTURE AND STORAGE

Life Cycle Assessment methodology

Life Cycle Assessment is a compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its entire life cycle, ranging from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal [17]. In order to deal with the complexity of LCA, the International Standards Organisation (ISO) established a methodological framework for performing LCA studies, which comprises four phases, including the goal and scope definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation, as shown in Fig. 1.

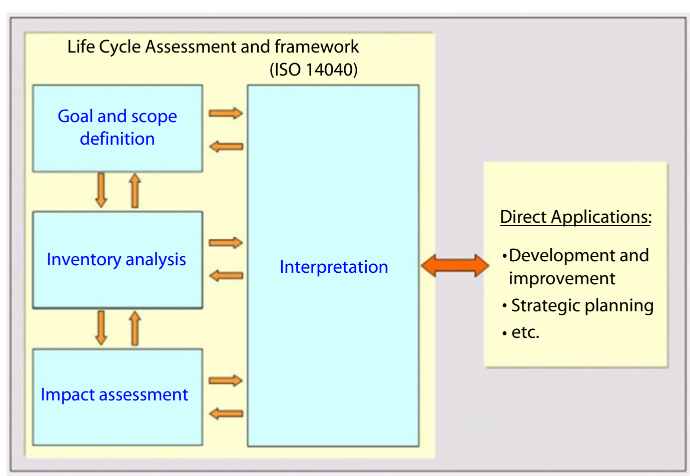

Figure 1. Methodological framework of LCA: phases of an LCA (After: [17]).

The goal and scope definition states the aim of an intended LCA study, the system boundary, the functional unit, competing systems considered, and the breadth and depth of (or level of detail) the LCA study in relation to this aim. Life Cycle Inventory Analysis is the phase where input/output relationships are quantified and an inventory of input/output data for all component processes involved in the life cycle of the system(s) under study is prepared. The input/output flows for a unit process to be quantified include economic and environmental flows as shown in Fig. 2.

The objective of Life Cycle Impact Assessment is to understand and evaluate the magnitude and significance of the potential environmental impacts of a product system [17]. In this phase, impact

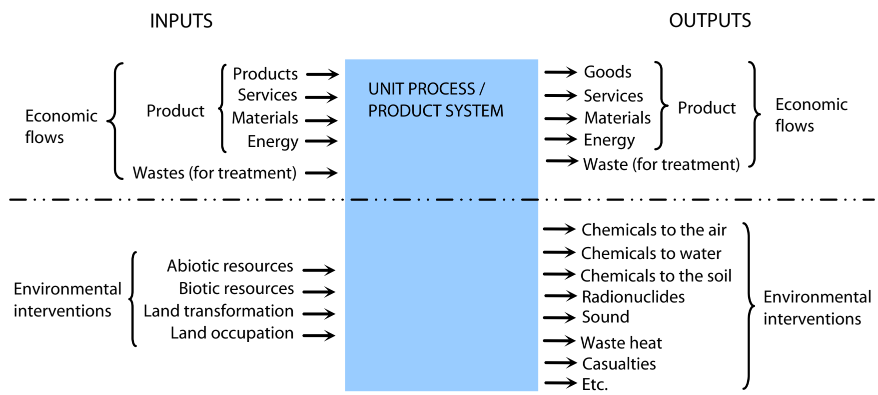

Figure 2. Environmental interventions and economic flows (After [18]).

categories (e.g. global warming, acidification, and human toxicity), category indicators, and characterisation factors are defined first. Then the LCI results are assigned to categories and converted into category indicators via characterisation factors. Characterisation factors can convert environmental flows into environmental impacts.

