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CAN TECHNOLOGY UNLOCK 'UNBURNABLE CARBON'?

WHITE PAPER

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Preface

Sustainable Gas Institute

The Sustainable Gas Institute (SGI) is a unique academic-industry partnership, and a ground-breaking collaboration between the United Kingdom and Brazil. Its role is to provide thought leadership and drive research into the technology that could underpin a sustainable role for natural gas in the global energy landscape.

The SGI is a multidisciplinary institute operating on a 'hub and spoke' model, with the international research hub in Imperial College, London and collaborating with leading universities in Brazil. SGI manages, leads and delivers world class research with global partners across the spectrum of science, engineering, economics and business.

SGI White Paper Series

The aim of the SGI White Paper series is to conduct systematic reviews of literature on topical and controversial issues of relevance to the role of natural gas in future sustainable energy systems. These White Papers provide a detailed analysis on the issue in question, along with identifying areas for further research to resolve any shortcomings in our understanding. The reviews also examine key future technologies and provide a critique of assessment processes.

Acknowledgement

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Executive summary

In 2015, the Conference Of the Parties in Paris (COP21) reached a universal agreement on climate change with the aim of limiting global warming to below 2 °C. In order to stay below 2 °C, the total amount of carbon dioxide (CO_2) released, or 'carbon budget' must be less than 1,000 gigatonnes (Gt) of CO_2. At the current emission rate, this budget will be eroded within the next thirty years. Meeting this target on a global scale is challenging and will require prompt and effective climate change mitigation action.

The concept of 'unburnable carbon' emerged in 2011, and stems from the observation that if all known fossil fuel reserves are extracted and converted to CO_2 (unabated), it would exceed the carbon budget and have a very significant effect on the climate. Therefore, if global warming is to be limited to the COP21 target, some of the known fossil fuel reserves should remain unburnt.

Several recent reports have highlighted the scale of the challenge, drawing on scenarios of climate change mitigation and their implications for the projected consumption of fossil fuels. Carbon capture and storage (CCS) is a critical and available mitigation opportunity that is often overlooked. The positive contribution of CCS technology to timely and cost-effective decarbonisation of the energy system is widely recognised. However, while some studies have considered the role of CCS in enabling access to more fossil fuels, no detailed analysis on this issue has been undertaken.

This White Paper presents a critical review focusing on the technologies that can be applied to enable access to, or 'unlock', fossil fuel reserves in a way that will meet climate targets and mitigate climate change.

The paper includes an introduction to the key issues of carbon budgets and fossil fuel reserves, a detailed analysis of the current status of CCS technology, as well as a synthesis of a multi-model comparison study on global climate change mitigation strategy. We also examine the extent of CO_2 geo-storage capacity available globally, as well as the influence of capture rates and residual emissions on CCS performance and potential.

Key findings

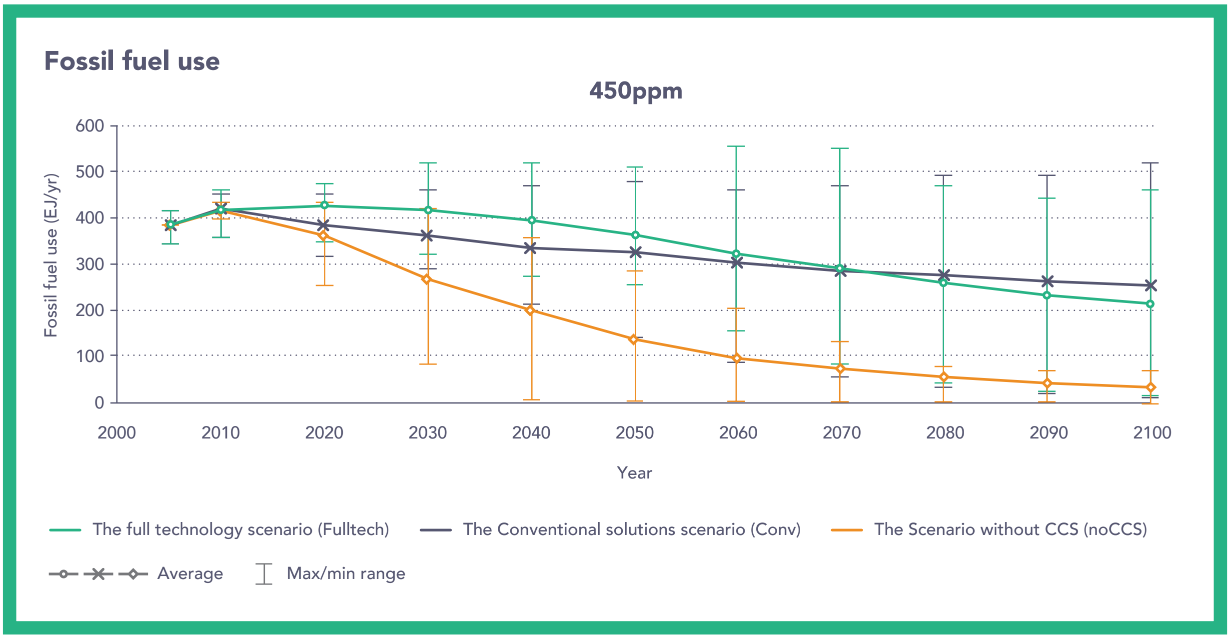
1. Carbon capture and storage (CCS) technology underpins the future use of fossil fuels in scenarios that limit global warming to 2 °C.
Recent studies have examined the extent to which CCS impacts on unburnable carbon but have only considered the timeframe to 2050, which showed a small impact. However, models used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report find that on average almost 200 exajoules (EJ) per year more fossil fuels are consumed by 2050 in a scenario with CCS compared to a scenario without CCS (Figure ES1). This margin continues to 2100. Therefore, while the difference in cumulative fossil fuel consumption between a CCS and no CCS scenario is only approximately

3,500–5,000 exajoules (EJ) in 2050, this will have increased to 14,000–16,000 EJ by 2100.

2. The potential role of CCS in unlocking unburnable carbon is greater in the second half of this century.
In modelled energy system transition pathways that limit global warming to less than 2 °C, scenarios without CCS result in 26% of fossil fuel reserves (defined according to McCollum et al. 2014 [1]) being consumed by 2050. This increases to 37% when CCS is available. However, by 2100, the scenarios without CCS have only consumed slightly more fossil fuel reserves (33%), whereas scenarios with CCS available end up consuming 65% of reserves. This is shown in Figure ES2, and demonstrates the significance of CCS in enabling access to fossil fuel reserves post 2050.

Among the three key fossil fuels, gas and coal consumption are the most strongly affected by the adoption of CCS, with an increase in coal use of 8,286 EJ/yr and of gas use of 65–104 EJ/yr by 2100, while oil consumption could increase by 29–31 EJ/yr.

FIGURE ES1
Average consumption of fossil fuels across a range of integrated assessment model outputs.
Scenarios plotted are Fulltech (all technologies available), Conv (renewables constrained), and noCCS (no CCS available).[1] Error bars represent the maximum and minimum model result observed.



1. "Fulltech" scenario has a full portfolio of technologies which may scaled up in the future in order to meet the climate targets. "Conv" scenario has limited solar, wind and biomass potentials and therefore energy demand is met by means of conventional technologies based on fossil fuel deployment in combination with CCS and/or nuclear. In the "noCCS" scenario carbon capture and storage never becomes available (see Box 1, section 5.3.2).

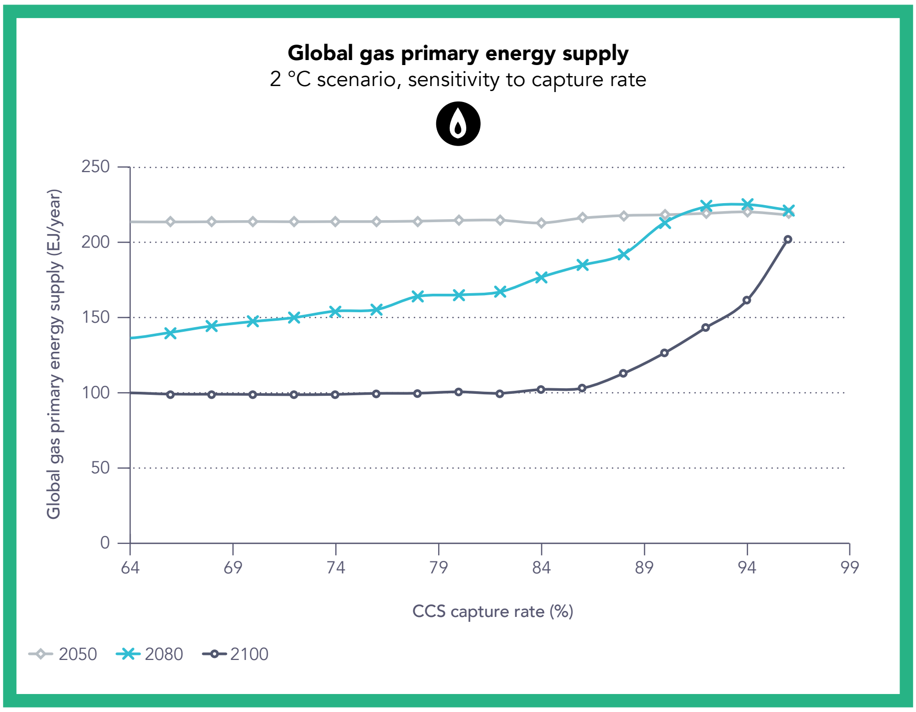
FIGURE ES2
Comparing cumulative fossil fuel use of estimated reserves with and without CCS for two timeframes (2005 to 2050 vs. 2005 to 2100) in a 2 °C scenario (450ppm). Reserves estimate is the 'low' value from McCollum et al. 2014 [1]. The "Without CCS" scenario corresponds to the EMF27 noCCS scenario while "With CCS" scenario corresponds to the EMF27 Fulltech scenario.

By 2100, the scenarios without CCS have only consumed slightly more fossil fuel reserves (33%), whereas scenarios with CCS available end up consuming 65% of reserves

3. The capture rate is a crucial factor in determining the extent of future use of fossil fuels.
In the vast majority of global abatement studies, an assumption is made that approximately 85–90% of the emissions produced can be captured by CCS technology. This assumption is rarely discussed, but the remaining 10–15% residual emissions is likely to be really important in determining the extent of the role for fossil fuels with CCS especially in extremely emissions-constrained global scenarios.

In this report, a global integrated assessment model (TIAM-Grantham), was applied to produce an initial investigation into the sensitivity of fossil fuel consumption to CCS capture rate. Figure ES3 presents the result of this investigation for natural gas. In the earlier stages of mass CCS uptake around the year 2050 the capture rate is not particularly important, but in the second half of the 21st century its role becomes pivotal, with high capture rates (>90%) leading gas to maintaining its 2050 share of primary energy supply. At 2015 UK wholesale gas prices, the additional 100 EJ global gas sales is worth almost £500bn per year. Further studies are needed to comprehensively understand the sensitivity of this result to energy prices, technology cost, performance and availability parameters, and modelling approach.

FIGURE ES3
Sensitivity of primary energy supply of natural gas in 2050, 2080 and 2100 to CCS capture rate.



4. In the short-term, there are a range of important barriers to overcome.
Short-term barriers include cost, lack of market and regulatory arrangements, potential supply chain gaps and cautious public perception. The use of CCS entails non-trivial capital costs and energy penalties, leading to relatively high overall cost versus unabated energy production. These costs are particularly high for early-stage demonstrations of the technologies. There are also no effective market arrangements to enable the value made by emissions reductions being incorporated into CCS investment decisions. For the long-term future of CCS to be realised, all of these issues need to be addressed via research, development and demonstration, along with an effective set of policy instruments to support early-stage demonstration through to mass-market application.

5. In the long-term, the cost of CCS is not a significantly limiting factor for the deployment of the technology.
The marginal abatement cost produced by the global climate change mitigation models reviewed is high, on average US2015$473–1,100/t$CO_2$ by 2050, and increases further by 2100. This is well above the abatement cost associated with CCS reported across the literature, which is a maximum of US2015$160/t$CO_2$ for the whole capture, transport and storage chain. Therefore, the cost of CCS is not limiting long-term adoption of the technology in the modelled climate mitigation scenarios. Competition with other low carbon energy technologies is also not limiting the uptake of CCS, otherwise a lower marginal abatement cost would be observed. As discussed, the key factor limiting uptake of CCS is likely to be the residual emissions.

6. Geo-storage capacity available for CO_2 is much larger than the CO_2 embodied in present-day fossil fuel reserves.
Whilst some uncertainty is still present, recent academic literature has assessed that the global capacity is well above the extent of known fossil fuel reserves, by approximately one order of magnitude. However, in the absence of pressure

management strategies, reservoir pressurisation limits (to prevent fracture of sealing caprock) in saline aquifers will limit the accessible CO_2 geo-storage capacity. Recent research using reservoir simulation has found that 0.01 – 1% of the pore volume of saline aquifers will be available for storage over decadal timescales, in the absence of brine production from the reservoir. This will not prevent access to the remaining ~99% of capacity, but the required pressure management will often entail higher costs.

7. Suggested priorities for Research, Development and Demonstration (R,D&D) are to:

a. Move forward with demonstration of large-scale CCS in power and industry sectors, and to establish what conditions will enable the technology to become mainstream.
b. Invest in research to establish the trade-off between CCS cost and maximum capture rate achievable, including further development of capture engineering, with a view to achieving a lifetime capture of greater than 95% of emissions produced.
c. Ensure any jurisdiction considering large-scale deployment of CO_2 storage perform regional dynamic assessments of the geo-storage resource and R,D&D on increasing storage efficiency (e.g. through brine extraction for pressure management).

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AR	Assessment Report
BECCS	Bio Energy with Carbon Capture and Storage (CCS)
BIGCC	Biomass Integrated Gasification Combined Cycle
C^4MIP	Coupled Climate Carbon Cycle Model Intercomparison
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CFB	Circulating Fluidised Bed
CO_2e	Equivalent Carbon Dioxide
COE	Cost Of Electricity
COP	Conference Of the Parties
CPS	Current Policies Scenario
ECBM	Enhanced Coal Bed Methane
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
ESM	Earth System Models
ETS	Emission Trading Scheme
EWS	Efficient World Scenario
FOAK	First Of A Kind
FT	Fischer Tropsch
GHG	Greenhouse Gas
HadSCCCM1	Hadley Centre Simple Climate-Carbon-Cycle Model
IAM	Integrated Assessment Model
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelized Cost Of Electricity
MAC	Marginal Abatement Cost
NET	Negative Emission Technology
NGCC	Natural Gas Combined Cycle
NGO	Non-Governmental Organization
NOAK	Nth Of A Kind
NPD	Norwegian Petroleum Directorate
NPS	New Policies Scenario
NPV	Net Present Value
PC	Pulverised Coal
PFBC	Pressurized Fluidized Bed Combustor
PIIP	Petroleum Initially In Place
PRMS	Petroleum Reserves Management System
R,D&D	Research, Development and Demonstration
RF	Russian Ministry of Natural Resources
SEC (US)	Security and Exchange Commission
SiMCaP	Simple Model for Climate Policy assessment
SPE	Society of Petroleum Engineers
SSE	Scottish and Southern Energy
TPA	Technical and Policy Assessment
TRL	Technology Readiness Levels
UKERC	UK Energy Research Centre
USGS	United States Geological Survey

Contents

1. Introduction

1.1. Background

The concept of 'unburnable carbon' is simple. It points out that known fossil fuel reserves cannot all be converted to CO_2 and emitted to the atmosphere (i.e. burned or as a byproduct of a chemical process) if the world is to avoid dangerous climate change. In most studies, this dangerous level is deemed to be a reasonable chance of peak global average surface temperature rise of more than 2 °C.

A number of reports have been published recently on the unburnable carbon topic, but it is not a new issue with analysis available from as early as the 1990s. These studies present a range of insights, from commentary on how the 'unburnable' issue may or may not imply the existence of a 'carbon bubble' in terms of impact on fossil fuel company value, through to analysis identifying specific fossil fuel related projects that may not be needed, given the perception of an impending reduction in fossil fuel demand combined with their potentially high cost relative to other projects.

1.2. Grey and academic literature

With a few notable exceptions, the analysis on unburnable carbon exists in grey literature, produced by banks, consultancies, insurers, think tanks and non-governmental organisations (NGOs). Academic research behind the insights is also available in specific areas, but few studies exist that span the whole topic. In particular, a substantial body of research exists in the climate science domain on the extent of the global carbon budget and the impacts of climatic change. Also, the extent of fossil fuel reserves is fairly well understood, at least to the extent that these reserves, if converted to CO_2 and released into the atmosphere, are demonstrably significantly larger than the allowable carbon budget for a 2 °C world. Less compelling evidence exists on likely outcomes for fossil fuel consumption, where the use of abatement technology such as carbon capture and storage (CCS) might unlock fossil fuel reserves.

1.3. A powerful tool: integrated assessment models

A key resource in 'unburnable carbon' assessments are global integrated assessment models[2] (IAMs), which are used to produce scenarios of energy system transition to a low carbon world, thereby providing estimates of the future use of fossil fuels that is consistent with climate change mitigation. These models use a range of methodological approaches that determine what technologies are selected, along with a range of input data assumptions like costs and performance, which all have a strong bearing on outcomes. A good example of the outcomes that can be produced is the IEA's (International Energy Agency) Energy Technology Perspectives 2012 scenario which allows CCS to unlock 125 $GtCO_2$ until 2050 [3].

1.4. Aim and structure

This report reviews the evidence for the potential role of CCS technology in unlocking fossil fuel assets that might otherwise be stranded in a world where CO_2 emissions are severely constrained.

Section 2 covers the evidence including the climate science, global data on fossil fuel reserves and resources and covers the quantification of unburnable carbon.

Section 3 outlines which technologies can reduce CO_2 emissions to the atmosphere, with a special focus on CCS, its applications and current state.

Section 4 summarises the potential barriers to the full development of CCS, which includes supply chain and building rate, geo-storage capacity, source-sink matching, operative and capital costs, policy regulation and market, public acceptance and requirements for research, development and demonstration (R,D&D).

Section 5 includes a review of a multi-model IAM comparison study that considered CCS in relation to the 'unburnable carbon' concept. The results are presented in section 6.

The final chapter (section 7) provides an analysis on the influence of residual CO_2 emissions on the adoption of CCS in the energy scenarios. This leads to some conclusions and recommendations on the treatment of this aspect of CCS in unburnable carbon assessments in the future.

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2. Integrated Assessment Models (IAMs) "include representations of climate, using models and data generated by the climate modelling and research community, and Earth systems, using models and data generated by the impacts, adaptation, and vulnerability (IAV) modelling and research community. In turn, IAMs provide the climate modelling community with emissions scenarios of greenhouse gases (GHGs) and short-lived species (SLS) and land-use projections. IAMs provide the IAV modelling community with projections of socioeconomic states, general development pathways, and the multiple stressors of climate change" [2].

1.5. Methodology

This comprehensive review of academic, industrial and governmental literature has drawn on the methodology created by the UK Energy Research Centre (UKERC) Technical and Policy Assessment (TPA) group and refined by the Sustainable Gas Institute. The methodology uses systematic and well-defined search procedures to document the literature review, providing clarity and transparency to the analysis. An external expert advisory panel was appointed with a broad range of perspectives to consult on the initial framing and specification of the review procedure, as well as providing additional contributions as required. The research outputs have been peer reviewed prior to publication.

2. Background

2.1. The global greenhouse gas budget

2.1.1. Climate models

It is unequivocal that climate change is influencing the planet, with a range of effects already observable [4]. It is also extremely likely that this is caused by emissions of greenhouse gases (GHGs) ensuing from human activities, either directly (e.g. fossil fuel combustion, cement production) or indirectly (e.g. deforestation). Given the observed impacts to date, the extreme nature of potential future effects on natural and human systems [5], and the rapidly increasing emissions [6], it is pressing that decision makers consider options to mitigate climate change by reducing emissions, and plan adaptation for existing strategies.

On the mitigation side, this has led to the concept that the world has a constrained greenhouse gas emissions budget; a cumulative emissions limit which if breached is likely to lead to a global mean surface temperature rise of more than 2 °C [7]. Peak warming given by cumulative emissions has been adopted by the scientific community as a reliable measure of climate change [8]. The 2 °C limit was chosen because the best evidence on projected impacts and damage indicate that effects are more limited and more certain below this level [9]. However, even 2 °C cannot be considered completely safe, and adaptation will still be required. Carbon budgets that lead to warming of greater than 2 °C have also been produced using climate models such as MAGICC 6.0, HadSCCCM1 and SiMCap EQW.

> The 2 °C limit was chosen because the best evidence on projected impacts and damage indicate that effects are more limited and more certain below this level [9]. However, even 2 °C cannot be considered completely safe, and adaptation will still be required.

The climate model MAGICC 6.0 (Model for the Assessment of Greenhouse Gas Induced Climate Change), was introduced in a paper by Meinshausen et al. [10] and then employed again a year later [7], where the authors showed a probabilistic analysis that quantifies cumulative GHGs emission budgets for the timeframe 2000–2050. The MAGICC 6.0 model is a reduced complexity coupled climate-carbon cycle model which relates emissions of GHGs, tropospheric ozone precursors and aerosols to gas-cycle and climate system responses [7]. The model is characterised by more than 400 parameters, which are constrained using observational data of surface air temperature (for the timeframe 1850–2006), linear trends in ocean heat content changes (for the timeframe 1961–2003) and the radiative forcing estimates for 18 forcing agents.

The coupled climate carbon-cycle model HadSCCCM1 (Hadley Centre Simple Climate-Carbon-Cycle Model) is characterised by key parameters including climate sensitivity, ocean/biosphere carbon uptake diffusivity and ocean thermal diffusivity [8]. The response of the model for a subset of 250 containment scenarios has been compared with the response of the eleven coupled Earth System Models (ESMs) [11], part of the Coupled Climate Carbon Cycle Model Intercomparison (C^4MIP) [12].

In the SiMCaP (Simple Model for Climate Policy assessment) EQW model [13], an iterative method is employed in order to meet a set of specified criteria by means of emission path generation. These criteria include the long-term goal, the dates of departures of emissions from 'business as usual' of four country groups and the maximum allowable annual reductions in global emissions [14].

2.1.2. Budget estimations

Climate models have been employed by different research groups and institutions in order to estimate the carbon budget. The carbon budget represents the maximum amount of CO_2 that can be released to the atmosphere in order to limit the temperature rise below a certain target.

For example, the IEA (International Energy Agency) described two scenarios, the 4DS and the 6DS, which project a long-term temperature rise of 4 °C and 6 °C. The 6 °C Scenario (6DS) is largely an extension of current trends and is characterised by the absence of efforts to stabilise atmospheric concentrations of GHGs. The IEA 2015 [15] also includes a 2 °C Scenario (2DS), which describes an energy system consistent with an emissions trajectory that would give an 80% chance of limiting average global temperature increase to 2 °C.

A range of studies have attempted to quantify the global GHGs budget for the 2 °C (and other) scenarios. Different climate system models are applied in these studies, and their results often report budgets of CO_2 as opposed to the full basket of greenhouse gases. Importantly, the authors' of these studies almost universally acknowledge the uncertainties associated with the estimations, in that the chain of causes and effects from emission through to temperature rise is very complex.

Table 1 summarises the carbon budgets as estimated by reported sources. Each carbon budget has an associated probability to not exceed the 2 °C temperature rise and has been estimated for a specific timeframe. Resources for estimating carbon budgets include the Potsdam Institute for Climate Impact Research [7], the University of Oxford [8], the IPCC Fifth Assessment Report (AR5) and the contribution given by the IPCC Working Group I [16] and III [17]. Those studies who have received most attention are Meinshausen et al. [7] for the budget until 2050 and Allen et al. [8] for the budget until 2100. Three timeframes have been considered in the literature, including time horizons until 2050 and until 2100 as well as the total emissions.

According to Meinshausen et al. [7], the probability of exceeding 2 °C can be limited to below 25% (and 50%) by keeping cumulative CO_2 emissions from fossil sources and land use change for the timeframe 2000 to 2049 to below 1,000 (and 1,440) $GtCO_2$ respectively. The authors also estimate that non-CO_2 greenhouse gases (including methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride [SF6]) may constitute 33% of overall emissions.

Allen et al. [8] estimate that if total emissions between 1750 and 2500 are 3,670 $GtCO_2$, then the most likely peak warming will be 2 °C. However, half of these emissions have already been released to the atmosphere since 1750. Therefore, this would mean a carbon budget of about 1,835 $GtCO_2$ in 2009, when the paper was published.

Other studies evaluating the carbon budget include IPCC (960 $GtCO_2$ until 2100 for a 68% probability to remain below a 2 °C increase) and the Carbon Tracker Initiative (975 $GtCO_2$ until 2100 for an 80% probability to remain below a 2 °C increase), also based on the MAGICC model. Most of the references report a quite small carbon budget remaining after 2050; 7.7% according to Carbon Tracker Initiative and 9.4% according to IPCC. This further highlights the importance of early action on climate change mitigation.

There are many sources of uncertainty in evaluating greenhouse gas budgets and no single author claims to be able to predict climate change precisely. Key sources of uncertainty include the level of climate sensitivity, carbon cycle feedbacks, aerosol emissions scenarios and unmodelled processes. Climate science is a rich and active area of research and as such estimates of the global carbon budget are likely to be refined over time. Rogelj et al. [18] provide a comprehensive overview on the differences between the main types of carbon budget and on what specifically affects the budget estimations. Their research identifies five key drivers: budget type definition, the underlying data and modelling, the scenario selection, temperature response timescales and accompanying pathway of CO_2 and non-CO_2 emissions [18].

TABLE 1
Global emissions budgets from a variety of sources.

Budget (Gt)	Gases	Timeframe	Probability (chance of exceeding 2°C)	Model
886	CO_2	2000–2049	20%	MAGICC 6.0 [7]
1000		2000–2049	25%	
1437		2000–2049	50%	
1356	Kyoto gases	2000–2049	20%	
1500		2000–2049	26%	
1678		2000–2049	33%	
2000		2000–2049	50%	
3670	CO_2	1750–2500	50% [20]	HadSCCCM1 [8]
1635–1752[3]	Kyoto gases	2000–2050	50% (low aerosol scenario)	SiMCaP EQW and MAGICC [14]
1631–1897		2000–2050	50% (high aerosol scenario)	

Scope = fossil sources, land use change

3. Note that these budgets required global emissions peak between 2014 and 2016, which is now accepted to be impossible.

The global carbon budget is also being rapidly eroded. From 2002 to 2011, the CO_2 emissions coming from global fossil fuel, cement and land use change were approximately 34 $GtCO_2$ per year [19]. Therefore the global carbon budget (1,000 $GtCO_2$) for temperature rise to remain below 2° C is likely to be exhausted in the next thirty years before 2050 unless action is taken quickly.

2.2. Fossil fuel reserves and resources

2.2.1. Classification

One of the first attempts to classify resources and reserves is represented by the McKelvey box, which classifies resources as undiscovered, discovered and economic (i.e. reserves) and discovered sub-economic (resources) [21]. Since 1972, various nomenclatures have been proposed and adopted and the most common ones include [22]:

- Petroleum Reserves Management System (PRMS) from the Society of Petroleum Engineers (SPE)
- US Security and Exchange Commission (SEC)
- United States Geological Survey (USGS)
- Norwegian Petroleum Directorate (NPD)
- Russian Ministry of Natural Resources (RF).

Society of Petroleum Engineers 2008 [23] is currently the most widely used oil and gas industry reference, whilst companies listed on the New York Stock Exchange generally use the US Security and Exchange Commission as a reference. The Petroleum Reserves Management System of the Society of Petroleum Engineers defines proved reserves as those resources that meet all the technical requirements for commercialisation and have 90% probability of being recovered [24]. Probable reserves have 50% probability of being recovered, where as possible reserves have a 10% probability of being recovered [22]. Proved reserves are also called 1P, while proved plus probable are called 2P and proved plus probable plus possible are called 3P [24].

> This White Paper does not attempt to assess the carbon bubble issue directly, but focuses more on the technical realities of 'unburnable carbon' rather than on the financial aspects.

The methodology for determining fossil fuel reserves is a contested subject. Broadly speaking, 'reserves' refers to the quantity of fossil fuels that is likely to be extracted under economic conditions (i.e. a given set of fossil fuel prices versus project costs) that make a specific project favourable. In basic terms, fossil fuel price is determined by the marginal cost of production, which is the cost of the most expensive fossil fuels at that point in time. Therefore, the extent of aggregate global reserves is a function of the prevailing fossil fuel price, which itself has proven to be a highly volatile quantity. This makes any estimate of reserves open to debate, and the supply curve for each fossil fuel dynamic in nature.

The extent of reserves is also contentious when examined in relation to the 'carbon bubble' concept. This concept is driven by the fact that if some reserves are unburnable the companies that own those reserves might be overvalued in the stock market [25]. However Mayer and Brinker [22] have argued that the perception of carbon risk has been inflated by the choice of definition for the reserves. For example, reserves estimated using the SEC method are not as high as some other methods, and also are likely to be monetised quickly. Others argue that regardless of a particular company's exposure in terms of ownership of fossil fuel reserves, the impact of the unburnable issue on fossil fuel prices is likely to have an influence on the degree that companies value their assets; an indirect carbon bubble effect [26].

This White Paper does not attempt to assess the carbon bubble issue directly, but focuses more on the technical realities of "unburnable carbon" rather than on the financial aspects.

TABLE 2
Correlation of status categories.
Modified from *Oil and Gas Reserves Committee 2005* [24].
*The NPD classification is for recoverable quantities only based on development projects.

	Society of Petroleum Engineers (SPE) 2001	US Security Exchange Commission (SEC) 1978	United States Geological Survey (USGS) 1980	Norwegian Petroleum Directorate (NPD) 2001	Russian Ministry of Natural Resources (RF) 2005
IN PLACE					
Total PIIP	Total PIIP		Total PIIP	*	Total PIIP
Discovered PIIP	Discovered PIIP		Discovered PIIP	*	Geological reserves
Undiscovered PIIP	Undiscovered PIIP		Undiscovered PIIP	*	Geological resources
RECOVERABLE					
Discovered + undiscovered	Resources			Recoverable resources	
Produced	Production	Production	Cumulative production	Historical production	Produced reserves
Discovered	Discovered	Discovered	Identified resources	*	Recoverable reserves
Discovered commercial	Reserves	Reserves	(Economic) reserves	Reserves	Economic-normally profitable reserves
Discovered sub-commercial	Contingent Resources		Marginal reserves	Contingent resources	Contingently profitable & subeconomic reserves
Discovered unrecoverable	(Discovered) unrecoverable		Demonstrated subeconomic resources	*	Unrecoverable reserves
Undiscovered	Prospective resources		Undiscovered resources	Undiscovered resources	Recoverable resources
Undiscovered unrecoverable	(Undiscovered) Unrecoverable			*	Unrecoverable resources

			Society of Petroleum Engineers (SPE) 2001	US Security Exchange Commission (SEC) 1978	United States Geological Survey (USGS) 1980	Norwegian Petroleum Directorate (NDP) 2001	Russian Ministry of Natural Resources (RF)* 2005
RECOVERABLE							
Commercial	Low	Increment	Proved	Proved	Measured		A+B+C1
		Cumulative	Proved (1P)			Low est	A+B+C1
	Best	Increment	Probable		Indicated		C2
		Cumulative	Proved + probable (2P)			Base est	
	High	Increment	Possible		Inferred		C2
		Cumulative	Proved + probable + possible (3P)			High est	
Sub-commercial	Low	Increment			Measured		
		Cumulative	Low est			Low est	Low est
	Best	Increment			Indicated		
		Cumulative	Best est			Base est	Best est
	High	Increment			Inferred		
		Cumulative	High est			High est	High est

TABLE 3
Correlation of certainty classes for discovered volumes.
Modified from *Oil and Gas Reserves Committee 2005* [24].
*The Russian classes A–Reasonable Assured, B–Identified, and C1–Estimated are roughly equivalent to: proved developed producing, proved developed non-producing and proved undeveloped. C2 is generally equivalent to probable and possible combined. Est = estimate

Table 2 and Table 3 summarise the adopted nomenclature according to the status category (Table 2) or the certainty classes (Table 3) for discovered volumes. The main criteria for classifying reserves and resources include discovery criteria, commercial criteria and uncertainty. The commercial criteria include commercial low and best and high estimates and depend on what can be defined as 'commercial'. In most definitions, commercial is used as being synonymous with 'economic', which means that "the project income will cover the cost of development and operations (at zero discount rate)" [27].

2.2.2. Reserves and resources estimations

Reserve databases include numerous sources, and have been employed in both the academic and grey literature in order to estimate the carbon content of overall reserves. Some examples include BP 2015 [28], IEA World Energy Outlook 2012 and 2014 [29, 30], World Energy Council 2013 [31], BGR 2014 [32], Oil & Gas Journal 2014 [33] and Deutsche Bank [34]. These databases have been analysed and compared, and are reported in Table 4.

In order to evaluate the amount of unburnable fossil fuel reserves in a low carbon scenario, the overall potential carbon emissions within these reserves has to be evaluated and compared with the global carbon budget. The exact quantity of reserves is a contentious issue as it depends on prevailing commodity price, prices for asset developments, and many other factors. A large range of estimates exist in the literature.

The extent of reserves has been reviewed by Meinshausen et al. [7], who state that the mid-estimate from the literature could produce 2,800 gigatonnes (Gt) of CO_2 emissions in a scenario of unabated combustion, with an 80%-uncertainty range of 2,541 to 3,089 $GtCO_2$. Reserve estimates have also been reported by McCollum [1], which summarised conventional and unconventional fuel estimates. They reported a lower estimate of 3,683 $GtCO_2$, which corresponds reasonably to that reported by McGlade and Ekins (3,613 $GtCO_2$) [35]. McCollum also presented an upper estimate of 7,118 $GtCO_2$. Clearly, there is great uncertainty regarding estimates of global fossil fuel reserves, particularly where undiscovered reserves are included.

Table 4 summarises minimum and maximum estimates for both reserves and resources. Three different units have been reported to represent the amount of reserves and resources: the quantity in gigatonnes (Gt), their energetic content (EJ) and the amount of CO_2 that they would release to the atmosphere if burned unabated ($GtCO_2$).

According to the values reported in the table, the overall amount of reserves (including oil, gas and coal) is equivalent to between 3,395 and 3,876 $GtCO_2$. Almost two thirds of these potential emissions is from coal, in the range of 56,577–58,929 $GtCO_2$.

Fossil fuel		Gigatonnes (Gt)	Exajoules (EJ)	Carbon ($GtCO_2$)
Oil	Reserves	219 → 240	9,264 → 10,145	679 → 744
	Resources	334 → 847	14,128 → 35,845	1,036 → 2,627
Gas	Reserves	125 → 155	6,016 → 7,461	338 → 453
	Resources	427 → 540	20,518 → 25,921	1,151 → 1,454
Coal	Reserves	892 → 1,004	25,141 → 28,313	2,378 → 2,678
	Resources	21,208 → 22,090	598,066 → 622,924	56,577 → 58,929
TOTAL	Reserves	1,236 → 1,399	40,421 → 45,919	3,395 → 3,876
	Resources	21,969 → 23,477	632,712 → 684,690	58,764 → 63,010

Minimum → Maximum

TABLE 4
Estimation of reserves and resources of oil, gas and coal.
[28–34]

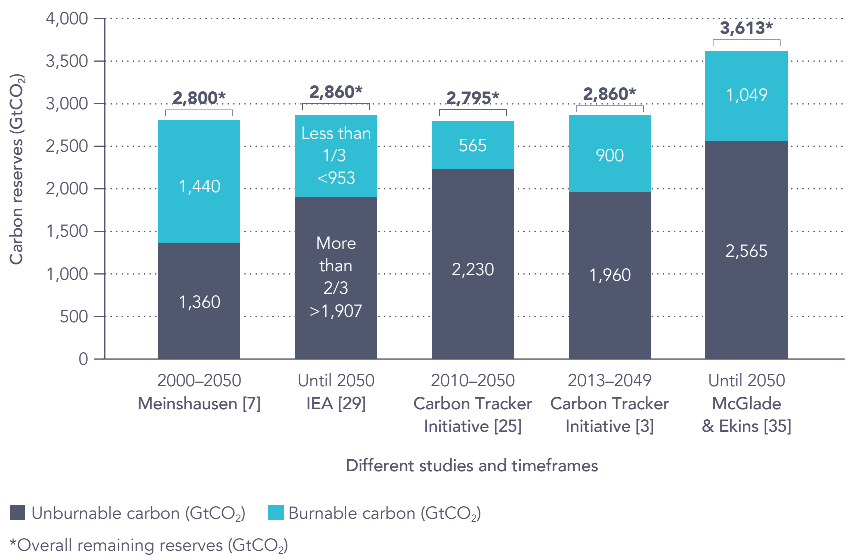
2.3. Unburnable carbon

Considering the range of carbon budgets and the extent of fossil fuel reserves discussed above, it is apparent that not all of the reserves can be converted to CO_2 and released to the atmosphere, if the world is to avoid temperature rise greater than 2 °C. In this context, the term 'stranded assets' or 'unburnable carbon' has been used to indicate any surplus of reserves greater than a given carbon budget. Therefore, this term refers to the amount of fossil fuel that cannot be burnt in a mitigated climate change scenario. Unburnable carbon has been recently investigated by the Carbon Tracker Initiative [25] and later by other institutions such as the International Energy Agency [36] and the Environmental Audit Committee of the UK Government [37] as well as banks and other organisations [26, 38–40].

Figure 1 shows overall reserves and unburnable and burnable carbon for different timeframes. In all the reported references, unburnable carbon is between 49% and 80% of overall reserves. A prominent example is the World Energy Outlook 2012 [29], which estimates overall reserves to be equal to 2,860 $GtCO_2$. Without CCS, less than a third (i.e. less than 953 $GtCO_2$) can be burnt in the 2 °C scenario. This finding is based on the IEA assessment of global carbon reserves, measured as the potential CO_2 emissions from proven fossil-fuel reserves. Almost two-thirds of these carbon reserves are related to coal, 22% to oil and 15% to gas. Although IEA considers CCS a key option to mitigate CO_2 emissions, it also highlights the uncertainty of its pace of deployment.

> The most stringent target (1.5 °C) would reduce the carbon budget by about 300 $GtCO_2$ in 2050 and by 330–370 $GtCO_2$ in 2100, while the more relaxed targets would increase the carbon budget by 1,610–1,790 $GtCO_2$ (3 °C) to 2,660–3,440 $GtCO_2$ (4 °C) in 2100

FIGURE 1
Unburnable and burnable carbon according to different studies.



2.3.1. Sensitivity to temperature rise targets

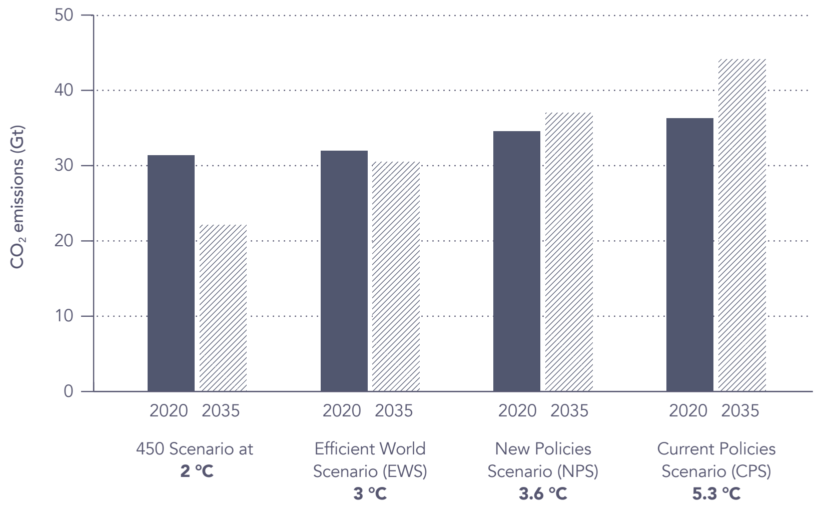
The amount of burnable carbon (or the carbon budget) varies considerably between studies (as shown in Figure 1). This is due to a number of factors: the reference, the modelling methodology, the assumptions and the timeframe under analysis. The carbon budget also depends on the temperature rise target. The 2 °C target has received a lot of attention since it was introduced as an EU climate target in 1996 [41]. However, other targets have been taken into account as well, which were more or less stringent than the 2 °C target. For example, at the recent COP21 (Conference Of the Parties), the Conference "invites the Intergovernmental Panel on Climate Change to provide a special report in 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways" [42]. While the most stringent target of 1.5°C was already requested in 2008 by the Alliance of Small Island States and the Least Developed Country group [7], other less stringent targets include temperature rises up to 5.3°C. The analysis of the scenarios that would bring about less stringent targets are motivated by the desire of researchers to show what would happen without an emission reduction framework in place.

Figure 2 shows four different scenarios proposed by the International Energy Agency [29], which correspond to four different temperature rise targets (with a probability of 50% of meeting the target):

- **450 Scenario (450S)** has a temperature rise target of 2 °C and aims to demonstrate a plausible path to achieve this climate target.
- **Efficient World Scenario (EWS)** has a temperature rise target of 3 °C and explores the emission reduction due to energy efficiency only.
- **New Policies Scenario (NPS)** has a temperature rise target of 3.6 °C and provides a benchmark to assess the potential of the recent development in energy and climate policy.
- **Current Policy Scenario (CPS)** has a temperature rise target of 5.3 °C and provides a baseline showing how the energy market would evolve if energy demand and supply are not changed. This target is similar to the target reported in the 6DS [15].

CO_2 emissions have been reported for the years 2020 and 2035 and shows how a reduction in global emissions could still bring the temperature rise to 3 °C. According to IEA 2012 [29], having a more relaxed temperature rise target increases the carbon budget by 2–16% in 2020 and by 38–100% in 2035.

FIGURE 2
IEA scenarios and corresponding CO_2 emissions for different temperature rise targets.
Modified from IEA (2012) [29].



Cumulative emission budgets have been reported by the IPCC 2014 [6] for temperature rise targets between 1.5 °C and 4 °C (Table 5). The most stringent target (1.5 °C) would reduce the carbon budget by about 300 $GtCO_2$ in 2050 and by 330–370 $GtCO_2$ in 2100, while the more relaxed targets would increase the carbon budget by 1,610–1,790 $GtCO_2$ (3 °C) to 2,660–3,440 $GtCO_2$ (4 °C) in 2100. Carbon budgets that have different likelihoods of meeting their temperature targets should not be compared directly. Therefore, these budget extensions represent only an indication of the sensitivity of the budget to various temperature targets.