There are two characterisation approaches: midpoint method (e.g. [18]) and endpoint method (e.g. [19]). The midpoint approach stops quantitative modelling at any point before the end of cause–effect chain (including fate, exposure, effect and damage) and uses midpoint indicators (such as global warming potential, acidification etc.) to reflect the relative environmental importance of an emission or extraction. The endpoint approach models the cause–effect chain up to the final environmental damages, the damages to human health, ecosystems and resources. Interpretation is the phase in which the findings of either the inventory analysis or the impact assessment, or both, are analysed in relation to the defined goal and scope in order to deliver conclusions, explain limitations and provide recommendations [17].

LCA application in power generation with CO_2 capture and storage

One of the objectives of the dynamic LCA model developed at Imperial College was to build a comprehensive LCI database for the analysis of power generation with alternative CO_2 capture and storage options and of fossil fuel supply chain, in a consistent and transparent manner. The underlying principle applied in developing this methodology can be summarised as follows:

1. Transparency: to show precisely how life cycle impacts are calculated and the extent to which the inputs/outputs of any unit process have been quantified.
2. Comprehensiveness: to identify all of the inputs/outputs that may give rise to significant environmental impacts.
3. Consistency of methodology: models and assumptions to allow valid comparisons to be made between technological or operational options for a unit process.

The system boundaries of LCA in power generation with CO_2 capture and storage, a generalised outline of which is presented in Fig. 3, covers power generation, alternative CO_2 capture options and upstream processes such as extraction and processing of fossil fuels, raw materials production, as well as CO_2 compression, transport and storage. The functional unit selected for the analysis was 1 MWh of electricity generated.

In this research, the power generation system has been broken down or modularised into subsystems or component unit processes for the natural gas combined cycle (NGCC) power plant with post-combustion CCS system. The component unit processes are connected through flows of intermediate products or emissions as illustrated in Fig. 4. The purpose of modularisation was to make complex systems more easily understood and more accurately modelled. Through modularisation, the LCI models quantify flows of materials, natural resources, energy, intermediate products or emissions at component or unit process level. This approach ensures that the technical, spatial and temporal differences that exist between different industrial sites and operations can be accounted for by modifying the parameters of the component unit processes as necessary.

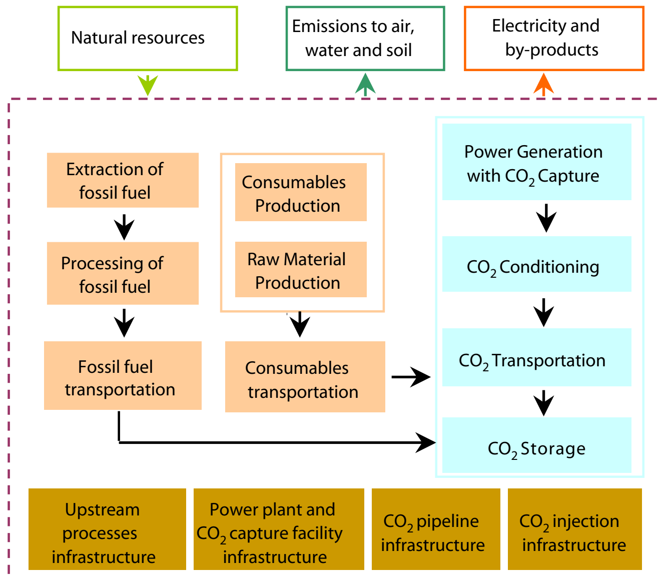

Figure 3. Generalised outline of the power generation with CCS LCA system and its boundaries.