TABLE 5
Fossil fuel carbon budget for different maximum temperature rises [3].
Timeframes: 2011–2050; 2011–2100.

	Fossil fuel carbon budget ($GtCO_2$)		
Temperature target (°C)*	**Until 2050****	**Until 2100****	**Probability (%)**
1.5	550–1,300	630–1,180	14–51
2	860–1,600	960–1,550	39–68
3	1,310–1,750	2,570–3,340	57–74
4	1,570–1,940	3,620–4,990	61–86

*relative to years 1850–1900
** from 2011 (minimum and maximum range)

2.3.2. Circumstances that would make unburnable carbon a reality

In order for fossil fuel reserves to become uneconomic or otherwise inaccessible, some important developments would be needed in the next decade. The three key developments are:

- **A potent global agreement to mitigate climate change:** the agreement [42] from COP21 indicates that this is possible. However, further more ambitious binding commitments will be required.
- **Implementation of effective policy, regulatory and market mechanisms at national and international levels** in order to meet the agreed commitments. This could include carbon trading or taxation mechanisms similar to those already included in the Emissions Trading System [43]. More details on these topics are presented in section 4.5.
- **Technological approaches that avoid or limit the emissions** associated with the use of fossil fuels (e.g. CCS) would not be commercialised, or proven uneconomic or otherwise unacceptable relative to other means to reduce global emissions, such as renewable energy technologies. Section 3.1 provides an overview on technologies able to limit CO_2 emissions.

Some sources have confirmed the possibility of 'unburnable carbon' becoming a reality [29, 44, 45], while others have denied the 'carbon bubble' as a real problem, such as Mayer and Brinker 2014 [22]. While climate change is generally acknowledged by oil and gas companies [46], their position on the 'carbon bubble' is cautious and highlights how the outcome depends on many factors and is therefore difficult to predict.

This report has distinguished between the concepts of 'carbon bubble' being a financial issue, and 'unburnable carbon' being a technological issue. However, the two issues are clearly linked and there are controversial opinions in the grey literature regarding the likelihood of 'unburnable carbon' becoming a major issue in the global energy system.

3. Can technology unlock unburnable carbon?

3.1. Technologies and approaches limiting CO_2 emissions

Many abatement technologies either directly or indirectly enable the use of fossil fuels. Those that have a direct impact are technologies such as CCS and CO_2 re-use. Those with indirect impact include any technology or approach that reduces emissions and thereby increases the remaining carbon budget available for fossil fuel emissions. The range of options is large, and includes:

Direct approaches [47, 48]

- Enhanced energy efficiency and conservation
- Replacement of coal by natural gas
- Adoption of higher efficiency coal technologies such as Integrated Gasification Combined Cycle (IGCC) and Pressurized Fluidized Bed Combustor (PFBC)
- Greater use of nuclear power
- Carbon capture and storage

Indirect approaches [47, 48]:

- Development of mass market renewable energy technologies
- Afforestation and reforestation.

The applications, advantages, limitations and impact on unburnable carbon of each of these possibilities have been summarised in Table 6. This report focuses only on direct technical measures that enable the use of fossil fuels, and does not focus on the indirect measures. The focus herein on technologies that directly enable the use of fossil fuels is important. In extremely emissions-constrained scenarios (e.g. achieving net zero emissions in the second half of this century as put forward in COP21), indirect measures will be ineffective because there will be no carbon budget left to open up.

Strategy	Applcation area/sector	Advantages	Limitations
Enhance energy efficiency and energy conservation	Applied mainly in commercial and industrial buildings.	Energy saving from 10% to 20% is easily achievable.	May involve extensive capital investment for installation of energy saving device.
Increase usage of clean fuels	Substitution of coal by natural gas for power generation.	Natural gas emits 40–50% less CO_2 than coal due to its lower carbon content and higher combustion efficiency; cleaner exhaust gas (lower particulates and sulfur dioxide emissions).	Higher fuel cost for conventional natural gas. Comparable cost for shale gas.
Adopt clean coal technologies	Integrated gasification combined cycle (IGCC), pressurised fluidized bed combustor (PFBC) etc. to replace conventional combustion.	Allows the use of coal with lower emissions of air pollutants.	Significant investment needed to roll out technologies worldwide.
Use of renewable energy	Hydro, solar (thermal), wind power, and biofuels highly developed.	Use of local natural resources; no or low greenhouse and toxic gas emissions.	Applicability may depend on local resources availability and cost. Power from solar, wind, marine etc. are intermittent and associated technologies are not mature; most current renewable energies are more costly than conventional energy.
Development of nuclear power	Nuclear fission adopted mainly in US, France, Japan, Russia and China.	No air pollutant and greenhouse gas emissions.	Usage is controversial; development of world's nuclear plant is hindered due to Fukushima nuclear accident in 2011, e.g. Germany will phase out all its nuclear power by 2022.
Afforestation and reforestation	Applicable to all countries.	Simple approach to create natural and sustainable CO_2 sinks.	Restricts/prevents landuse for other applications.
Carbon capture and storage (CCS)	Applicable to large CO_2 point emission sources.	It can reduce vast amounts of CO_2 with a capture efficiency greater than 80%.	CCS full chain technologies not proven at full commercial scale.

TABLE 6
Summary of CO_2 reduction strategies.
Reproduced from Leung et al. 2014 [47].

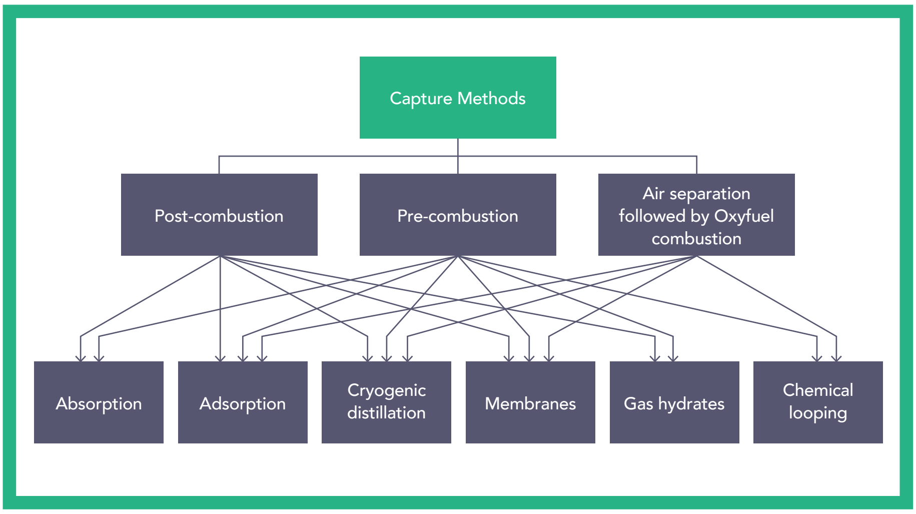
3.2. Carbon Capture and Storage

Carbon capture and storage (CCS) refers to a process that separates CO_2 from a gas stream and stores it underground. CCS can be applied to power generation and industrial facilities and includes three main steps:

- The separation of CO_2 from the gas stream
- CO_2 compression and transport (via pipeline or shipping)
- CO_2 storage in a suitable geological site (e.g. saline aquifers and depleted oil and gas reservoirs).

CCS is categorised according to the class of capture process (post-combustion, pre-combustion, and oxy-combustion) and type of separation technology (absorption, adsorption, membranes, cryogenic distillation, gas hydrates, and chemical looping) [48], as represented in Figure 3.

FIGURE 3
Various technologies and methods used for the capture of CO_2 [48].



3.2.1. Capture processes

The three main capture processes include post-combustion capture, pre-combustion capture and oxy-combustion capture:

- **Post-combustion** capture involves the separation of carbon dioxide from a flue stream after a fossil fuel has been combusted. Figure 4 represents an example of post-combustion capture applied to a coal-fired power plant.
- **Pre-combustion** CCS separates CO_2 from a hydrogen-rich gas called syngas prior to combustion. The syngas is obtained by gasification of a fuel, as represented in Figure 5.
- **Oxy-combustion** capture is characterised by the combustion of a fossil fuel with enriched oxygen. This generates a flue stream without impurities, where CO_2 can be separated more easily by condensing the water vapour (Figure 6).

Advantages and disadvantages of the various capture processes are summarised in Table 7. Technology Readiness Levels (TRLs) evaluate the stage of development for various technologies. The National Aeronautics and Space Administration (NASA) has proposed a range of TRLs from 1 to 9, where TRL1 means "basic principles observed and reported" and TRL 9 means "actual system flight proven through successful mission operations" [49, 50].

The same evaluation system has been adopted by Rubin et al. [51] who classified:

- **Post-combustion** capture processes between TRL 1 and TRL 5 (due to the early stages of technology development for this capture process);
- **Pre-combustion** capture processes as still "likely (to be) decades away from commercial reality";
- **Oxy-combustion** processes as "at the early stages of development", without a clear possibility to understand its future development.

While post-combustion and pre-combustion capture technologies are widely used, at the moment there is only one full-scale installation of a coal-power plant, the Boundary Dam Carbon Capture Project [52]. Oxy-combustion capture is still under development and not yet commercial [51].

FIGURE 4
Simplified schematic of a coal-fired power plant with post-combustion CO_2 capture using an amine scrubber system.
Other major air pollutants (nitrogen oxides, particulate matter and sulphur dioxide) are removed from the flue gas prior to CO_2 capture [51, 53].

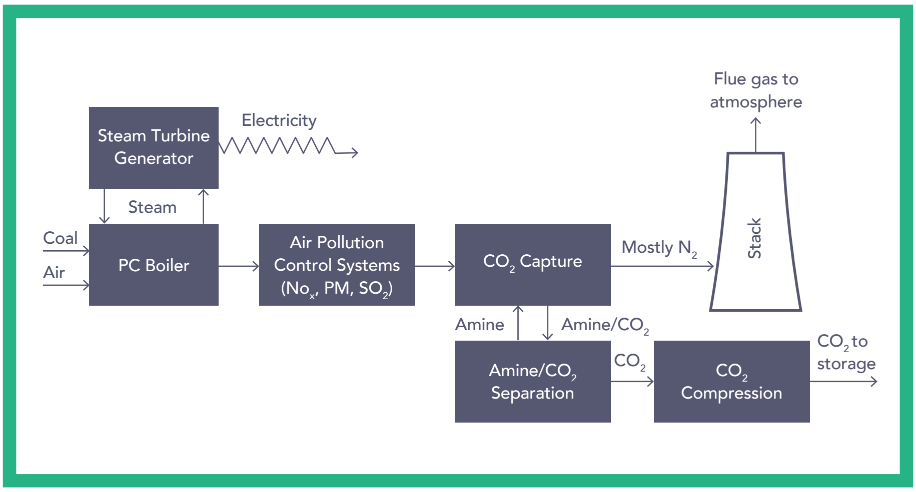


FIGURE 5
Simplified schematic of an integrated gasification combined cycle (IGCC) coal power plant with pre-combustion CO_2 capture using a water-gas shift reactor and a Selexol CO_2 separation system [51, 53].

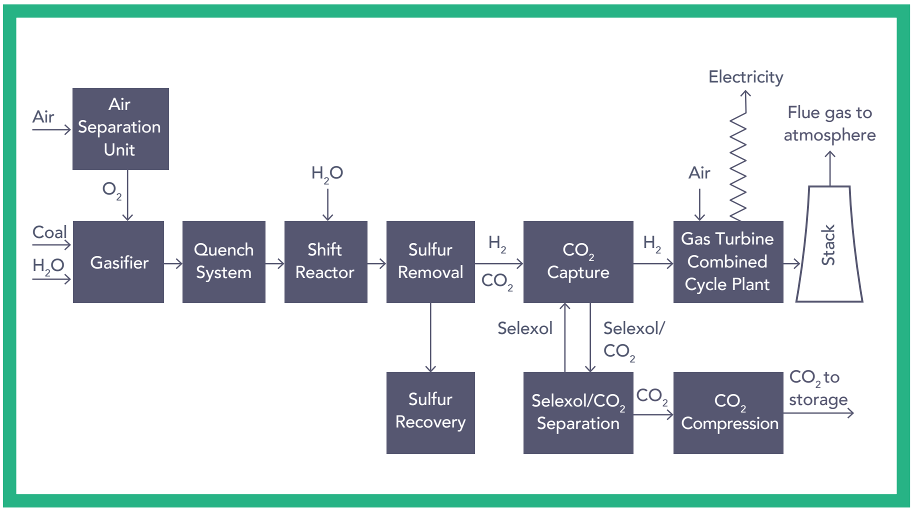
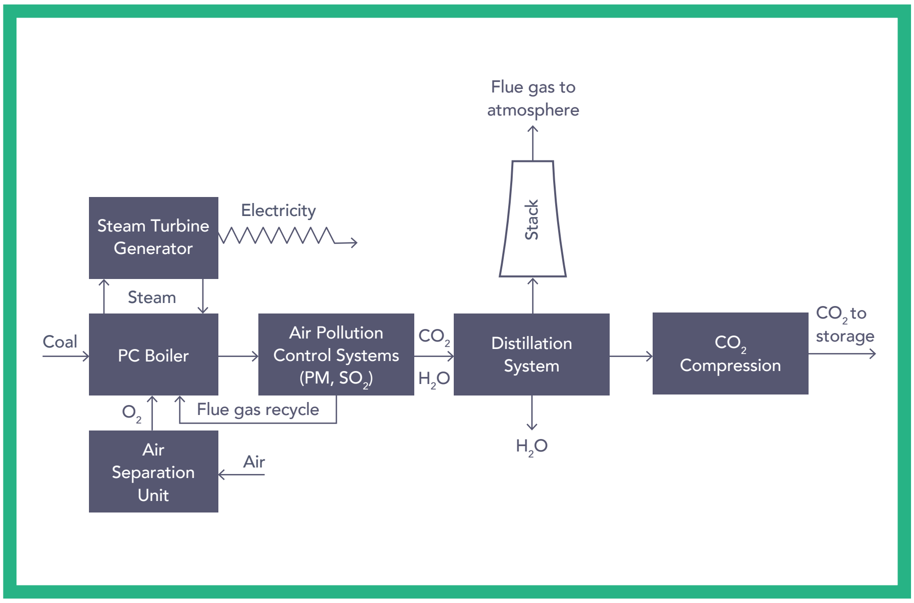


FIGURE 6
Simplified schematic of a coal-fired power plant using oxy-combustion technology.
Details of plant designs vary across studies. The step shown as a distillation system may include the removal of trace pollutants. Removal of water vapour often is integrated with CO_2 compression [51, 53].



Capture process	Application area	Advantages	Disadvantages
Post-combustion	Coal-fired and gas-fired plants	• Technology more mature than other alternatives. • Can easily retrofit into existing plants.	• Low CO_2 concentration affects carbon efficiency.
Pre-combustion	Coal-gasification plants	• High CO_2 concentration enhance sorption efficiency. • Fully developed technology, commercial deployed at the required scale in some industrial sectors. • Opportunity for retrofit to existing plant.	• Temperature associated heat transfer problem and efficiency decay issues associated with the use of hydrogen-rich gas turbine fuel. • High parasitic power requirement for sorbent regeneration. • Inadequate experience due to few gasification plants currently operated in the market. • High capital and operating costs for current sorption systems.
Oxyfuel combustion	Coal-fired and gas-fired plants	• Very high CO_2 concentration that enhances absorption efficiency; mature air separation technologies available. • Reduced volume of gas to be treated, hence requited smaller boiler and other equipment.	• High efficiency drop and energy penalty. • Cyogenic oxygen production is costly. • Corrosion problem may arise.
Chemical looping combustion	Coal gasification plants	• CO_2 is the main combustion product, which remains unmixed with nitrogen thus avoiding energy intensive air separation.	• Process is still under development and there is inadequate large-scale operation experience.

TABLE 7
Advantages and disadvantages of different CO_2 capture technologies.
Reproduced from Leung et al. 2014 [47].

3.2.2. Separation technologies

The main separation technologies include absorption, adsorption, membranes, cryogenic distillation, gas hydrates and chemical looping [48, 54, 55]. CO_2 capture based on absorption processes include amine-based process, chilled ammonia process, carbonation/calcination cycles and amino acid salt solutions while adsorption include pressure/vacuum swing adsorption and thermal/electric swing adsorption [55]. All these technologies can be used in the three capture processes previously mentioned (see Figure 3). Advantages and disadvantages of the CO_2 separation technologies have been summarised in Table 8.

Photo caption: Inside Imperial College London's Carbon Capture Pilot Plant

Technology	Advantages	Disadvantages
Physical absorption	• Low toxicity. • Low corrosion. • Low energy consumption.	• Low capacity. • High capital and operational costs.
Chemical absorption	• Well-understood technology, already implemented in large-scale in different industries. • Suitable for retrofit. • Applicable to separation of CO_2 at low concentrations. • Recovery rates of up to 95%. • Product purity >99 volume percent (vol%). • Low vapour pressure. • Non-toxicity. • Thermal stability.	• Significant energy requirement due to solvent regeneration. • Solvent loss. • Degradation and equipment corrosion. • Environmental impacts due to solvent emissions. • Large absorber volume. • High viscosity. • High regeneration energy requirement. • High unit costs.
Physical adsorption	• Regeneration and CO_2 recovery is less energy extensive. • CO_2 and Hydrogen Suphide (H_2S) capture can be combined. • High pore size and tunable pore structure (mesoporous silica and metal-organic frameworks).	• Difficulty in handling solids. • Slow adsorption kinetics. • Low CO_2 selectivity. • Thermal, chemical, and mechanical instability in cycling.
Chemical adsorption	• High adsorption capacity. • Low cost in natural minerals. • Exothermal reaction.	• Loss of sorption capacity over multiple cycles. • Low CO_2 selectivity. • Diffusion resistance issue.
Membrane technology	• No regeneration process. • Simple modular system. • No waste streams.	• Plugging of membranes by impurities in the gas stream. • Not proven industrially.
Oxy-fuel	• Relatively simple technology. • Suitable for retrofit. • Significantly less NOx.	• Significant energy requirement for separation of oxygen (O_2) from air.
Chemical looping combustion	• Well-known technology. • Suitable for retrofit. • Cheap and abundant sorbent (limestone). • Harmless exhaust gas stream. • No thermal formation of NOx. • Less energy penalty and operational costs.	• No large-scale demonstration. • Decay in sorbent's capture capacity.
Hydrate-based separation	• Small energy penalty.	• New technology and more research and development is required.
Cryogenic distillation	• Mature technology. • Adopted for many years in industry for CO_2 recovery.	• Only viable for very high CO_2 concentration > 90% volume/volume (v/v). • Should be conducted at very low temperature. • Process is very energy intensive.

TABLE 8
Advantages and disadvantages of different CO_2 separation technologies.
Modified from [47, 48].

3.2.3. Negative emission technologies and bio-energy with CCS

Carbon capture and storage (CCS) can be integrated in processes classified as carbon-positive, near carbon-neutral or carbon-negative. Carbon-positive processes still emit CO_2 to the atmosphere, while near-carbon neutral do not and carbon-negative process reduce the amount of CO_2 which is already in the atmosphere [56].

Carbon-negative processes include Bio-Energy with CCS (BECCS) such as co-firing of biomass in power generation plants and capturing and storing CO_2 with CCS. Some bio-CCS technologies include electricity production [pulverized coal (PC)-CCS co-firing, circulating fluidised bed (CFB)-CCS dedicated and integrated gasification combined cycle (IGCC)-CCS co-firing] and biofuel production [bio-ethanol advanced generation and fischer tropsch (FT) biodiesel] [57]. BECCS are part of a class of technologies known as Negative Emission Technologies (NETs), which also include reforestation and afforestation, various forms of geo-engineering, carbon dioxide removal (CDR) such as CO_2 capture from the air and ocean fertilisation [58].

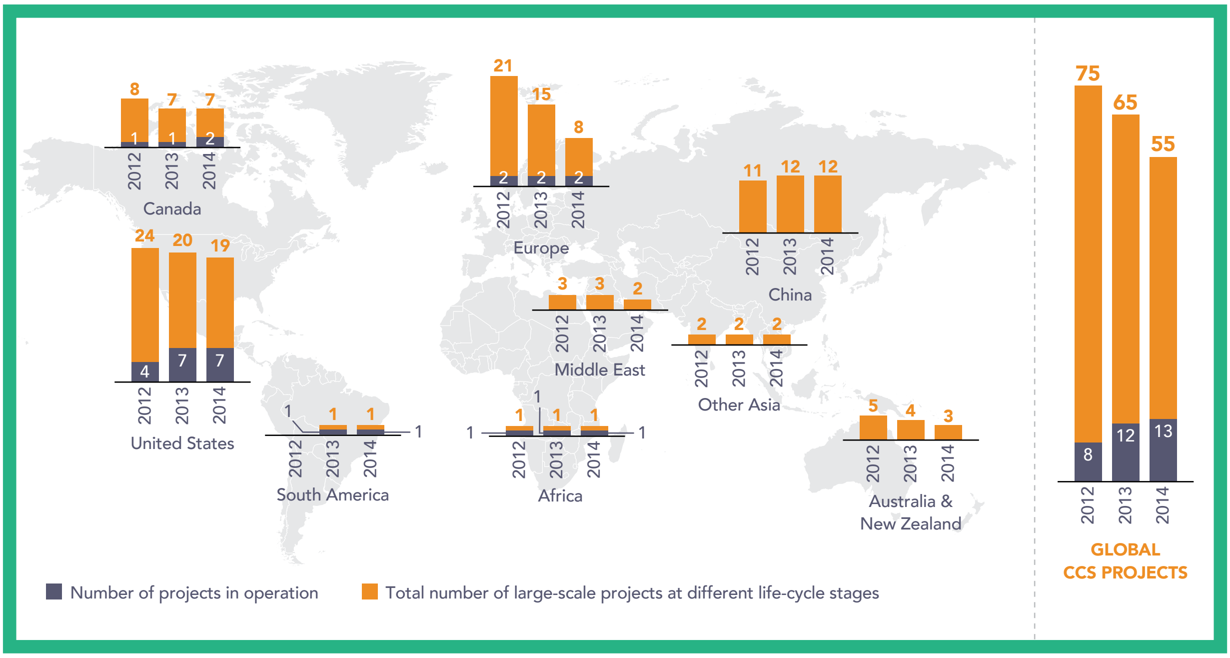
BECCS and reforestation would arguably be the most attractive options to create negative emissions [58]. According to McLaren [59], NETs cannot be expected to offer an economically viable alternative to mitigation in the coming decades. At the same time, their limited deployment (10–20 $GtCO_2$/yr) can help reducing the overall CO_2 emissions by 2030–2050.