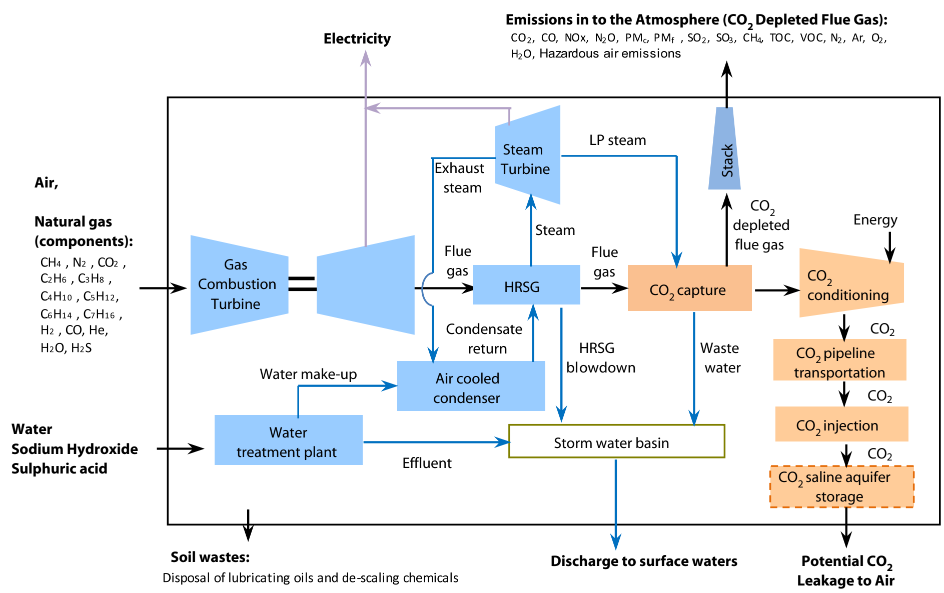

Figure 4. The level of detail involved in the LCA of NGCC with post-combustion CCS system.

Furthermore, modularisation allows plant operators and designers to model and compare different technical and engineering scenarios from a life cycle perspective. Ultimately, modularisation eliminates the limitations introduced by the linear input/output coefficients used by conventional LCI models.

The following paragraphs demonstrate the LCI model developed for a chemical absorption CO_2 capture unit as an example. A typical chemical absorption unit is based on an aqueous CO_2 absorption and CO_2 stripping system, which is comprised of two sections (Fig. 5). In the absorber, CO_2 is chemically absorbed from the inlet gases by contacting it with the countercurrent CO_2-lean solvent, e.g. monoethanolamine (MEA). The treated gas exits the top of the absorber column. The CO_2-rich solvent is passed to the stripper, where, by heating the CO_2-rich solvent solution, the CO_2 is stripped off and the CO_2-lean solvent is regenerated. The regenerated CO_2-lean solvent is then recycled back to the absorber and the CO_2 is passed to compression processes. The system, especially MEA solvent system, also uses chemicals (such as NaOH) for proposes of solvent

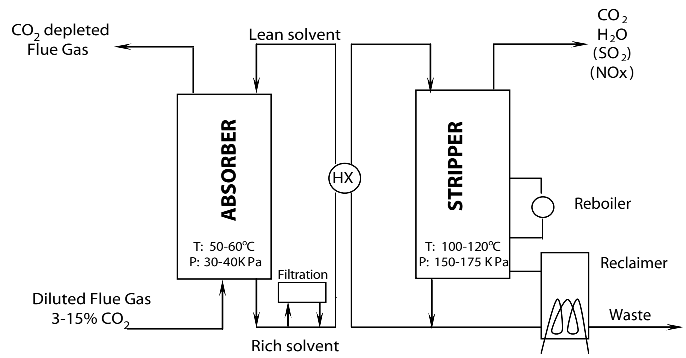

Figure 5. A typical chemical absorption CO_2 capture unit.

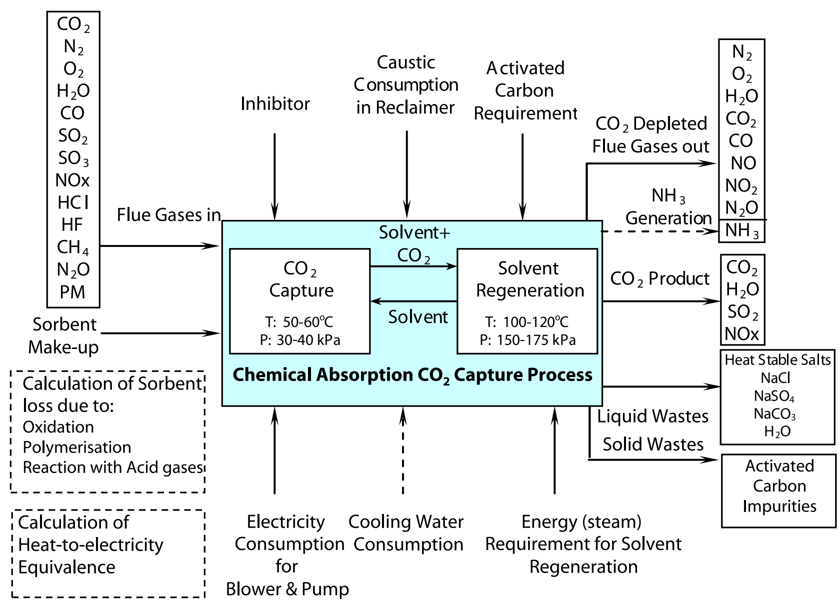

Figure 6. A schematic representation of chemical absorption CO_2 capture processes LCI model developed.

reclamation, solid filtration, and a corrosion inhibitor. Sorbent make-up is also required for the compensation of sorbent loss in the absorption/stripping process.

The schematic of the LCI model developed is shown in Fig. 6, which describes the inputs/outputs to be quantified. The inputs/outputs of chemical absorption CO_2 capture processes are modelled using engineering calculations. In order to characterise the technological differences of different chemical absorption CO_2 capture processes, the LCI model developed accounts for 8 types of solvents. Fig. 7 shows the LCI results of a MEA CO_2 capture system applied to a coal-fired power plant with post-combustion configuration.

CASE STUDY: QATAR NATURAL GAS PRODUCTION, LNG TRANSPORT TO THE UK AND USE IN POWER GENERATION

The LCA models developed at Imperial College have been applied to an idealised case of natural gas production in Qatar, LNG transport to the UK and use in power generation systems with alternative CO_2 capture options and saline aquifer CO_2 storage. The whole value chain is illustrated in Fig. 8.

The gas is produced from an offshore platform at the Qatar North Field. The produced gas is transported by undersea pipeline to Ras Laffan, where the gas is processed and is liquefied to LNG. The LNG is shipped to UK South Hook receiving terminal via Suez by advanced Q-Max and Q-Flex LNG ships. The gas received is regasified at South Hook terminal. The regasified gas is transported to power plant by pipeline. Four types of gas power plant configurations have been investigated in the case study. They are conventional natural gas combined cycle (NGCC) plant, NGCC plant with

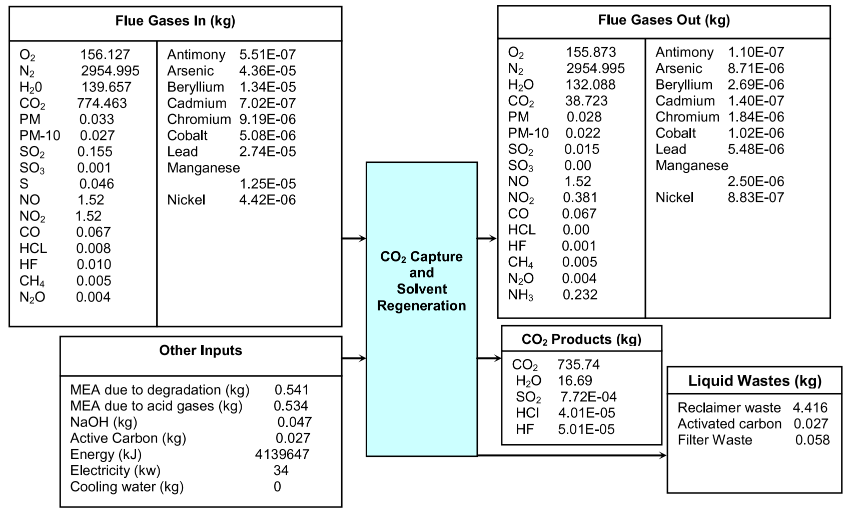

Figure 7. LCI results of a MEA CO_2 capture system (per 1 MWh electricity generated).