3.2.4. Current status of CCS

According to the Global CCS Institute [60], there are currently 55 large-scale CCS projects worldwide in either 'identify', 'evaluate', 'define', 'execute' or 'operate' stage. Nineteen of these projects are based in the US, followed by China (12 projects) and Europe (8 projects). Ten of the operating projects are based in the US [61] and all of these are part of industrial applications where CO_2 separation is already employed for other purposes.

Figure 7 reports the number of large-scale CCS projects and how it has changed in the past three years. The total number has reduced from 75 (2012) to 65 (2013) to 55 currently (2014). At the same time, the number of projects in the "operate" phase has increased from eight (2012) to 13 (2014).

FIGURE 7
Large-scale CCS projects by year and region/country [62–64].



4. Barriers to CCS development

The main challenges identified as barriers to the uptake up of carbon capture and storage (CCS) are cost, energy penalty, and location as well as capacity of storage sites.

Several barriers are non-technical, including [47, 65, 66]:

- Lack of market mechanism/incentive
- Few effective mechanisms to penalise major CO_2 emitting sources
- Inadequate legal framework allowing transport and storage (both inland and offshore)
- Public awareness and perception.

At the current CO_2 capture rate (i.e. the percentage of CO_2 that will be captured and ultimately sequestered), no major purely technological barriers exist for all stages of the process of capture, transport and storage of CO_2. In fact CO_2 separation and reinjection is a common feature of regular oil and gas industry operations. At the same time, the cost of capturing CO_2 in a non-regulated market is preventing progress.

The main factors determining the feasibility of location and capacity of storage sites include [67]:

- Cumulative capacity of carbon storage
- Rates of release and uptake
- Connection from source to store
- Climate impact of storage timescale.

This section of the report investigates the major barriers that have been identified, including: supply chain and building rate; geo-storage capacity and source-sink matching; cost of CCS; market and regulation; public acceptance and requirement for Research, Development and Demonstration (R,D&D).

4.1. Supply chain and building rate

In the literature, the rate of technology deployment and cost reduction of CCS has been compared to development timescales in the oil and gas industry (e.g. 3–5 years for the build-up of a giant gas field, according to Söderbergh et al. [68]), and also to the more recent experience of implementation of post-combustion capture of sulphur oxides and nitrogen oxides at coal-fired power plants based in the US [51].

In 2012, IEAGHG commissioned a study on the potential supply and capacity constraints associated with equipment for CCS plants [69]. The study focused on the global scale and included the full CCS chain (capture, transport and storage) but excluded the power or industry equipment. Part of the purpose of this study was to understand if the CCS roadmap proposed by the IEA [70] could meet major barriers of supply or capacity constraints. The results of the study have been summarised in Figure 8, where major potential supply chain constraints include hydrogen turbines for the capture step, pipelines for the transport step, geo-engineers and drilling rigs for the storage step as well as a shortage of petroleum engineers across the full CCS chain.

The conclusion of the IEAGHG study did not identify any insurmountable obstacles to the deployment of CCS suggested in IEA 2011 [70]. However, they found that the construction rate for CCS applied to the power industry would be lower than historical power plant construction rates. In addition, the suggested deployment of CCS in the industrial sectors (capture of 65% of current emissions by 2050) has been considered optimistic. Overall, the most significant risk is represented by the competition between CCS and the oil and gas sector for experienced staff and drilling equipment necessary for exploration activities. Similar issues have been identified in a study on the UK market [71].

Similar challenges have been discussed in an interview with CCS developers during the course of this project, where the following issues were cited to be important when considering barriers to CCS:

- **Geological appraisal and power station build.** The geological appraisal of a store takes 3–4 years, while a power station build takes 3–4 years for gas turbines and 5–6 years for solid-fuelled systems. Therefore, if appraisal and power station build are simultaneous, the CCS aspect may be on the critical path. But if the power station build is dependent on the suitability of the store, appraisal may need to proceed prior to power station build. However, if national CO_2 transportation infrastructure were already present, any dependency would be largely eliminated.
- **Availability of skilled labour.** The availability of a sufficiently skilled labour force could represent a bottleneck in the long-term. However, in the short-term, there may be a larger workforce available due to the recently depressed oil and gas prices which has resulted in a number of job losses [72]. For example, the White Rose project in the UK was estimated to need on-average 4,000–5,000 people over approximately five years, with a peak demand for 9,000 people.
- **Regulatory shortfalls.** At present the regulatory environment for CCS infrastructure is not well developed, which has lead to uncertainty regarding development timeframes and price models.

The process of the 3–4 year appraisal period for a CCS site is not new, and is already regularly undertaken by the oil and gas industry. Overall, construction-related barriers to CCS development appear to be a minor issue so the risk is largely non-technical in nature, which could mean that financial environments and/or regulation will change significantly over the construction period.

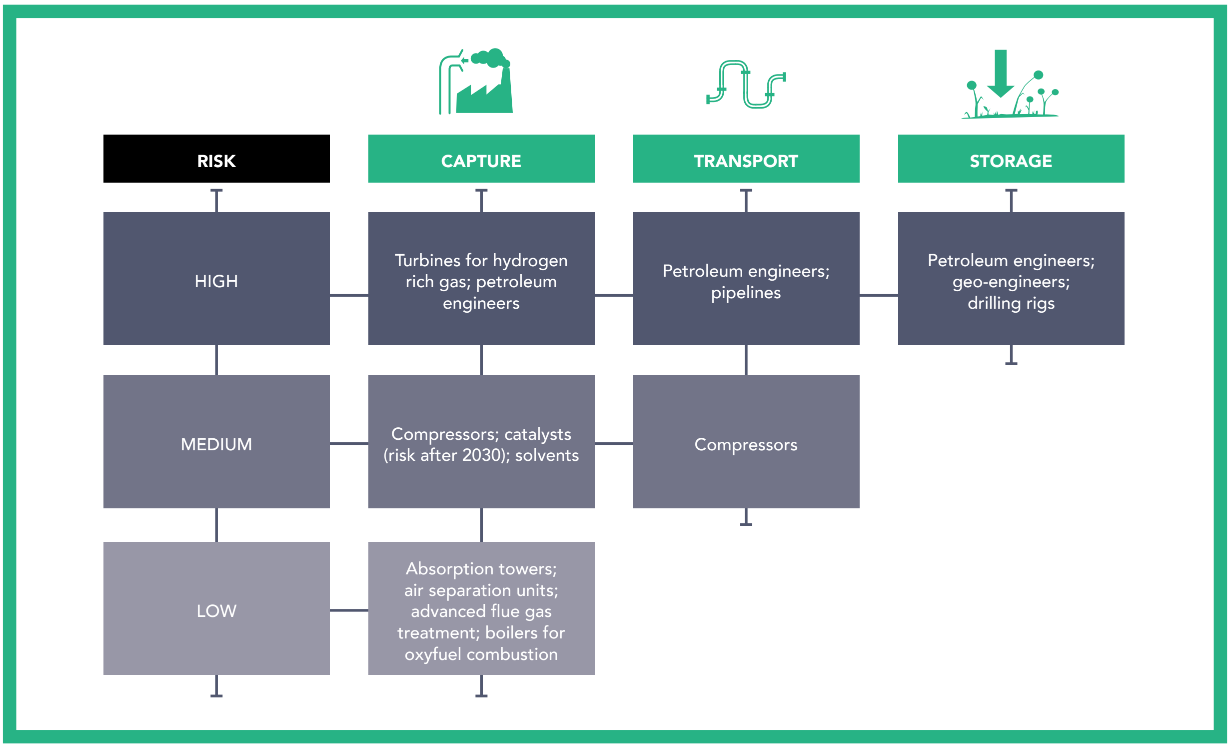


FIGURE 8
Overview of the risks of supply chain constraints for CCS equipment and services and skills.
Modified from IEAGHG [69].

4.2. Geo-storage capacity

A recent report by IEAGHG in 2016 [73] has drawn some important conclusions on geo-storage capacity for carbon dioxide and reservoir pressurisation in saline aquifers. The report concluded that global CO_2 geo-storage capacity is much larger than the CO_2 embodied in present-day fossil fuel reserves. The global capacity is reported in the range of 10,000–30,000 $GtCO_2$ including 1,000 Gt in depleted oil and gas reservoirs. This is well above the extent of known fossil fuel reserves, by approximately one order of magnitude. These assessments compile regional estimates of capacity which as a rule calculate capacity as a fraction of the total volume of the pore space in the geologic formation, which is known as the volumetric approach.

The paper by IEAGHG [73] also concluded that reservoir pressurisation in saline aquifers will limit the accessible CO_2 geo-storage capacity in the absence of pressure management strategies. Recent work using detailed reservoir simulation and other modelling approaches has found that only 0.01–1% of the pore volume of saline aquifers will be available for storage, in the absence of brine production from the reservoir. This is due to the requirement that pressures in the reservoir remain below that which would fracture sealing caprock. The exact fraction of available pore space has complex dependencies on reservoir, rock, and fluid properties and is only reasonably estimated using dynamic modelling.

Dynamic models provide time-varying resource estimates and provide the most realistic estimates of a true storage capacity. Currently, only one such dynamic estimate has been made for an entire region – the US, by Szulczewski et al. [74]. However, due to storage capacity in oil and gas fields, and high quality saline aquifer reservoirs, the impact of this issue is not likely to be felt until after the first generation of CCS plants have been deployed (i.e. post 2050).

Figure 9 summarises recent estimates of CO_2 storage resources and their regional distribution. The reported storage capacity implies that decades to centuries of storage resource is available. On the other hand, these estimates are as a rule volumetric and it appears possible that, in the absence of pressure management, the amount of storage space available within 50 years of the start of commercial deployment are one to two orders of magnitude lower in some locations.

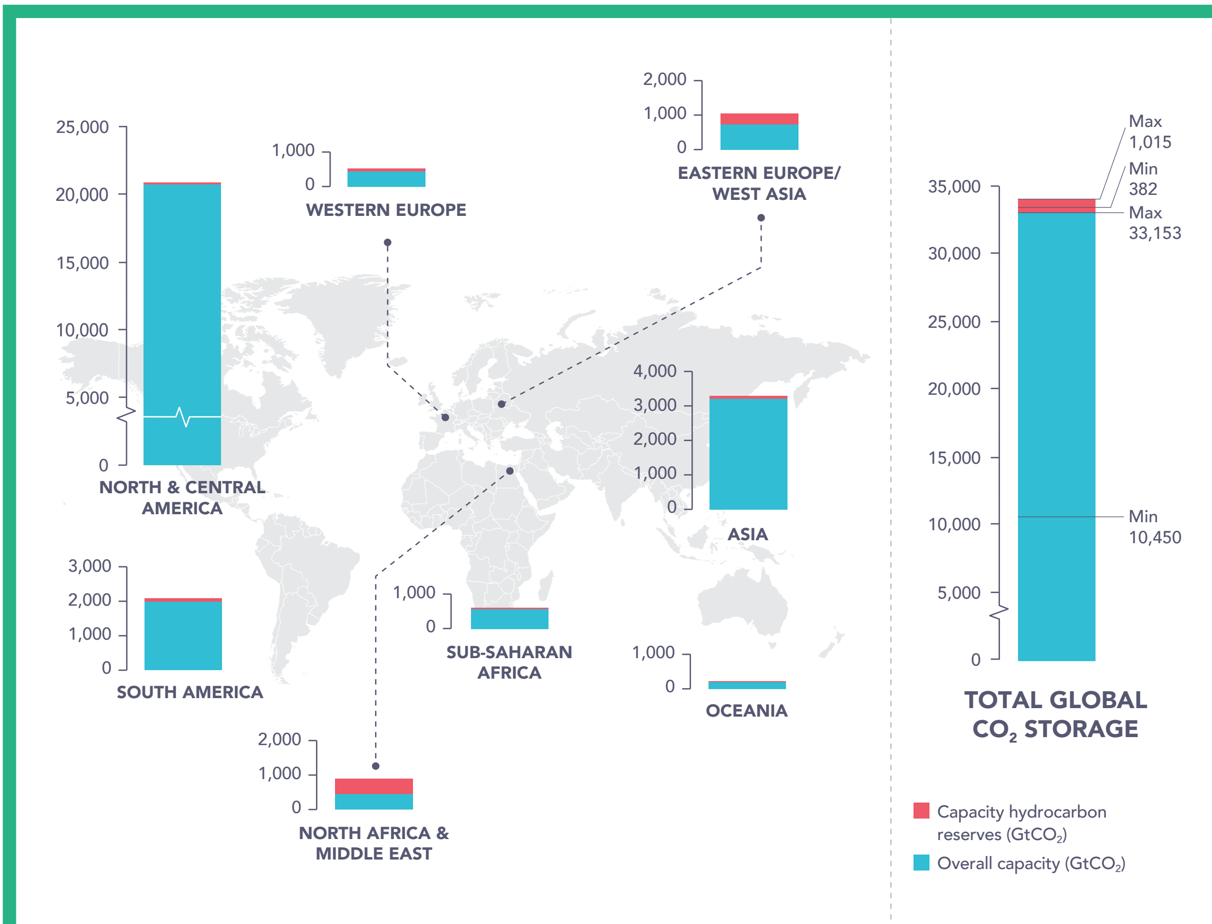
A more significant measure than total CO_2 emissions is the demand for CO_2 storage resource, which is generally only a fraction of a total emissions reduction portfolio. A paper by Dooley et al., in 2013 [75] has placed global demand for CO_2 storage in a climate scenario maintaining CO_2 concentrations at 400–500 ppm at an accumulated store of 1,340 $GtCO_2$ by 2100. Thus, there is sufficient pore space available to accommodate CO_2. The major uncertainty is the extent to which pressure management strategies would be required to use the demanded storage space, and the subsequent cost impact on total deployment.

Only a few studies have evaluated the impact of a potential limit on storage capacity on the deployment of CCS in integrated assessment models [76–79]. In Koelbl et al. [78] the varying levels of deployment of CCS in 12 integrated assessment models were assessed against several assumptions, including the existence of global and regional capacity constraints, which ranged from 3,500 to 20,000 Gt, similar to the range in Figure 9. The maximum cumulative storage demand was 3,000 $GtCO_2$ by 2100. Because the limiting capacity was not reached, the varying levels of deployment in the models were not correlated to the total CO_2 storage supply.

A sensitivity study of one model in Koelbl et al. [79], also showed that the deployment of CO_2 storage until 2050 was not sensitive to a regional storage capacity estimates ranging from 4,500 – 10,000 $GtCO_2$. The primary reason was again because the capacity in most regions was not reached by 2050. On the other hand, the study found that storage could be limited beyond 100 years of full-scale deployment should there be significant uptake of CCS.

Keppo and van der Zwaan in 2012 [77] analysed the impact of more severe constraints on CO_2 storage capacity until 2100 – comparing a scenario with baseline capacity similar to those provided in Figure 9 with a pessimistic scenario where capacity is limited to half that available in depleted oil and gas fields alone. This corresponds to a reduction of global capacity from approximately 10,000 to 500 $GtCO_2$ (when comparing hydrocarbon and non-hydrocarbon storage resources). By 2100, CCS deployment is very limited due to the capacity constraints. However, the early deployment of CCS until 2050, prior to the approach of capacity constraints, is mostly unaffected. Implicit in this is that volumetric estimates of global storage capacity are only an order of magnitude from levels where the deployment over the next century would be affected.

In Figure 9, an estimated 1,000 Gt of storage capacity is available in oil and gas (hydrocarbon) reservoirs alone. The analysis of integrated assessment models in Koelbl et al. [78] showed that from 2010 to 2050 between 100 and 500 Gt of storage demand would be consistent with a 2 °C pathway. This suggests that there will be few storage capacity limits for the first generation of commercial CCS deployment, even under scenarios of high demand for CCS, as all of the demand can be met with very low cost storage options, such as capacity within oil and gas fields.



	1. Cook/Zakkour [86]		2. Benson [87]		3. Hendriks/Graus [82] Koebl [78]	
	Overall capacity ($GtCO_2$)	Capacity hydrocarbon reserves ($GtCO_2$)	Overall capacity ($GtCO_2$)	Capacity hydrocarbon reserves ($GtCO_2$)	Overall capacity ($GtCO_2$)	Capacity hydrocarbon reserves ($GtCO_2$)
North and Central America	1,949 → 20,821	140	1,856 → 20,473	143	8,321	116
South America	2,003	3	2,000 → 2,000	89	163	69
Asia	2,651 → 2,801	9	1,447 → 3,226	72	490	82
Oceania	40 → 202		59 → 59	20	31	18
North Africa and Middle East	10 → 10	210	449 → 449	440	362	304
Western Europe	136 → 455	20	117 → 381	20	142	77
Eastern Europe/West Asia			177 → 177	177	737	316
Sub-Saharan Africa	152 → 152		48 → 48	37	569	33
Global	11,954 → 30,109	382	10,450 → 33,153	997	10,817	1,015

Minimum → Maximum

FIGURE 9
Regional distribution of CO_2 storage capacity in hydrocarbon and non-hydrocarbon reservoirs [73, 78, 82, 86, 87].

Integrated assessment models incorporate potential storage cost limitations through a set of rules that generally ignore the issues of pressurisation and pressure management. The most flexible storage cost supply curves have been developed by Dooley and Friedman [80] for North America, and by Dahowski et al. [81] for China. A commonly used regionally distributed supply cost curve for the rest of the globe was developed by Hendriks and Graus [82]. Notably, these datasets were developed prior to the work done by Birkholzer and Zhou [83], demonstrating the first order impacts of regional pressure build-up on storage capacity. Key capacity constraints built into the supply curves include total capacity, and the requirement that supply must be available for a particular source for a minimum of 10 years.

Pressurisation is partially taken into account by limiting the amount of CO_2 that can be injected into a single well – a proxy for the risk of near wellbore fracturing. The impact of this limit, however, is the construction of a new well in the storage basin when costs are justified. While local injectivity may be dealt with in this way regional pressurisation of the storage resource may not [84]. Thus, an additional constraint should be built into the models in which regional pressurisation may trigger the deployment of pressure management strategies. Pressure management and the handling of waste brine are longstanding practices in the oil and gas industry. As such, costs estimates suitable for use in integrated assessment models should be readily available from existing literature [85], or by interviews with relevant oilfield operators.

4.3. Source-sink matching

Some studies have evaluated the impact of a potential limit on storage capacity on the deployment of CCS in integrated assessment models [77, 79]. Koelbl et al. [79] addresses the issue of regional distribution of storage. In his study, storage supply was found to be limited in China, Japan, and South Korea. Storage capacity in Japan and South Korea is highly uncertain with some estimating significant resources offshore, particularly in Japan that would provide a sufficient supply for decades at least [88]. In the case of China, the model appears to use values for storage capacity that are a factor of three less than those reported in the source data of Dahowski et al. [81] and CCS is being actively pursued as a large-scale mitigation technology [89].

In general, where regional storage supply estimates are most developed (e.g. North America, Europe including Scandinavia, and Brazil), source-sink matching shows that CCS will not be constrained by local availability of storage resources. Outside of these areas, storage availability is highly uncertain, although the global distribution of sedimentary basins is such that it is possible that there will be few locations where local storage availability will be a limiting factor.

4.4. Cost of CCS

While it is evident that the cost of carbon capture and storage is one of the main barriers, estimating actual cost and expressing it in a clear way is challenging.

The reasons relate to:

- A lack of empirical data (currently, there is in the power sector only one full scale CCS plant in operation [52])
- Difficulty in choosing the baseline when comparing different CCS plants
- A variety of currencies and currency base year in the reported literature
- Marginal cost differences due to availability/unavailability of transport and storage infrastructure
- A variety of processes, operating conditions and capture processes.

This section reports on how the cost of CCS can be expressed and which values have been estimated in the literature. Costs have been reported in $2015 by converting single currencies into US dollars and then taking inflation into account.

4.4.1. How to express the cost of CCS

Various metrics have been suggested to estimate or measure the cost of carbon capture and storage and they depend on the system under analysis and on the purpose of the analysis itself.