Figure 8. The value chain of Qatar natural gas production, LNG transport to the UK, power generation.

post-combustion CO_2 capture, steam reforming plant with membrane CO_2 capture (SMR), and auto-thermal reforming (ATR) plant with pressure swing adsorption (PSA) CO_2 capture. The captured CO_2 is transported by pipeline to saline aquifer storage site, where CO_2 is injected underground.

Tables 1–4 provide the key parameters or operational parameters of the supply chain, of alternative power plant configurations without or with CO_2 capture, CO_2 transportation, and of CO_2 injection to a saline aquifer. The LCA model developed not only accounts for these key parameters but also the operational parameters at unit processes level. The user can change these parameters in order to apply fully and dynamically the LCA models to a specific case study, allowing for the assessment of operational, technical and geographical differences at unit process level.

With respect to the gas supply chain from the Qatar North Field to South Hook in the UK, the majority of GHG emissions come from natural gas processing, LNG processing, LNG shipping and the LNG receiving terminal as demonstrated in Fig. 9. The GHG emissions from the offshore platform and pipeline transportation are not significant. Fig. 9 also indicates that insignificant GHG emissions are due to the construction and installation of the gas production plants, gas processing plant, LNG plant, LNG receiving terminal and the gas pipelines.

With respect to alternative power plant configurations, Fig. 10 shows that the ATR with CO_2 PSA capture has lower plant energy efficiency than SMR with membrane plant and CCGT with MEA

Table 1. Supply chain parameters/operational parameters.

Qatar North Field Platform	**Natural gas platform production rate**	**1,730**	**MMscf/day**
	Natural gas reservoir life span	**20**	**years**
	Platform drilling	**3.5**	**years**
	Number of wells predrilled	**10**	**wells**
Offshore pipeline: from North Field platform to Ras Laffan	Distance	80	km
Onshore NG processing plant at Ras Laffan	Plant throughput	1,730	MMscf/day
Ras Laffan LNG plant	Plant capacity	15.6	MTPA
	Number of trains	2	
	CO_2 content in NG to be processed	0.50	%
LNG shipping	Distance	11,281	km
	Velocity	36.12	km/hour
	Carrier volume	266,000	m^3
Onshore LNG receiving terminal at South Hook, UK	Capacity	1,730	MMscf/day
Onshore pipeline: South Hook to Power plant	Distance	100	km

Table 2. Operational parameters of gas power plant without/with alternative CO_2 capture routes.

CCGT power plant	Power plant capacity (MW)	500
	Atomic ratio of H/C, ψ	3.886
	Fuel to air equivalence ratio	0.85
	Pressure drop rate in the combustor, $\Delta p_c/p_c$ (%)	3
	Combustor inlet pressure/reference pressure, P_c/P_{ref}	15.8
	Combustor inlet temperature/reference temperature, T_c/T_{ref}	1.8
	combustor inlet pressure, p_c (Pa)	1,600,000
	Steam/fuel ratio	0
CCGT with MEA CO_2 capture power plant	Power plant capacity (MW)	500
	Atomic ratio of H/C, ψ	3.886
	Fuel to air equivalence ratio, Φ	0.85
	Combustor inlet pressure, p_c (MPa)	1.6
	Flue gas bypass rate	0
	Gas turbine plant thermal efficiency (%)	55
ATR with PSA power plant	Power plant capacity (MW)	500
	Natural gas hydrogen/carbon ratio, HC	3.886
	Steam/Carbon ratio, SC	2
	O_2/Carbon ratio, OC	0.5
	H_2 recovery ratio, HR (%)	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/carbon ratio H/C	3.8862
	SMR + Membrane temperature (K)	1,075
	SMR + Membrane pressure (bar)	10
	Steam/carbon ratio	3
	H_2 to electricity efficiency (%)	60

Table 3. CO_2 transportation operational parameters.