The cost of CCS is often expressed as an energy or efficiency penalty, where the performance of a plant without CCS is compared with the performance of the same plant with CCS. Energy penalty applies to the power generation sector while efficiency penalty can be used for both power and industrial sectors.

Energy penalty and efficiency penalty have been expressed by means of the following equations:

$$\text{Energy penalty} = 100\left(\frac{\text{Power output without CCS} - \text{Power output with CCS}}{\text{Power output without CCS}}\right) \quad (1)$$

$$\text{Efficiency penalty} = \text{Efficiency without CCS (\%)} - \text{Efficiency with CCS (\%)} \quad (2)$$

While Equation (1) gives “the proportional loss in power output capacity with reference to a base case without capture”, Equation (2) shows “the decrease in plant efficiency percentage points due to capture” [90].

For the power sector, the Levelized Cost Of Electricity (LCOE) is often used ($/MWh). LCOE is often labelled as increased Cost Of Electricity (COE), expressed as [91]:

$$\text{COE} = \left(\frac{\text{(TCC) (FCF)} + \text{(FOM)}}{\text{(CF) (8,766) (MW)}}\right) + \text{VOM} + \text{(HR) (FC)} \quad (3)$$

where COE = cost of electricity generation ($/MWh), TCC = total capital costs ($), FCF = fixed charge factor (fraction/year), FOM = fixed operating and maintenance costs ($/year), VOM = variable non-fuel operating and maintenance costs ($/MWh), HR = net power plant heat rate (MJ/MWh), FC = unit fuel cost ($/MJ), CF = plant capacity factor (fraction), 8,766 = total hours in an average year and MW = net plant capacity (MW).

The cost of CCS can also be expressed as a cost of carbon ($/t$CO_2$), which may refer to the CO_2 avoided, captured or abated, as reported in equations (4), (5) and (6) [91, 92]. The equations refer to the power generation sector, where COE is the cost of electricity generation ($/MWh) while NPV is the net present value cost of the specified scenarios. The subscripts "CCS", "ref" and "cc" refer respectively to plants with CCS, plants without CCS and to the capture step only.

The cost of avoided CO_2 is inclusive of capture, transport and storage steps, and therefore represents the full CCS chain. At the same time, it heavily depends on the baseline ("ref") that is used for the comparison, which may or may not be the same type of plant as "CCS". The cost of captured CO_2 refers only to the capture step, without taking into account transport or storage. Finally, the cost of abated (or reduced) CO_2 refers to multiple CO_2 emission sources and therefore has been suggested as being more appropriate for integrated assessment models as it enables comparison of different energy systems. The subscripts "ref" and "low-C" refer to values before and after a specified carbon reduction scenario [91].

$$\text{Cost of avoided } CO_2 = \left(\frac{(COE)_{cc} - (COE)_{ref}}{(tCO_2/MWh)_{ref} - (tCO_2/MWh)_{ccs}} \right) \quad (4)$$

$$\text{Cost of captured } CO_2 = \left(\frac{(COE)_{ccs} - (COE)_{ref}}{(tCO_2/MWh)_{captured}} \right) \quad (5)$$

$$\text{Cost of abated } CO_2 = \left(\frac{(NVP)_{low-c} - (NVP)_{ref}}{(tCO_2)_{ref} - (tCO_2)_{low-c}} \right) \quad (6)$$

Finally, the cost of CCS can be reported in the literature in a more traditional way by estimating capital and operating costs.

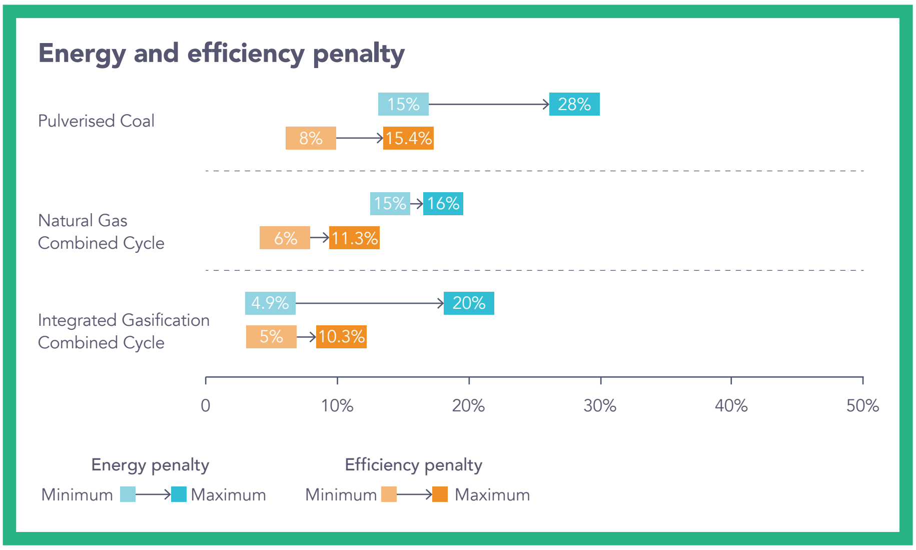
4.4.2. Energy and efficiency penalty

According to Clark and Herzog [93], the major barrier to CCS in the power industry is the high capital cost and energy penalty compared to traditional fossil fuel fired generators. For example, the net efficiency penalty (lower heating value, LHV) of CCS for coal-fired power generation is about 10% [94]. This penalty does not depend on the type of power plant but rather on the capture process, which contributes to about two thirds of the overall energy penalty.

In a study by Hammond et al. [95], the energy penalty of a pulverised–coal (PC) power plant is about 16% and it is higher than the energy penalty associated with integrated gasification combined cycle (about 9%) and natural gas combined cycle (NGCC) plants (about 7%) when combined with carbon capture and storage.

According to Page et al. [90], energy penalty values for PC plants with capture range from 15% to 28% while efficiency penalties range from 8% to 15.4%. For (NGCC) plants, the energy penalty is around 15–16% while the efficiency penalty varies between 6% and 11.3%. Finally, the energy penalty for IGCC plants varies from 4.9% to 20% while the efficiency penalty ranges from 5% to 10.3%.

FIGURE 10
Energy and efficiency penalty for pulverised coal (PC), natural gas combined cycle (NGCC) and integrated gasification combined cycle (IGCC) power plants.
[90, 94, 95]



4.4.3. Capture cost

The cost of captured CO_2 refers only to the capture step and does not include transport or storage costs. However, various sources report different capture costs depending on the type of storage site. This is because the cost of captured CO_2 depends on Cost Of Electricity (COE) [equation (5)], which in turns depends on the type of storage site [equation (3)].

FIGURE 11
Cost of captured CO_2 for different process plants, capture technologies and storage solutions.
*References are in brackets

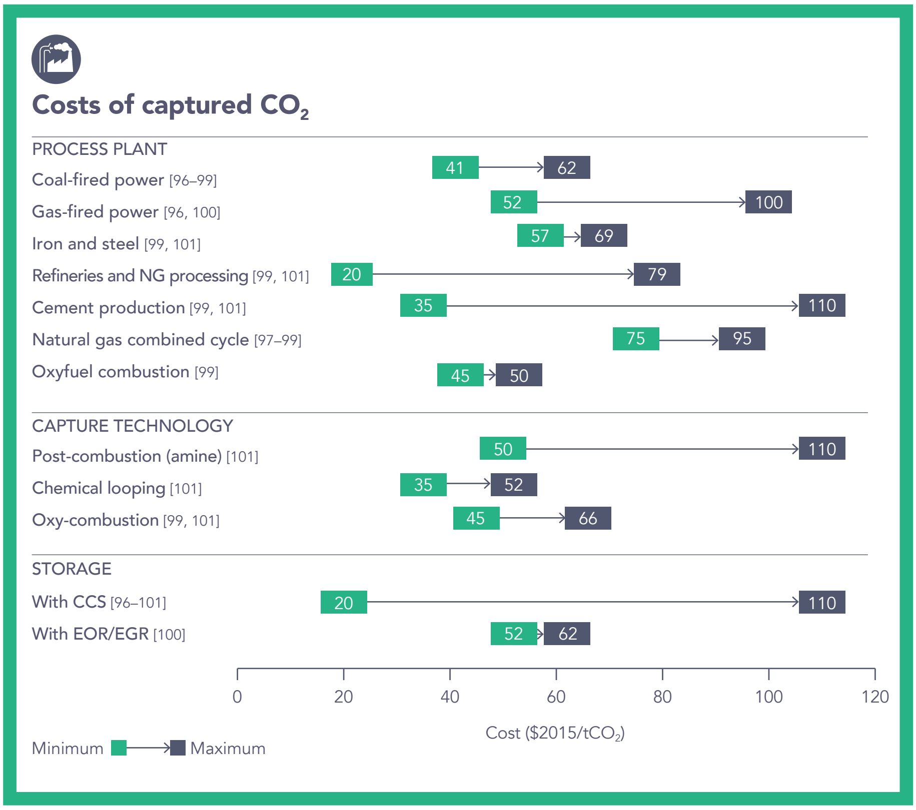


Figure 11 reports the cost of captured CO_2 for process plant, capture technology and storage solution. The main reported industries include power generation, refineries, iron and steel and cement production. The main reported capture technologies include post-combustion separation with amine, oxy-combustion and chemical looping combustion. There is a wide variety of reported costs, ranging from 20 \$2015/tCO_2 (refineries and natural gas processing) to 100 \$2015/tCO_2 (cement production). Post-combustion with amine separation presents the highest maximum cost (110 \$2015/tCO_2) while storage via enhanced oil recovery/enhanced gas recovery (EOR/EGS) has a smaller range characterised by a higher minimum cost but a lower maximum cost when compared to CCS storage.

4.4.4. Transport cost

Figure 12 reports the cost of CO_2 transport depending on the pipeline capacity (MtCO_2/yr) and its location (onshore or offshore). As expected, the lowest cost of transport refers to the onshore pipelines which have a higher capacity (1.3–2.2 \$2015/tCO_2/250 km with capacity 30 MtCO_2/yr).

FIGURE 12
Cost of CO_2 transport for onshore and offshore pipelines with different capacities.
Modified from Rubin, E.S., et al [102].

4.4.5. Storage cost

Figure 13 reports the cost of storage depending on the storage site (depleted oil and gas fields or saline formations), the location (onshore or offshore) and the possibility to reuse already existing oil and gas wells. The cheaper storage solution corresponds to the onshore depleted oil and gas fields, with a small positive margin given by reusing already existing wells.

4.4.6. Cost of avoided CO_2

Figure 14 reports the cost of avoided CO_2 according to process plant, capture technology and storage solution. This cost includes capture, transport and storage steps and depends heavily on the selection of the reference plant. Therefore, a wide variability in the cost is observed depending on the type of process plant.

FIGURE 13
Cost of CO_2 storage for various storage sites.
Modified from Rubin, E.S., et al [102].

FIGURE 14
Cost of avoided CO_2 for different process plants, capture technologies and storage solutions.

4.4.7. Cost of electricity

Figure 15 reports the cost of electricity ($2015/MWh) depending respectively on process plant, capture technology and storage solution. The lowest cost corresponds to gas-fired power generation (54 $2015/MWh) while the highest cost corresponds to integrated gasification combined cycle plants (278 $2015/MWh). The cost of electricity does not depend on the capture technology (111–265 $2015/MWh) but may be much higher when CCS is adopted instead of enhanced oil recovery/enhanced gas recovery (EOR/EGS) for the storage of CO_2.

FIGURE 15
Cost of electricity for different process plants, capture technologies and storage solutions.

4.4.8. Capital and operating costs

Capital and operating costs are shown in Table 9 for coal-fired and gas-fired power generation. Capital costs are expressed in $2015/kWel.net and represent capital expenditure (CAPEX) costs or overnight capital costs while operating costs are either fixed ($2015/kW-yr) or variable ($2015/MWh). The operating fixed costs appear to be much higher when CCS is applied to coal-fired power generation (69–84 $2015/kW-yr) compared to gas fired power generation (around 8 $2015/kW-yr).

TABLE 9
Capital and operating costs for coal and gas fired power plants.
Modified from [97, 104–105, 110]

Process plant	Capital costs ($2015/kWel.net)	Operating fixed costs ($2015/kW-yr)	Operating variable costs ($2015/MWh)
Coal-fired power	3,552 → 6,816	69 → 84	9 → 10
Gas-fired power	2,313 → 5,088	14 → 33	11 → 16

4.4.9. Discussion

The cost of CCS reported shows a great variability among sources, with a lack of data for specific processes or capture technologies.

- The capture step is definitely the most expensive step of the CCS chain, with a cost of carbon equivalent to 20–110 \$2015/tCO_2.
- Transport cost ranges between 1.3 and 15.1 \$2015/tCO_2/250km, depending on the location and length of the pipeline.
- Storage cost depends on the type of storage site and the possible reuse of existing facilities and is between 1.6 and 31.4 \$2015/tCO_2.

The overall cost of carbon for CCS can be estimated by summing the cost of carbon for capture, transport and storage steps. For example, for a pipeline length of 250 km, this cost would range between 22.9 and 156.5 \$2015/tCO_2. These numbers are comparable to those reported in Figure 14, which report the cost of carbon for the avoided CO_2.

> The operating fixed costs appear to be much higher when CCS is applied to coal-fired power generation (69–84 \$2015/kW-yr) compared to gas fired power generation (around 8 \$2015/kW-yr).

It is important to remember that the cost of CCS reported in the academic and grey literature is based on estimations which are comparing CCS technology to other similar technologies that have been recently developed. The Boundary Dam Carbon Capture Project [52] is the only full-scale commercial project currently working and therefore it represents a First Of A Kind (FOAK) project. Costs related to FOAK projects are not representative of the costs of the technology when it will be fully developed into Nth Of A Kind (NOAK) solutions. The transition from FOAK to NOAK takes place along a technology learning curve, which depends on many factors including policy regulations and market, which are discussed in the next sub-section. According to the Global CCS Institute in 2011 [99], the cost reduction of CCS from FOAK to NOAK varies between 3.4% and 8.1% for the power generation sector, while it is around 9.3% for the industrial sector (US\$ per tonne of CO_2 avoided).

Other aspects that are important to consider when estimating the cost of CCS include:

- The considerable uncertainties associated with costs of emerging CCS processes. Longer timescales are usually associated with introducing new technologies, and so far major delays have been experienced in the deployment of first generation CCS technology
- Cost comparisons that are based on baselines which keep moving due to technology development
- The CCS operating experience, which is limited and therefore capital and operating costs are subject to greater uncertainty.

4.5. Policy regulations and market

The previous sub-section summarised the cost of CCS for power generation and industrial sectors, highlighting the dominant cost of the capture step. At the moment, there is no market for CCS and this is mainly because a plant with CCS will always be more expensive (in terms of capital and operating costs) than the same plant without CCS. Enhanced oil and gas recovery options represent the only exception and have been employed for many decades. Without effective mechanisms to underpin uptake, for example a carbon price, the deployment of CCS to a level that would be adequate to meet the climate change targets will remain implausible.

Possible policy options include [111]:

- **Carbon trading**, such as the EU Emissions Trading System (EU ETS) mechanism, or carbon taxation,
- **Targeted investment support**, especially needed for the initial capital costs,
- **Feed-in schemes**, which guarantee a fixed fee in order to compensate for the higher costs of the project when compared to conventional alternatives,
- **A guaranteed carbon price for CCS**,
- **Low-carbon portfolio** standard with tradable certificates, and
- **Minimum standards**, such as a CCS obligation for new installations after 2020.

Some low-carbon initiatives that could encourage CCS include the Clean Energy Future Package in Australia, the Regional Greenhouse Gas Initiative in the US, the Western Climate Initiative (British Columbia, Manitoba, Ontario, Quebec and California), the Framework Act on Low Carbon and Green Growth in Korea, the General Law on Climate Change in Mexico, the National Policy on Climate Change in Brazil etc. [112]. According to Lohwasser and Madlener [113], the effectiveness of policies promoting 'learning-by-doing' (i.e. cumulative deployment) or 'learning-by-searching' (i.e. cumulative R&D efforts) depends on their spending levels. At lower policy costs (up to €500M), both methods are about equally effective, while at higher spending levels policies promoting cumulative deployment are more effective than those promoting R&D efforts.

In May 2015, some of the major oil and gas companies wrote to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat asking for "clear, stable, long-term, ambitious policy frameworks", stating that a price on carbon "should be a key elements of these frameworks" [114]. This would encourage a reduction of CO_2 emissions by means of increased efficiency, a fossil fuel switch (from coal to gas) as well as investment in CCS, renewable energy, smart buildings and grids and adopting new mobility business models. Moreover, a price on carbon in such a framework would avoid "uncertainty about investment and disparities in the impact of policy on business".

4.6. Public acceptance

Public acceptance has a key role in the deployment of carbon capture and storage, locally and globally. There is no general model able to explain the public acceptance of new technology; however, a framework has been proposed that includes a range of different factors affecting acceptance. These factors include attitude, knowledge, experience, trust, fairness, affect, perceived costs, risk and benefits, outcome efficacy and the perception of the problem [115].

This framework has been adapted to CCS by Seigo et al. [116], who has reviewed the analyses on public perception. According to Seigo et al. [116], the public knows that climate change exists, but is unsure about what causes it and the various mitigation options. In particular, estimates of the emissions reduction needed are underestimated while the role of renewable energies is overestimated. The risk perception focuses on sustainability of CCS, leakages and overpressurisation of the storage sites.

A further concern is that public investments in CCS would reduce the budget for renewable alternatives [116–118]. A survey of 60 participants from Pittsburgh (Pennsylvania, US) on preferences for emission reductions reported that the most preferred portfolio included energy efficiency, followed by nuclear power, integrated gasification combined-cycle coal with CCS and wind [119]. Therefore these studies report a moderate public acceptance of CCS as long as it is part of a wider portfolio of carbon emission reduction options.

The importance of informing the public in an adequate and neutral way is highlighted by Seigo [116] and other publications. For example van Alphen et al. [117] explored the effect of the media (in particular the Dutch press) on public perception of CCS and reported that media and stakeholders (government, industry, NGOs) share the same concerns on CCS, including those previously cited (i.e. sustainability, leakages from the storage site and reduced investments in renewable energy). At the same time, a lack of knowledge seems in some cases to be responsible for decreased support, and in others, for increased risk and reduced benefit perception [118]. This suggests a need for a closer collaboration between experts from engineering and communications in order to inform the public.

4.7. Requirements for Research, Development and Demonstration (R, D&D)

In 2007, the UK Government launched a competition for demonstrating post-combustion capture of CO_2 on a coal-fired power plant. In 2010, the competition was opened to gas as well and in 2013, two bidders were announced: the White Rose project and the Peterhead project.

The White Rose project includes a coal-fired power plant proposed by Capture Power, which was formed by GE, Drax and BOC [120]. The Peterhead project was proposed by Scottish and Southern Energy (SSE) and Shell and is a full-scale gas CCS project. However, in November 2015, by means of the Chancellor's Autumn Statement, the UK Government confirmed that the £1 billion ring-fenced capital budget for the Carbon Capture and Storage (CCS) Competition was no longer available [120, 121]. At the time of writing, Capture Power, SSE and Shell have not released formal communications regarding the destinies of these two projects. Outside the UK, the Boundary Dam project [52] is the only commercial full-scale CCS plant currently working in the power sector.

Given the cost of CCS-enabled facilities relative to their non-CCS counterparts, it is clear that CCS demonstration projects will not proceed unless there is policy support for them. According to Boot-Handford et al. [54], this technology risks being squeezed between low variable cost technologies such as nuclear and wind, and low capital cost technologies such as combined cycle gas turbine (CCGT). Moreover private investment in CCS is hampered by various risks including technology and construction issues, high up-front capital costs, infrastructure barriers, and significant operating costs (also affected by a fuel price risk).

5. Analysis of Integrated Assessment Models

5.1. Transformation of the energy sector

5.1.1. Outlooks produced by industry

The reduction of atmospheric emissions has also been taken into account in some scenarios produced by industry. Examples include BP [28], Shell [122] and ExxonMobil[4] [123]. While BP highlights the role of gas as a cleaner fossil fuel for power generation in future projections, encouraging research and development toward higher energy efficiency routes, Shell and ExxonMobil explicitly mention CCS as a technology that is able to reduce carbon emissions. While ExxonMobil says that the development of CCS could be significantly limited by "economic and practical hurdles", Shell propose energy scenarios in which CCS plays a key role, having a world capacity of 20 GW by 2020 and capturing 10 $GtCO_2$/yr by around 2045. This would help to decarbonise electricity by 2060 and reduce world CO_2 emissions to zero by 2100 [122].

5.1.2. Selected analyses

The role of CCS in future energy scenarios has been analysed by various authors. In this report, we focus on three sources that have explicitly investigated CCS in the context of unburnable carbon in their projections. These sources are:

1. **Carbon Tracker Initiative:** www.carbontracker.org
2. **University College London (UCL) Institute for Sustainable Resources:** www.bartlett.ucl.ac.uk/sustainable
3. **Intergovernmental Panel on Climate Change:** www.ipcc.ch

According to the Carbon Tracker Initiative [25], CCS would increase the percentage of burnable fossil fuel reserves. However, this would apply only to the power generation sector, where coal and gas are employed, and would not directly affect the transportation sector which is mainly based on oil use. The Carbon Tracker Initiative initially referred to the carbon budget estimated by Meinshausen et al. [7] (565 $GtCO_2$ by 2050) and estimated the total known fossil fuels reserves to be equal to 2,795 $GtCO_2$, composed by 65% coal, 22% oil and 13% gas.

Carbon Tracker Initiative estimated fossil fuels reserves with data from Raw Materials Group (coal) and from Evaluated Energy (oil and gas). CO_2 emission

4. These forward looking statements from companies consider current trends and make scenarios on future occurrences based on a number of assumptions including (but not limited to) global energy demand, renewables, CCS, fossil fuel demand and carbon intensity.

factors were estimated using IPCC guidelines. They conclude that because the carbon content of the known reserves is almost five times higher than the carbon budget, 80% of fossil fuel reserves will be 'unburnable'.

Their second report on the topic of 'unburnable carbon' was published in 2013. In their report, the carbon budget is higher (900 $GtCO_2$ for an 80% probability to stay below 2 °C and 1,075 $GtCO_2$ for a 50% probability) as greater reductions in non-CO_2 emissions (e.g. methane and nitrous oxide) have been assumed. Various emissions pathways were employed in their analysis, and the climate outcome for each of them has been validated by means of the MAGICC model. Negative emissions were not considered while CO_2 emissions from land use were assumed to be 7.3% of total CO_2 emissions.

According to Carbon Tracker Initiative, applying the scenario proposed by IEA on CCS [36] would extend the budget by 125 $GtCO_2$ between 2015 and 2050. Moreover, under that scenario a total of nearly 3,800 CCS projects would need to be operating by 2050. According to Carbon Tracker, with full investment in CCS, this technology would extend the carbon budget for the 2 °C scenario by 12–14%. These results have been confirmed in a more recent report [124]. The UCL Institute for Sustainable Resources released two publications by McGlade and Ekins focussing on unburnable carbon. While the first paper focused on oil only [20], the second paper considered all types of fuels and their geographical distribution [35].

The first UCL publication on the topic of unburnable carbon [20] focused on the volumes of oil that cannot be used up to 2035. The emissions of CO_2 have been limited to 425 ppm in all years up to 2100. According to the IEA, this is equivalent to 450 ppm greenhouse gases with a 50% probability of staying below a 2 °C rise. Two scenarios were simulated.

In the first scenario, a global effort to mitigate emission is assumed and CCS is widely adopted while the second scenario assumes that CCS never becomes available. The results estimate that 500–600 billion barrels (Gb) of current 2P (both proved and probable) reserves should not be burnt. The lower estimate (500 Gb) excludes CCS from the energy scenario while the higher estimate (600 Gb) assumed a widespread adoption of this technology. When CCS is not available, the cost of decarbonisation increases and therefore affects the cost of CO_2 emissions. The consequence of this is that oil consumption is affected as well, not because CCS would otherwise be applied to oil consumption but rather because it would generate a larger carbon budget for oil consumption when applied to gas and coal.

According to McGlade and Ekins [20], between 40% and 55% (this range relates to with CCS and without CCS) of yet to be found deepwater oil resources should not be developed. In both technological scenarios, arctic oil and most light tight oil resources remain undeveloped while unconventional oil production is generally incompatible with a low CO_2 energy system.

The second UCL publication [35] considers all fuels and their geographical location. The model employed was the integrated assessment model, TIAM-UCL, in combination with the oil-field Bottom-Up Economic and Geological Oil field production model (BUEGO), while the MAGICC model has been used to estimate the approximate temperature rise trajectories. The climate module of TIAM-UCL is used to restrict the temperature rise to certain levels and is calibrated to the MAGICC model. The proposed scenarios include three mitigation scenarios (2, 3 and 5 °C increase of temperature) and two technology scenarios (with and without CCS). The results for the 2 °C scenario are summarised in Table 10, which presents the overall reserves, divided by fossil fuel type, and the unburnable/burnable carbon in the two technology scenarios. Table 11 reports the same information as Table 10, but in $GtCO_2$. CCS enables use of 1% more oil, 3% more gas and 7% more coal by 2050. According to McGlade and Ekins 2015 [35], CCS has the largest effect of any technology on cumulative fossil fuel production levels. However its effect before 2050 is modest because of its cost, late introduction and maximum rate of construction.

In essence, both the Carbon Tracker Initiative, and McGlade and Ekins, suggest that CCS makes little difference to the extent of unburnable carbon. However, these scenarios are not the only resource that can be used to assess the impact of CCS on fossil fuel use. As part of the Fifth Assessment Report, the International Panel on Climate Change (IPCC) made an open call to collect energy projections coming from various integrated assessment models. A detailed analysis on the scenarios included in AR5 Database as part of the EMF27 project is presented in sections 5.3 and 6 in order to gain a broader understanding of the impact of CCS across a variety of models.

TABLE 10 (TOP) Unburnable reserves before 2050 for the 2 °C scenarios with and without CCS in different units (modified from from McGlade and Ekins [35]).

Fossil fuel	Unit	Overall reserves	With CCS: Unburnable	With CCS: Burnable	Without CCS: Unburnable	Without CCS: Burnable
Oil	Gb	1,306	431	875	449	857
Gas	Tm^3	194	95	99	100	94
Coal	Gt	999	819	180	887	112

(Bar scale: 0, 20%, 40%, 60%, 80%, 100%)

TABLE 11 (BOTTOM) Unburnable reserves before 2050 for the 2 °C scenarios with and without CCS in $GtCO_2$ (modified from McGlade and Ekins [35]). Unit: $GtCO_2$

Fossil fuel	Unit	Overall reserves	With CCS: Unburnable	With CCS: Burnable	Without CCS: Unburnable	Without CCS: Burnable
Oil	$GtCO_2$	531	175	356	183	349
Gas	$GtCO_2$	418	205	213	215	202
Coal	$GtCO_2$	2,664	2,185	480	2,366	299
TOTAL		3,613	2,565	1,049	2,764	850

(Bar scale: 0, 20%, 40%, 60%, 80%, 100%)

5.1.3. Integrated assessment models

Integrated Assessment Models (IAMs) are models that can depict scenarios of global change related to climate change. They are inherently multi-disciplinary, incorporating climate science, engineering and economics as a minimum. They are global in geographical scope, incorporate the century-long time horizons relevant to climate change, and cover all sectors of the economy and land use. This very broad scope is required to adequately assess potential responses to the threat of climate change, allowing modellers to capture the key interrelationship in complex systems of energy production, climate, and economics.

The IEA 2013 has proposed a roadmap to assist governments and industry in integrating CCS in their emissions reduction strategies. This roadmap would enable storage of a total cumulative mass of approximately 120 $GtCO_2$ between 2015 and 2050.

IAMs are naturally predisposed to analyses on unburnable carbon, given their coverage of technology options, economics and climate.

As the energy sector is the primary source of CO_2 emissions, several studies have used IAMs to estimate how the current energy system may evolve in order to be compatible with climate change objectives. Most of them suggest that CCS will be crucial to meet the 2 °C limit cost-effectively [61].

In these studies, decarbonising electricity generation is a core component of cost effective mitigation strategies. This is usually accompanied by electrification of end-use sectors, particularly heating of buildings and transport. In most of the integrated modelling scenarios which are part of the IPCC Fifth Assessment Report Database, decarbonisation happens first in electricity generation, followed by industry, buildings, and transport sectors [125].

In this context, the importance of CCS is evident. This technology is applicable to power generation (and upstream and downstream industry) and could enable countries to continue to include fossil fuels in their energy mix [92] and therefore can unlock assets that would otherwise be stranded [93, 126]. For example, the IEA 2013 [36] has proposed a roadmap to assist governments and industry in integrating CCS in their emissions reduction strategies. This roadmap would enable storage of a total cumulative mass of approximately 120 $GtCO_2$ between 2015 and 2050.

5.2. Carbon removal technologies depicted in IAMs

Carbon removal technologies include carbon positive, near neutral and negative technologies [56]. CCS can be combined with Negative Emission Technologies (NETs) in order to generate negative emissions. NETs include afforestation, agricultural soil carbon storage, biochar, bioenergy with carbon capture and storage (BECCS), direct air capture, ocean liming, enhanced weathering, and ocean fertilisation. The technical potential of NETs has been estimated to be 120 $GtCO_2$ until 2050. This amount of CO_2 represents an extension of the 2050 carbon budget by 11–13% for a 50–80% probability to remain below a 2 °C temperature increase [127]. Estimations of NETs potential until 2100 are affected by great uncertainties, especially with regard to the availability and accessibility of geological storage, and are therefore difficult to estimate.

BECCS technologies are part of NETs and combine biomass with CCS, for processes in the bio-refining sector, biofuel sector, power and heat sector and in industrial processes for the cement, steel and paper sector. Future projections of BECCS potential estimate negative greenhouse gases up to 10.4 $GtCO_2eq/yr$ by 2050 [57]. These results come from biomass integrated gasification combined cycle (BIGCC) and circulating fluidized bed (CFB) combined with CCS, while other technologies result in lower negative emission potentials.

5.3. Review of a model comparison exercise: EMF27

This sub-section provides an overview of results from the multi-model Energy Modelling Forum 27 (EMF27) scenarios, focusing on the impact of CCS on burnable/unburnable carbon. The section describes the project, the models and the scenarios and reviews the assumptions on CCS modelling, cost and storage. However, the section does not propose a new modelling tool.

5.3.1. Description of the project and models involved

The Scenario Database of the IPCC Fifth Assessment Report (AR5) includes 31 models and 1,184 scenarios [128]. The scenarios were collated by means of an open call and all meet the following requirements including:

- Being published in peer-reviewed literature,
- Containing a minimum set of required variables,
- Being generated by models with full energy representation,
- Providing data to at least 2030.

The majority of the scenarios were provided via model inter-comparison exercises, so the outcome of various models for the same scenarios can be compared. The scenarios have been classified within the AR5 Scenario Database according to the following factors: their climate target, radiative forcing levels, scale of deployment of CO_2 removal, availability of mitigation technologies and policy configurations [128]. In order to overcome issues related to the representation of radiative forcing in the single models, the emissions of all the scenarios included in the database were run through the single climate model MAGICC 6.3. This was carried out to correlate CO_2-equivalent concentration, radiative forcing and climate outcome between scenarios.

The model inter-comparison exercises included in the database are the following:

- **ADAM:** Adaptation and Mitigation Strategies
- **AME:** Asian Modelling Exercise
- **AMPERE:** Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates
- **EMF22 and EMF27:** Energy Modelling Forum 22 and Energy Modelling Forum 27
- **LIMITS:** Low climate IMpact scenarios and the Implications of required Tight emission control Strategies
- **POeM:** Policy Options to engage Emerging Asian economies in a post-Kyoto regime
- **RECIPE:** Report on Energy and Climate Policy in Europe
- **RoSE:** Roadmaps towards Sustainable Energy futures.

While models could identify transformation pathways under the 550 ppm carbon dioxide equivalent (CO_2e) target for all limited mitigation technology portfolios, only four models could achieve the 450 ppm CO_2e target without CCS.

Since 1976, the Energy Modelling Forum (EMF) centred at Stanford University has been one of the first major model comparison efforts. EMF27 builds on previous model inter-comparison exercises such as EMF19, EMF21 and EMF22 and compares 18 integrated assessment models [129]. Some of the models included in EMF27 have also been analysed in AMPERE2 [130] and AMPERE 3 [131]. The main properties of the EMF27 models have been summarised in Table 12 and include equilibrium concept, solution dynamic, time horizon, land use sector representation and coverage of greenhouse gases.

One of the main purposes of EMF27 is to analyse the role of technology for achieving climate policy objectives. According to Kriegler et al. 2014 [129], CCS is deployed at a substantial scale in almost all the EMF27 mitigation scenarios with full technology availability. While models could identify transformation pathways under the 550 ppm carbon dioxide equivalent (CO_2e) target for all limited mitigation technology portfolios, only four models could achieve the 450 ppm CO_2e target without CCS. According to Krey 2014 [132], the importance of CCS is mainly due to its flexibility, which includes the capability of sequestering carbon dioxide from the atmosphere when applied with bioenergy.

Time horizon	Model	Equilibrium concept	Solution dynamics	Land use sector representation	Coverage of greenhouse gases (GHGs)
2050	**AIM-Enduse**	Partial equilibrium	Recursive dynamic	MACs* for land use emissions	All GHGs and other radiative agents
	DNE21+	Partial equilibrium	Intertemporal optimization	MACs* for land use emissions	All GHGs and other radiative agents
	ENV-Linkages	Computable general equilibrium	Recursive dynamic	MACs* for land use emissions	Kyoto gases
	Phoenix	Computable general equilibrium	Recursive dynamic	None	CO_2 from fossil fuel combustion and industry
2100	**BET**	General equilibrium	Intertemporal optimization	None (land use emissions exogenous)	CO_2
	EC-IAM	General equilibrium	Intertemporal optimization	None	Kyoto gases from fossil fuel combustion and industry
	FARM	Computable general equilibrium	Recursive dynamic	Land is competed across crops, pasture, forests, and biomass	CO_2 from fossil fuel combustion and industry
	GCAM	Partial	Recursive dynamic	Endogenous land use dynamics, afforestation	All GHGs and other radiative agents
	GRAPE	General equilibrium	Intertemporal optimization	Endogenous land use dynamics	All GHGs and other radiative agents
	IMACLIM	General	Recursive dynamic	None	CO_2 from fossil fuel combustion and industry
	IMAGE	Partial	Recursive dynamic	Endogenous land use dynamics	All GHGs and other radiative agents
	MERGE	General equilibrium	Intertemporal optimization	MACs* for land use emissions, No CO_2 emissions from land use	All GHGs and other radiative agents
	MESSAGE	General	Intertemporal optimization	MACs* for land use emissions, Afforestation	All GHGs and other radiative agents
	POLES	General	Recursive dynamic	None	Kyoto gases from fossil fuel combustion and industry
	REMIND	General	Intertemporal optimization	MACs* for land use emissions	All GHGs and other radiative agents
	TIAM-World	Partial equilibrium	Intertemporal optimization	MACs* for land use emissions	Kyoto gases with the exception of fluorinated greenhouse gases
	WITCH	General	Intertemporal optimization	MACs* for land use emissions	Kyoto gases

TABLE 12
General properties of the models included in the EMF27 project.
Modified from Kriegler, E et al. [129]
*MACs are marginal abatement costs

5.3.2. Scenarios investigated in EMF27

The analysis presented in this White Paper includes all the models in EMF27 that have been employed for generating the scenarios included in the AR5 database. The scenarios are characterised by climate mitigation target, technological availability and the timeframe covered.

The climate mitigation scenarios include a baseline scenario, where future policies dedicated to climate change mitigation are not followed, as well as two climate mitigation scenarios. The mitigation scenarios '450 ppm' and '550 ppm' aim to reach atmospheric GHG concentration at levels of respectively 450 ppm carbon dioxide equivalent (CO_2eq) and 550 ppm CO_2eq by 2100 [131]. The technology scenarios include a series of options from the availability of a full portfolio of technologies to specific technologies limitation to reliance on conventional fossil fuel technologies only (Box 1).

Two timeframes have been considered. The first includes projections until 2050 while the second timeframe extends to 2100. The scenarios of the four models of EMF27 with a time horizon limited to 2050 have not been included in the analyses here (AIM-Enduse, DNE21+, ENV-Linkages and Phoenix).

The variables of interest which have been included in this report are CO_2 emissions ($GtCO_2$/yr), CO_2 storage via CCS ($GtCO_2$/yr) and use of primary energy, either overall or by fuel type (EJ/yr).

Not all the models (13 in total) were able to give an output for specific scenarios. This behaviour has been taken into account as an indication that the specific target was technically or economically infeasible, following the approach by Kriegler et al. 2014 [129].

Box 1: Technology scenarios

In this report, three technology scenarios have been selected in order to analyse the role of CCS [130]:

- The Full technology scenario ("Fulltech")
- The Conventional solutions scenario ("Conv")
- The scenario without CCS ("noCCS").*

These scenarios have been reported in numerous publications [129, 130, 132]. However, the amount of information is limited and repeated throughout the different papers.

According to Riahi et al. 2014 [130], the **full technology scenario** has a full portfolio of technologies which may be scaled up in the future in order to meet the climate targets.

In the **conventional solution scenario**, renewable technologies such as solar, wind and biomass potentials are limited and therefore energy demand is met by means of conventional technologies based on fossil fuel deployment in combination with CCS and/or nuclear.

In **the scenario without CCS** carbon capture and storage never becomes available.

*These colours are used in section 6.

For the 450 ppm scenario, the number of models that were able to produce a solution were:

- Fulltech scenario: 10 models
- Conv scenario: 8 models
- noCCS scenario: 4 models (GCAM 3.0, POLES, REMIND 1.5, TIAM-WORLD 2012.2).

For the 550 ppm scenario, the number of models that were able to produce a solution were:

- Fulltech scenario: 13 models
- Conv scenario: 13 models
- noCCS scenario: 12 models.

These numbers highlight the importance of CCS in climate change mitigation scenarios and also confirm what was previously reported by Kriegler et al. 2014 [129] and Krey et al. 2014 [132]. Both papers reported that most of the models were not able to run the noCCS scenario under the climate mitigation scenario 450 ppm. In a specific case (referring to the IMAGE model), it was reported that the scenario was not feasible due to the lack of sufficient alternative mitigation potential [133]. The availability of CCS has the strongest impact on carbon prices [134] and on the variation of mitigation costs [129, 130].

5.3.3. Review of CCS modelling in EM27

As part of the EMF27 project, Koelbl et al. 2014 [78] looked at the way CCS was characterised in each model. They reported model assumptions based on coverage detail of the CCS chain, sector coverage, CCS power plant lifetime and early retirement, CCS availability and cumulative storage for the timeframe 2010–2100. With regard to CO_2 storage and transport only, they looked into storage rate, types and capacity. Part of the purpose of the paper was to relate model results to model assumptions, with a special focus on CCS assumptions. The authors identified some factors as affecting the large variation in the model results [78]:

- Fuel prices
- Baseline emissions
- The type of model
- Modelling technology change
- The way CCS is modelled.

However, in Koelbl et al. [78] none of the model assumptions could clearly be associated with the amount of CO_2 captured. Therefore, the authors suggested that further research is needed in order to investigate the impact of CCS modelling parameters on the simulation outcomes.

5.3.4. Storage availability assumptions for CCS

Table 13 summarises some of the CCS modelling assumptions [78]. Most of them refer to the storage of CO_2. The assumptions on the availability of CCS cover today (four models), 2020 (seven models) and 2030 (one model). Half of the models assume unlimited storage capacity while most do not include a limit to the maximum storage rate. This means that most of the models do not include any limitation on both storage rate and capacity. The number of storage types varies from one to 11, where only one model includes all the types of storage sites: on and offshore enhanced oil recovery (EOR), depleted gas, undepleted gas, depleted oil, as well as enhanced coal bed methane (ECBM) onshore, and two types of aquifers.

TABLE 13
CCS properties of some of the models included in the EMF27 project.
Modified from Koelbl, B.S., et al [78]

Model name	Availability	Is there a maximum storage rate?	Number of storage types	Storage capacity ($GtCO_2$)
BET	2020	No	1	3,538
FARM			1	Unlimited
GCAM			2	7,178
GRAPE			4	~20,000
IMACLIM	Always		1	Unlimited
IMAGE	2005		11	5,856
MERGE	2020		1	Unlimited
MESSAGE	2020–2030		1	
POLES	2015		2	
REMIND	2020	Yes	1	3,959
TIAM-WORLD	2030	No	8	11,600
WITCH	Always		1	Unlimited

5.3.5. Cost assumptions for CCS

Among the 64 references listed in the AR5 database webpage, 11 explicitly refer to cost or economic evaluations of CCS technology performed by means of integrated assessment models. Most of these papers include emission prices and global aggregate mitigation costs rather than capture or storage prices. Only one reference [135] reports the marginal abatement cost of CCS. Annex III of the IPCC report "Climate Change 2014: Mitigation of Climate Change" [17] reports the following costs for CCS combined with power generation:

- Overnight capital expenditure: 2,000–4,000 \$2010/kW
- Construction time: 4–5 years
- Fixed annual operation and maintenance cost: 13–58 \$2010/kW
- Variable operation and maintenance cost: 8.3–15 \$2010/kW.

Investment costs and efficiencies for power generation combined with CCS have been estimated by Koelbl et al. 2014 [79] and the results have been reported in Table 14 and Table 15 for capture and transport of CO_2, respectively.

Data presented in Table 14 are representative of only a small subsection of potential CCS technologies, and exclude coal with either post-combustion or oxy-combustion capture technologies. Similarly, in the near term (2020), investment costs and efficiency penalties for the technologies presented here are relatively high. For example, a state-of-the art combined cycle gas turbines (CCGT) plant with currently commercially available amine scrubbing technology (e.g. Shell's Cansolv technology) might be expected to incur a 7–8% points efficiency penalty. Similarly, recent IEA World Energy Outlook data would suggest that the CCGT and CCS technology could be available for approximately 20% less than is quoted in Table 14, for a similar time horizon. A detailed exploration of this topic is, however, out of scope for this review.

When comparing the costs reported by Koelbl et al. [79] with the costs reported in the literature (section 4.4), the following considerations apply that relates to: 1. CCS investments costs, 2. efficiency penalties and 3. cost of transport and storage.