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 pressure (MPa)	15
CO_2 outlet pressure (MPa)	15
CO_2 temperature (°C)	25

CO_2 capture. This also results in the highest GHG emissions per MW generated, compared to the other power plants with CO_2 capture. ATR with CO_2 PSA capture power plant has low energy efficiency. This is due to the fact that the configuration of ATR with CO_2 PSA capture requires pure O_2 from the Air Separation Unit, which consumes energy. On the other hand, the concentration of H_2 in the offgas exiting from PSA unit is high. The H_2 in the offgas is combusted, rather than being converted to electricity. This also reduces the whole plant energy efficiency.

Table 4. CO_2 injection operational parameters.

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

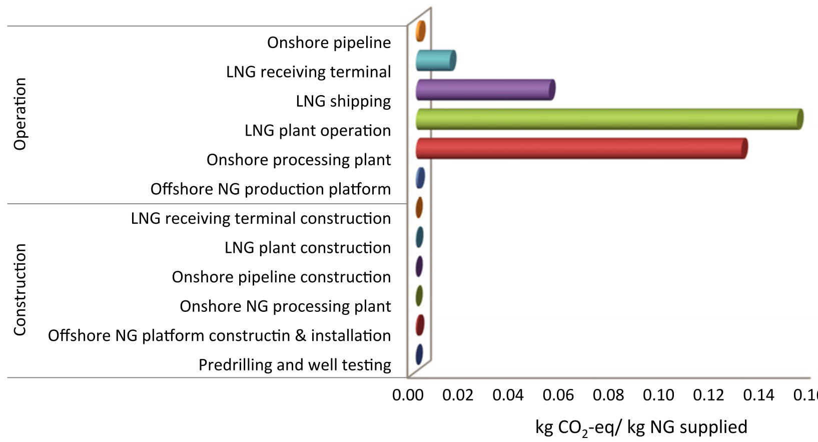

Figure 9. GHG emissions per kg NG supplied from North Field (Qatar) to South Hook (UK).

Compared to conventional CCGT plant, the energy penalties of CO_2 capture for SMR with H_2 membrane plant, CCGT with MEA CO_2 capture plant and ATR with CO_2 PSA capture plant are 3.51%, 6.09% and 11.75% respectively. The energy penalties of CO_2 capture by SMR with H_2 membrane plant and CCGT with MEA CO_2 capture plant are lower than energy penalties of CO_2 capture from coal based plant, which are normally great than 10% [4,6].

Figure 11 shows that gas power plants with CO_2 capture can reduce life cycle GHG emissions by 74%–85%. With respect to gas power plants with CO_2 capture, the majority life cycle GHG emissions are from gas processing plant, LNG plant, LNG shipping and power plant. Our operation processes or construction processes account for insignificant GHG emissions in the life-cycle perspective.

CONCLUSIONS

This paper described the development of a dynamic LCA framework for the "cradle-to-grave" assessment of alternative CCS technologies in fossil fuel power generation. The functionality of the LCA model developed is demonstrated using natural gas produced in Qatar shipped to the UK by LNG and used in power plant with alternative configurations and CO_2 capture routes. The LCI models developed quantify flows of materials, natural resources, energy, intermediate products and emissions at component unit process level, based on fundamental physical/chemical principles or empirical relationships which, to a greater extent, account for the technological, spatial and temporal characteristics of the power generation systems considered. This approach not only addresses the limitations of conventional LCI models that use linear input/output coefficients, but also facilitates the screening of technological options in order to improve the life cycle environmental performance of a power generation system with CCS.

The development of the LCI models at component unit process level and the use of fundamental physical/chemical principles in the calculations have improved the ability of the LCI models to handle the complexity of fossil fuel power generation systems and reduced the LCA model uncertainty. The models referred to in the literature address LCA needs of the existing power generation plants. However, they do not offer solutions for novel systems that are not commercially operational. The LCI methodology developed at Imperial College provides an innovative and robust approach for conducting LCA for novel systems by configuring virtual systems at unit process level.

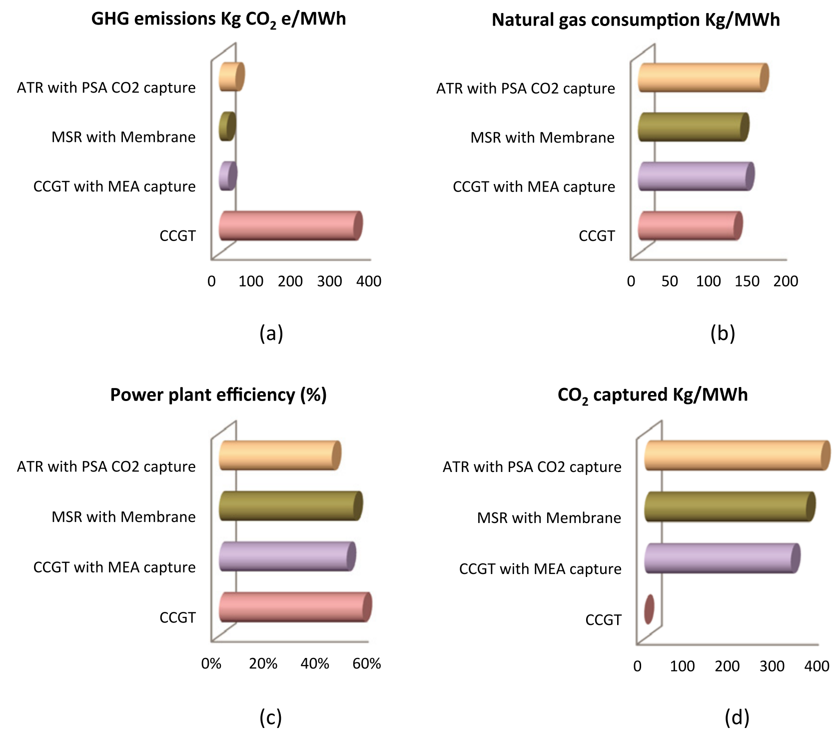

Figure 10. Comparison of alternative power plant configurations.

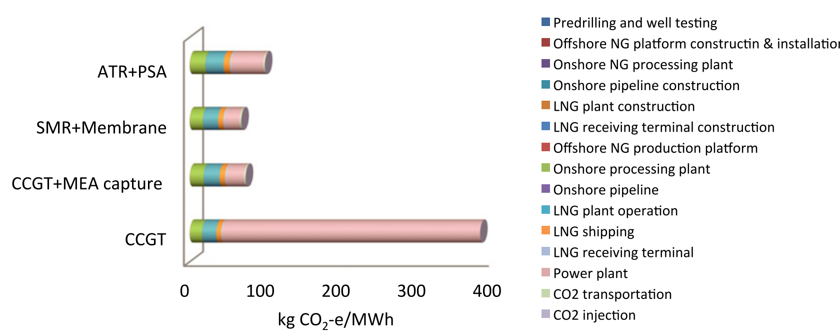

Figure 11. Life cycle of GHG emissions for alternative power plant configurations with gas supplied from Qatar.

The results of the case study suggest that gas-fired power generation with alternative CO_2 capture systems can significantly reduce life-cycle GHG emissions by 74%–85%. For gas power plants with alternative CO_2 capture routes, the majority life cycle GHG emissions are from the gas supply chain. This implies that the reduction of GHG emissions from the supply chain has the potential to decrease life-cycle GHG emissions significantly. This also implies that gas power plants with CO_2 capture using gas from different supply chains can have considerable variation in their carbon foot print.

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