1. CCS investments costs reported in Table 14 for 2020, are lower than the capital costs reported in the literature (see Table 9, see section 4.4.8) for both coal-fired ($2015/kWe 1,181–4,942 vs. 3,552–6,816) and gas-fired ($2015/kWe 856–2,394 vs. 2,313–5,088) power generation.
2. The efficiency penalties reported in Table 14 are similar to the penalties reported in Figure 10 (see section 4.4.2.). The penalties were 6–11% for combined cycle gas turbines and 5–11% for integrated gasification combined cycle (IGCC).

TABLE 14
Ranges of investment costs, efficiencies and efficiency losses for power plants and capture unit.
Modified from Koelbl, B.S., [79]. Investment costs are expressed in $2015 per kWe
Note: p.p. = percentage points of capture efficiency loss
CCGT = Combined Cycle Gas Turbines
IGCC = Integrated Gasification Combined Cycle

CAPTURE

	Investment costs		Efficiency	
	2020	2050	2020	2050
	Without CCS		Without CCS (%)	
IGCC Coal	914 → 3,464	643 → 3,300	38 → 52	40 → 58
IGCC Biomass	1,416 → 3,966	997 → 3,780	32 → 50	35 → 54
CCGT	532 → 1,158	432 → 1,055	48 → 64	50 → 67
	2020	2050	2020	2050
	Capture		Capture (p.p.)	
IGCC Coal	267 → 1,479	107 → 1,353	4 → 11	3 → 9
IGCC Biomass	669 → 1,100	333 → 1,007	5 → 11	3 → 7
CCGT	325 → 1,236	156 → 1,058	6 → 11	5 → 9

Minimum → Maximum

3. The transport costs reported in the literature (see Figure 12, see 4.4.4.) varies between 1.3 (onshore pipelines, capacity 30 $MtCO_2$/yr) and 15.1 (offshore pipelines, capacity 3 $MtCO_2$/yr) \$2015/tCO2/250km compared to figures reported in Table 15, where the transport costs varies between 0.5 and 42.5 \$2015/tCO_2/250km.

   This shows that a larger range of transport costs has been adopted in the EMF27 models. The same consideration applies to the cost of storing CO_2 in depleted oil and gas fields. According to Rubin et al. 2015 [102], it varies between 1.6 and 22 \$2015/tCO_2 (as reported in Figure 13, see section 4.4.5.), while according to Koelbl et al. [79] it varies between 1 and 35.1 \$2015/tCO_2. Negative storage costs represent an income, which comes from fossil fuel recovery.

TABLE 15
Ranges of CO_2 transport costs per distance category.
Modified from Koelbl et al. [79]

TRANSPORT

Distance (km)	<50	50–200	200–500	500–2000	2000–∞
\$2015/t CO_2	0.06 → 3.9	0.13 → 21.96	0.83 → 59.78	1.95 → 244	7.32 → 263.52
\$2015/t CO_2/km	0.002 → 0.16	0.001 → 0.18	0.002 → 0.17	0.001 → 0.2	0.002 → 0.09

Minimum → Maximum

STORAGE

\$2015/ tCO_2	Eonhanced Oil Recovery (EOR)	Remaining gas	Depleted oil	Depleted gas	Enhanced Coal Bed Methane Recovery (ECMR)	Aquifer
Onshore	-128.3 → 64.1	1 → 16.9	1 → 16.9	1 → 16.9	-36.7 → 210.5	0.5 → 12.1
Offshore	-128.3 → 125.8	1.9 → 35.1	1.9 → 35.1	1.9 → 35.1		1 → 42.4

Minimum → Maximum

TABLE 16
CO_2 storage cost ranges per storage type.
Modified from Koelbl et al. [79]. Cost is for ton of stored CO_2.

6. Overview of unburnable carbon and CCS in EMF27 results

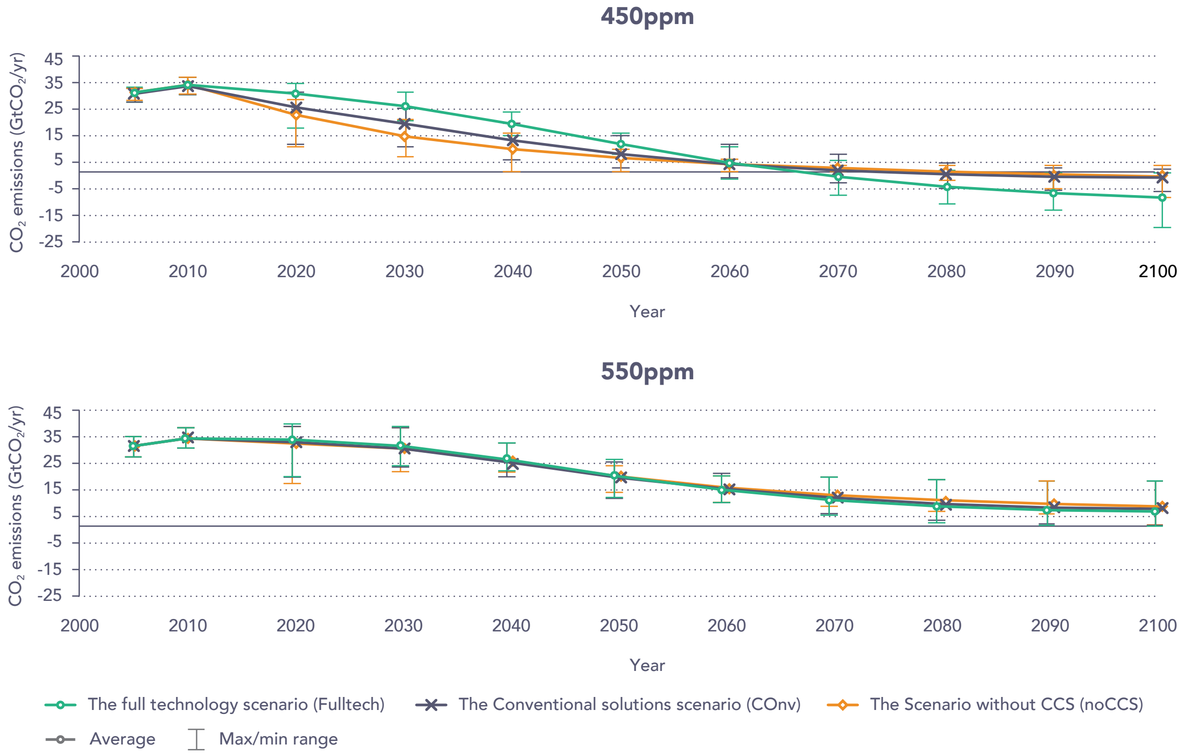
6.1. Emissions and capture of carbon dioxide

Figure 16 reports the emissions of the three selected technology scenarios (Fulltech, Conv, noCCS) for a 450 ppm and 550 ppm CO_2 equivalent atmospheric concentration until 2100.

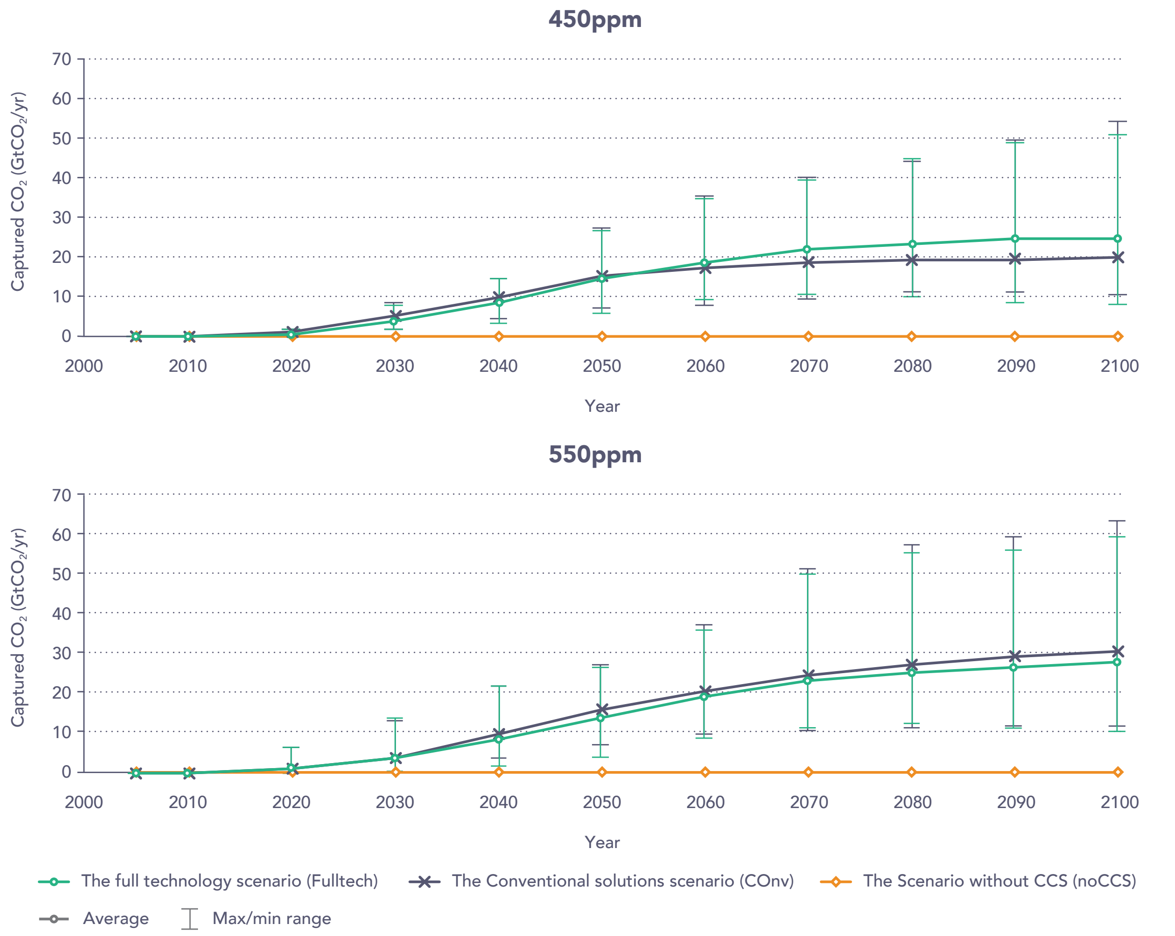
As expected, all of these scenarios have approximately the same cumulative emissions of CO_2, as they all reach the same atmospheric concentration over the time period. However, the shapes of the profiles are slightly different, reflecting the impact of technology options and constraints on the abatement pathway chosen by the models.

Figure 17 reports the projections for the captured CO_2 over the timeframe 2005–2100. As expected, the 'noCCS' scenario does not capture any CO_2 emissions in any scenario. Both 'Conv' and 'Fulltech' reach very significant levels of capture and storage by both 2050 and 2100, and in virtually all scenarios the rate of capture is still increasing at the end of the time horizon in 2100.

CO_2 emissions



Captured CO_2



The Carbon Capture Pilot Plant in the Chemical Engineering Department at Imperial College London

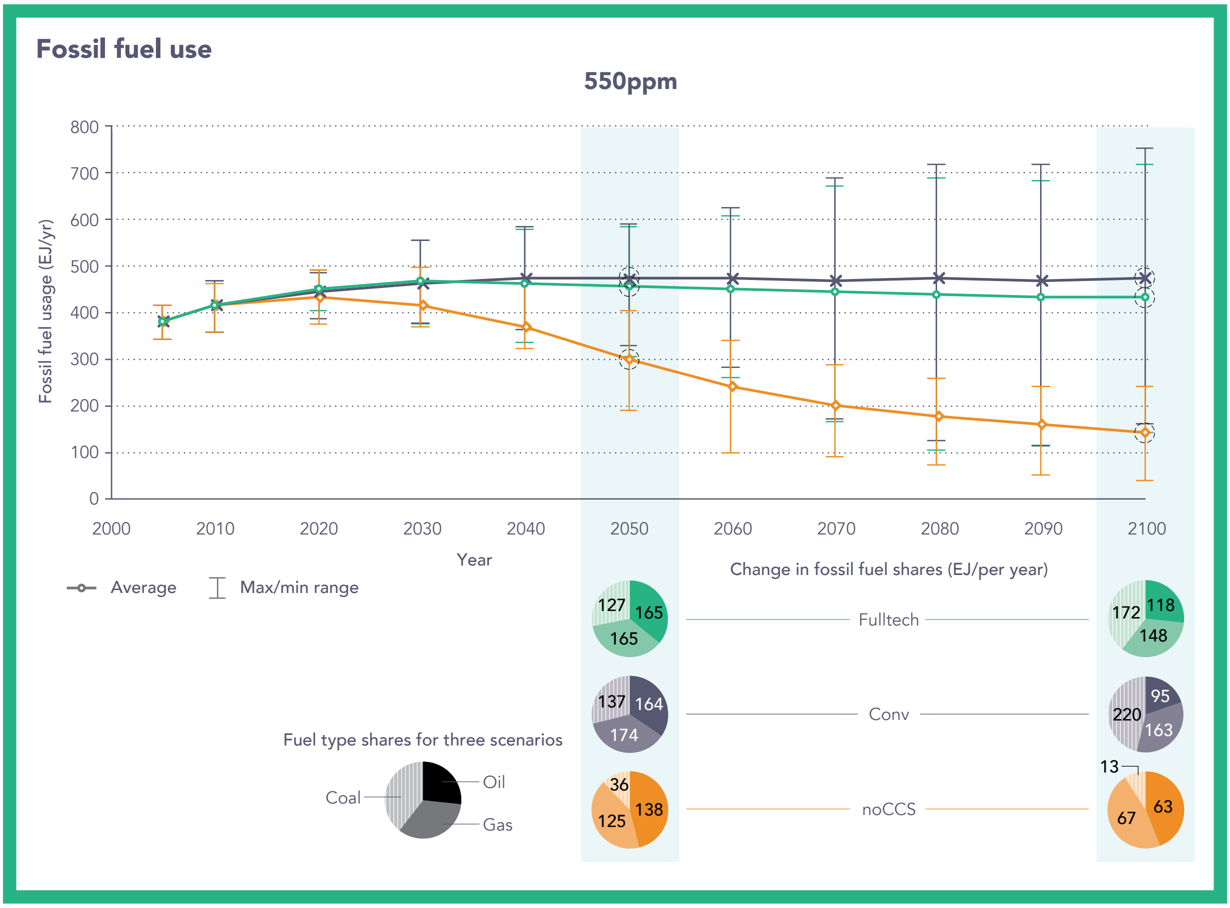
FIGURE 16 (TOP)
Average global emissions of CO_2 ($GtCO_2$/yr) for 450 ppm and 550 ppm scenarios across EMF27 models.

FIGURE 17 (BOTTOM)
Average capture of CO_2 ($GtCO_2$/yr) for 450 ppm and 550 ppm scenarios across EMF27 models.

In Figure 17, the total level of capture and storage achieved in the 450 ppm (i.e. more climate-constrained) scenario is lower than that of the 550 ppm scenario. This could be explained by the fact that the residual emissions from CCS in the 450 ppm scenario are far more important than in the 550 ppm scenario due to the more onerous overall constraint on emissions. This limits the usefulness of CCS in the 450 ppm scenario.

When comparing 'Conv' and 'Fulltech' in the 450 ppm scenario, 'Conv' uses CCS less than 'Fulltech'. On first consideration, this may seem unexpected because 'Conv' has more constrained access to the alternatives to CCS for decarbonisation. However, 'Fulltech' has greater access to biomass than 'Conv', meaning that 'Fulltech' can use BECCS to a greater extent, and therefore displays greater overall use of CCS. Overall, many factors contribute to these outcomes including the availability of biomass/BECCS, relative costs of fossil fuels and biomass, technology performance and lifetimes, which are important topics for further research. The residual emissions challenge is discussed further in section 7.

Fossil fuel use
450ppm
600
500
400
300
200
100
0
Fossil fuel usage (EJ/yr)
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
Average
Max/min range
Change in fossil fuel shares (EJ/per year)
96
129
140
Fulltech
84
58
73
109
87
131
Conv
56
88
112
7
52
81
noCCS
2
8
27
Fuel type shares for three scenarios
Coal
Oil
Gas



Fossil fuel use
550ppm
800
700
600
500
400
300
200
100
0
Fossil fuel usage (EJ/yr)
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Year
Average
Max/min range
Change in fossil fuel shares (EJ/per year)
127
165
165
Fulltech
172
118
148
137
164
174
Conv
95
220
163
36
138
125
noCCS
13
67
63
Fuel type shares for three scenarios
Coal
Oil
Gas

6.2. Fossil fuel consumption with and without CCS

Figure 18 reports fossil fuel use for the three technology scenarios for coal, gas and oil for the 450 ppm scenario. It also splits out the share of each fossil fuel at snapshot years of 2050 and at 2100. The error bars represent the minimum and maximum values from all of the models providing a solution at each time period. There is a large variation in model results, and this variation increases for the timeframe 2005 until 2100, thus highlighting the increased uncertainty that characterises the model outputs after 2050.

In Figure 18, fossil fuel use drops in all scenarios, revealing the challenges faced by these energy forms over coming decades and the competition from renewable sources of energy under climate change mitigation scenarios. This is in contrast with what has been reported by IEA 2014 [30] and also by BHP Billiton 2015 [136], who still forecast a growing fossil fuel demand in the future. However, the range of outcomes (i.e. the error bars) for the consumption of fossil fuels is large, with some models indicating a stabilisation or increased fossil use in the 'Conv' and 'Fulltech' scenarios. The range of outcomes from the models for the 'noCCS' case are much closer towards the end of the time horizon, and fossil fuel use rapidly drops to very low levels late in the century. From the analyses, it is possible to conclude that CCS is extremely important for the continued use of fossil fuels in the medium to long term, with the technology having significant impact on usage from 2030 onwards.

In the pie charts in Figure 18, gas and coal are the fuels there is an increase in use through the availability of CCS. While coal has the most significant difference between 'Conv' and 'noCCS' scenarios, gas is the only fossil fuel where there is increased use between 2005 and 2050, and also almost maintains its share in the fossil fuel energy mix in absolute terms between 2050 and 2100.

Figure 19 is similar to Figure 18 but reports the projections of fossil fuel usage for the three technology scenarios for the 550 ppm scenario. As expected, the presence of CCS in these scenarios unlocks more fossil fuel reserves than in the 450 ppm scenario, though at the expense of the climate, manifesting as a higher probability of exceeding 2 °C peak warming.

When considering the impact of CCS on a fuel-by-fuel basis, again coal sees the greatest gains from the addition of CCS to the technology mix, and in fact becomes the dominant fossil fuel in energy terms by 2100, almost doubling consumption on 2005 levels. Gas usage also increases due to CCS availability, and increases aggregate utilisation in the energy mix.

Numerical average values for fossil fuel usage in 2050 and in 2100 across EMF27 models are reported in Table 17. Values from individual models are presented in Figure 20 and Figure 21, showing the range of outcomes observed. Furthermore, the range of outcomes for each fossil fuel are individually presented in the Annex.

In summary, Table 18 shows the average cumulative consumption of fossil fuels over two timeframes (2005–2050 and 2005–2100) observed across the models. CCS has a very significant impact on fossil fuel consumption post 2050, enabling 65% of reserves to be used instead of 33% in the scenario without CCS, whilst

FIGURE 18 (TOP)
Total primary energy from fossil fuel use (EJ/yr) and fuel-type shares of single fossil fuel usage in 2050 and 2100 (EJ/yr) for the three technology scenarios at 450ppm. (Data for 2005: oil 164–167 EJ/yr, gas 98–99 EJ/yr, coal 121–122 EJ/yr). Values are averages across the EMF27 models.

FIGURE 19 (BOTTOM)
Total primary energy from fossil fuel use (EJ/yr) and distribution of single fossil fuel usage in 2050 and 2100 (EJ/yr) for the three technology scenarios at 550ppm. (Data for 2005: oil 164–167 EJ/yr, gas 98–99 EJ/yr, coal 121–122 EJ/yr). Values are averages across the EMF27 models.

still meeting climate targets. This means that CCS would allow access to twice the amount of energy from fossil fuels by the end of the century while still staying below a 2 °C limit (see Table 18 showing 32,376 vs 16,823 exajoules).

FIGURE 20
Emissions from fossil fuel use according to the EMF27 models (scenario 450 ppm timeframe 2005–2050).

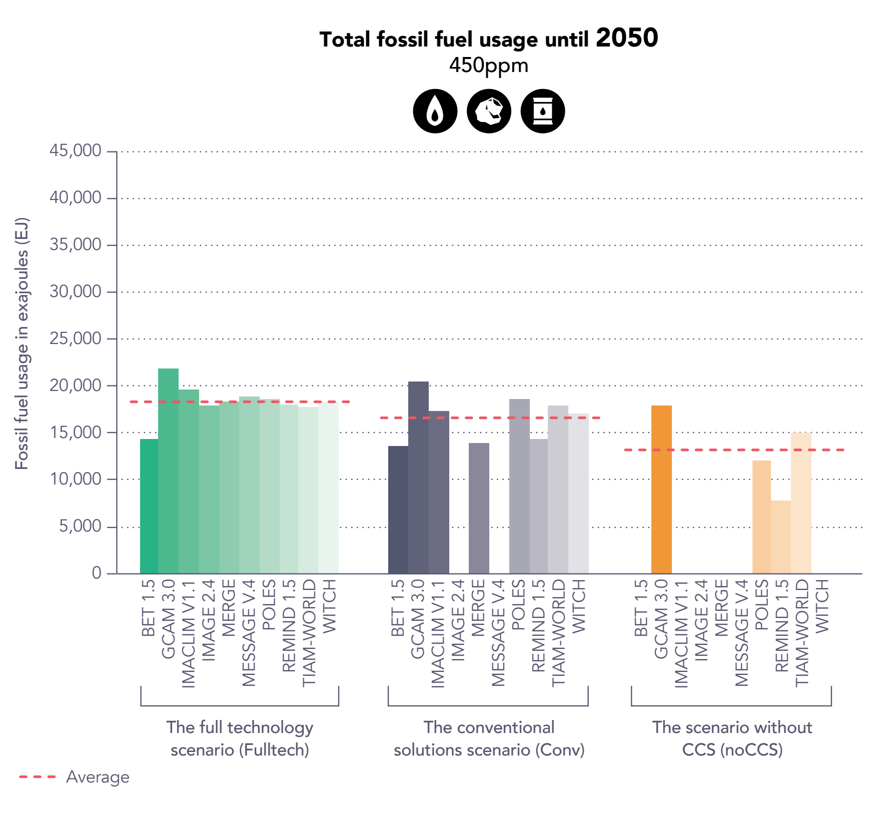


FIGURE 21
Emissions from fossil fuel use according to the EMF27 models (scenario 450 ppm timeframe 2005–2100).

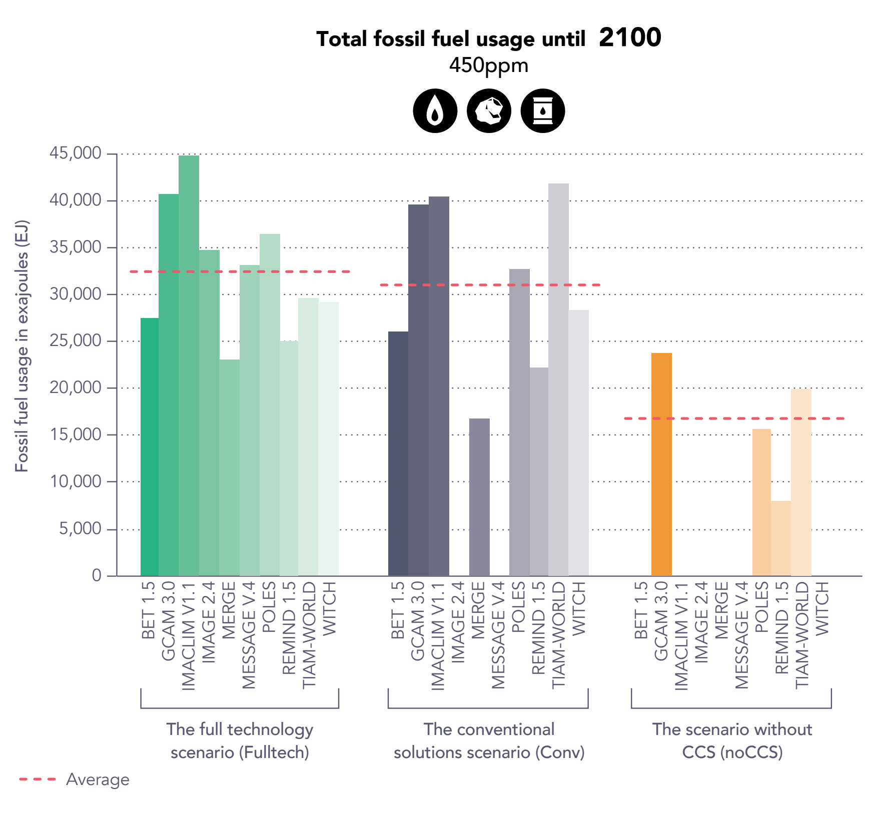


TABLE 17
Average primary energy use in 2050 and 2100 across EMF27 models in exajoules (EJ).

Climate mitigation scenario	450 ppm			550 ppm		
Technology scenario	Conv	Fulltech	noCCS	Conv	Fulltech	noCCS
Fossil fuels use (EJ) in 2050	326	364	140	474	457	299
Fossil fuels use (EJ) in 2100	256	215	36	478	437	143

	$GtCO_2$		Exajoules (EJ)		% of reserves	
	Without CCS	With CCS	Without CCS	With CCS	Without CCS	With CCS
Up until 2050	953	1,347	13,166	18,356	26%	37%
Up until 2100	1,208	2,380	16,823	32,376	33%	65%

TABLE 18
Cumulative fossil fuel use in the timeframes 2005–2050 and 2005–2100.
Results reported in three different units ($GtCO_2$, EJ and % of reserves). Reserves 'low' estimate from McCollum et al. 2014 [1]. The "without CCS" scenario corresponds to the noCCS scenario while "with CCS" scenario corresponds to the Fulltech scenario

6.3. Discussion

When considering the potential of CCS as seen by integrated assessment models (IAMs) it is important to understand what factors in the models are limiting its uptake. While the results presented clearly point to the importance of CCS in underpinning the role of fossil fuels in future low carbon energy systems, they still leave a significant question unanswered: why CCS is not being adopted to a greater extent?

Akimoto et al. 2012 [135] suggests that the marginal cost of CCS across the entire possible range of fossil fuel reserves (i.e. up to ~4,000 $GtCO_2$) is less than US$100/$tCO_2$. However, as shown in Figure 22, the marginal cost of abatement produced in the 450 ppm 'Conv' scenario is well above this value, indicating that the model would adopt the technology at the maximum possible rate if it were able to do so.

The cost of carbon reported in Figure 22 for both the 450 ppm and the 550 ppm scenarios is well above the cost of carbon assumed by the IEA 2014 [137] for the 450 Scenario ($140/$tCO_2$ in most OECD countries in 2040). However it is worth noting that the costs reported here are not an assumption of the Energy Modelling Forum (EMF) models, but rather an output of the models.

One possible explanation for this phenomenon is that the rate of uptake of CCS-equipped facilities is limited in the models. From Table 13 (see section 5.3.4.), we can conclude that CCS uptake is not limited by storage capacity or growth thereof. Therefore, another option is a limit on the rate that CCS-enabled facilities can be built (e.g. maximum capacity or activity growth rates, maximum new capacity installation by region, etc.), or how quickly infrastructure related to CCS can be built. However, the detailed review produced on CCS assumptions in the relevant models [78] did not cite any limits on uptake of these technologies, and further personal communications with the relevant modellers confirmed that any such limits were likely to be non-binding, particularly in later model years.

This report hypothesises that the constraint on CCS is therefore not cost related or supply chain related (i.e. build rate limited), particularly in later years. The key remaining possibility is that the residual emissions from CCS make it an unfavourable option in climate change mitigation scenarios; even these low levels of emissions are sufficiently high to conflict with extremely constrained global carbon budgets. This hypothesis is supported by previous work produced by the UK Energy Research Centre (UKERC) [138] and IEAGHG [139], who both report a capture rate of 90% for coal based power generation with CCS. IEAGHG 2014 [139] demonstrated that increasing the capture rate from 90% to 98% would not increase but rather reduce (-3%) the cost per tonne of CO_2 avoided for oxy-combustion and IGCC applications. Capture technology developers have so far focussed on 85–90% capture rates however this could not be sufficient with tighter global emission limits. However, the lack of data regarding state-of-the-art capture rates of CCS plants makes the evaluation difficult.

Testing the hypothesis on residual emissions is outside the scope of this report. However, it will be the subject of further investigation in future research.

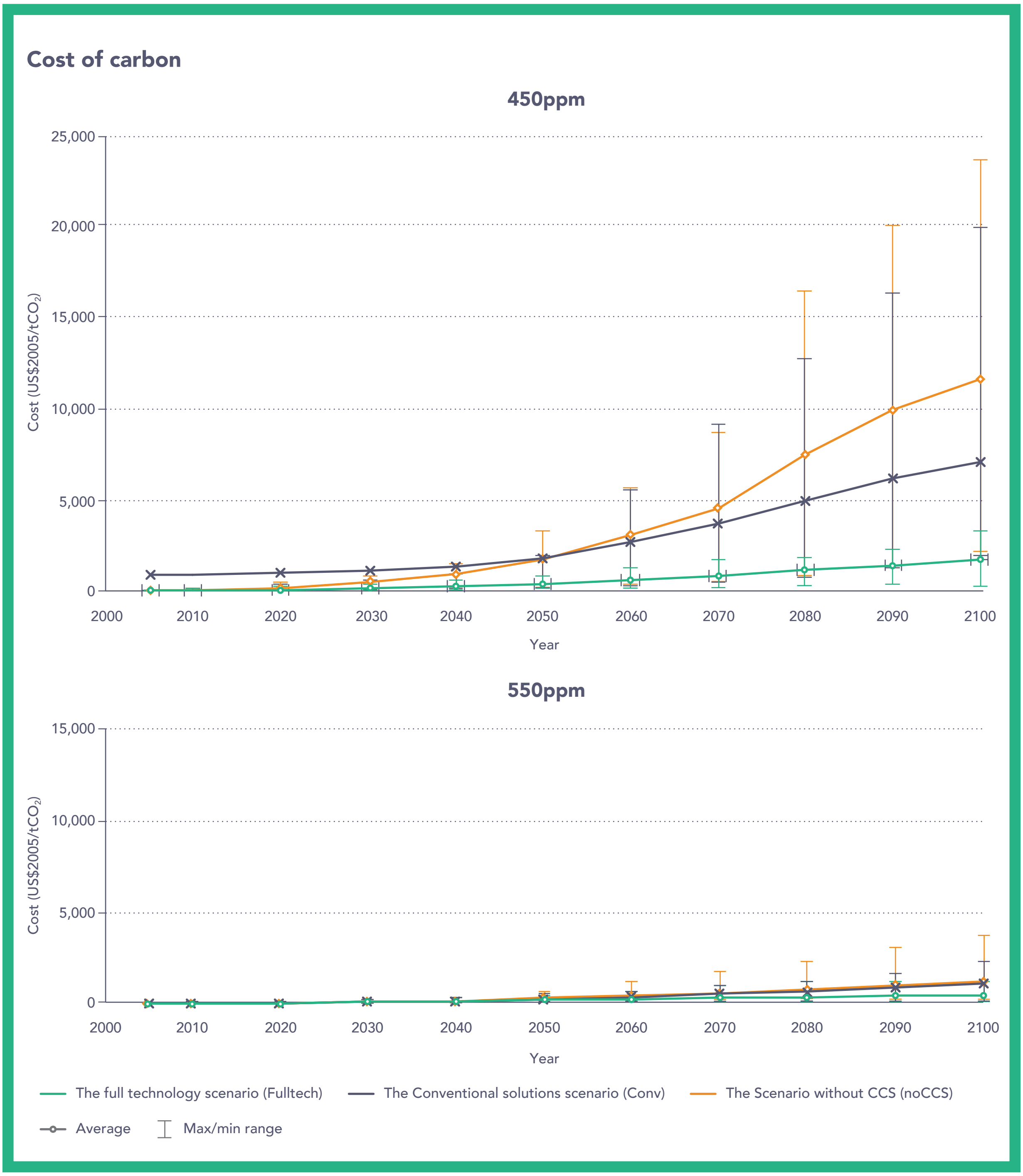


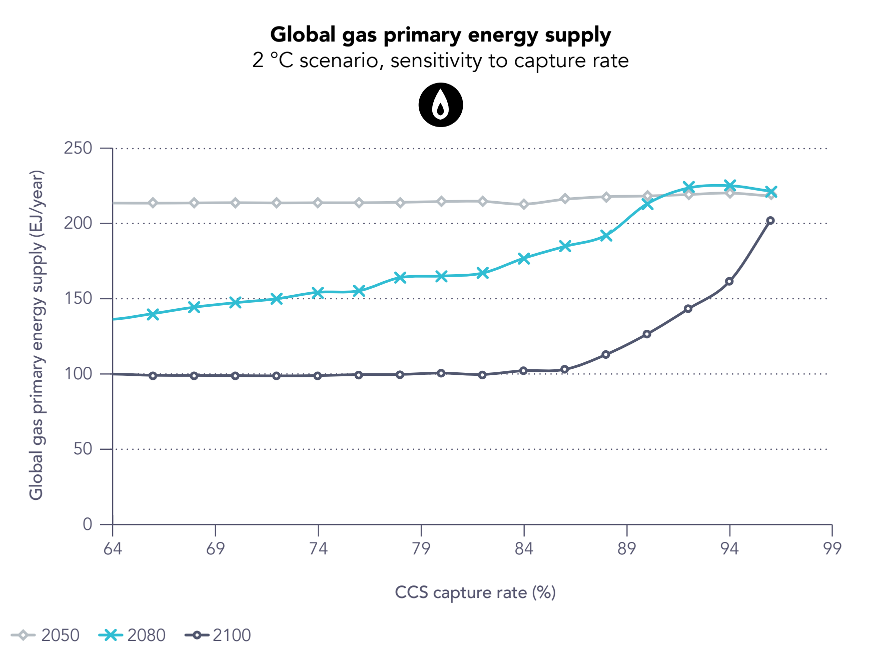
FIGURE 22
Cost of carbon (CO_2) for 450 ppm and 550 ppm scenarios.

7. Analysis of residual emissions

Most CCS studies assume a capture rate for CO_2 emissions. The residual emissions of the process are the remaining percentage of emissions that are released to the atmosphere. The capture rate assumed in most studies is in the range of 85–90% for power generation. However, there is no evidence that these capture rates represent the maximum rate technically achievable, and indeed the basis for this assumption is rarely discussed. Though additional cost would be incurred, higher capture rates (even greater than 95%) may be technically achievable.

This study does not seek to quantify the technical limits or economic impact of higher capture rates, but instead seeks to provide an initial investigation into the implications for unburnable carbon if such a technology were available. To support this analysis a global integrated assessment model, TIAM-Grantham [140], has been applied to examine the impact of a range of capture rates on the use of fossil fuels in the global energy system. The range of capture rates investigated was 64% to 98% in 2% increments, with results as shown in Figure 23, 24 and 25.

FIGURE 23
Sensitivity of primary energy supply of natural gas in 2050, 2080 and 2100 to CCS capture rate, produced by TIAM-Grantham.



Of the three core fossil fuels, gas sees the strongest impact of altering the capture rate of CCS in this initial study. Earlier in the time horizon the capture rate does not have a large impact due to the relatively low price of other abatement opportunities across the global economy at that time. However, beyond 2050 the capture rate becomes very important, and by 2100 a high capture rate of 96% leads to an almost doubling of the primary gas supply relative to an 85% capture rate. This additional 100 EJ per year of primary gas supply has a wholesale value of approximately £500 billion per year at UK gas prices at the time of writing.

FIGURE 24
Sensitivity of primary energy supply of coal in 2050, 2080 and 2100 to CCS capture rate, produced by TIAM-Grantham.

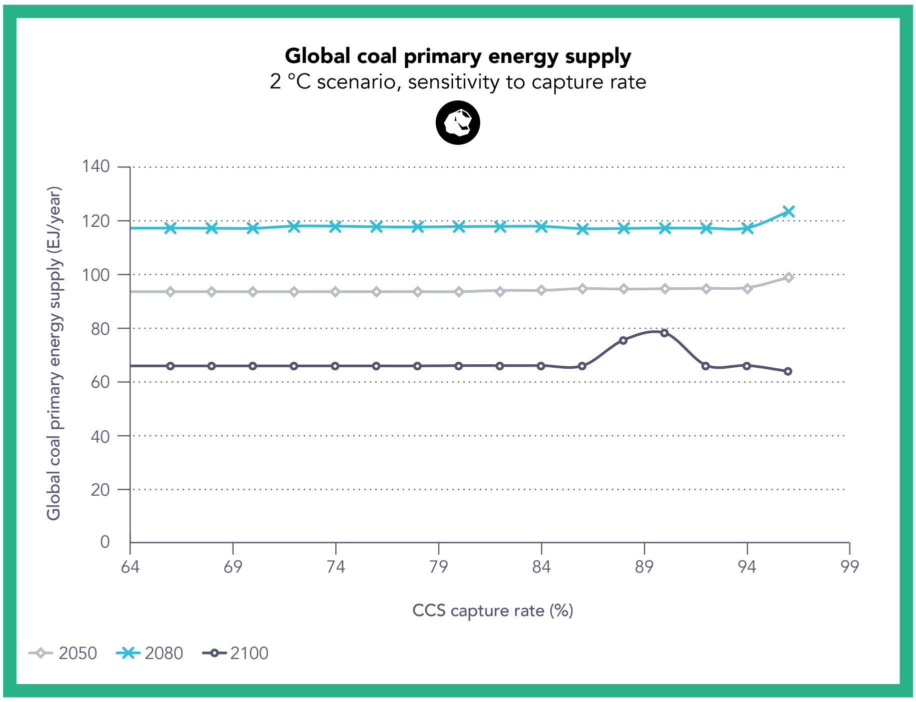
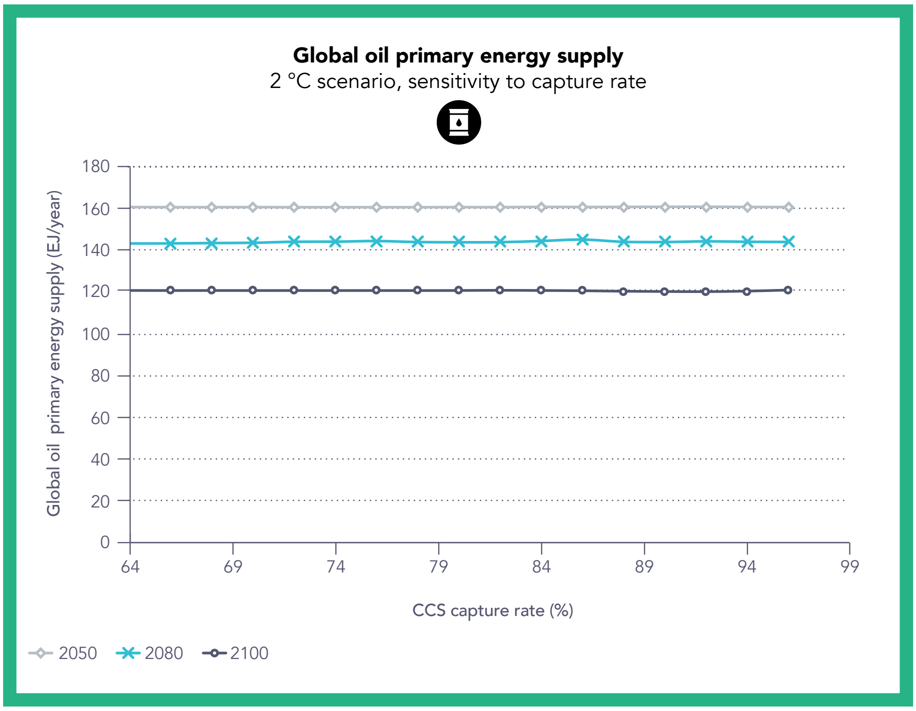


FIGURE 25
Sensitivity of primary energy supply of oil in 2050, 2080 and 2100 to CCS capture rate, produced by TIAM-Grantham.



However, beyond 2050 the capture rate becomes very important, and by 2100 a high capture rate of 96% leads to an almost doubling of the primary gas supply relative to an 85% capture rate.

Neither coal nor oil experience significant changes across the capture rate sensitivity examined. The quantity of these fuels in primary energy supply consistently declines over time. Only coal is directly influenced by CCS capture rate, and it is possible to observe an increase in primary supply of coal in 2100 at capture rates just below 90%, falling back above 90%. This is likely to be caused by competition between coal and bioenergy between sectors. Further research is required, including multi-model comparison studies, in order to fully explore the capture rate issue. Such a study is out of the scope of this White Paper, but will be pursued in future research.

The results produced here are dependent on a range of assumptions in the model, including the relative fossil fuel extraction costs, bioenergy cost, CCS technology cost, performance and availability of CCS, and regional or global constraints on CO_2 geo-sequestration and total technology uptake. Therefore, it is recommended that further IAM modelling studies are undertaken to understand the drivers of the shift of impact of reduced residual emissions between gas and coal (and, to an extent, oil), with the expectation that some sensitivity in the results produced in this study is likely to be observed.

8. Recommendations for further research

The results of this report have highlighted the need for further research relating to the potential impact of technology on the extent of unburnable fossil fuels.

Key areas for future research topics are summarised below:

- This report has investigated the impact of the CCS capture rate on the long-term use of fossil fuels, and found it to be an important factor. However, further modelling studies are required to clarify the nuances of this point. What still needs to be investigated further is how the relationship between capture rates and 'unburnable carbon' is affected by: fossil fuel prices, CCS technology cost, CCS performance and availability, and competition with other low carbon technologies. Future studies should not only perform sensitivity analysis on these parameters, but should also examine results across multiple models in order to determine robustness of results to modelling approach.

- Analysing the literature has highlighted a lack of data on the state-of-the-art capture rate for CCS plants. Most references indicate a capture rate of 90%; however this value may not be enough. Previous research [139] has already shown that increasing the percentage of capture to 98% would not increase the cost per tonne of CO_2 abated for oxy-combustion and pre-combustion applications. Therefore, further research is needed to increase the capture rate of CCS plants closer to 100% and to understand the technology and cost implications of this.

- It should be a high priority for all countries considering large-scale deployment of CO_2 storage to perform regional dynamic assessments of the available CO_2 storage resource. This will provide important information on their future requirements and need for reservoir pressure management and management of the produced brine. Moreover, there is a need for further Research, Development & Demonstration (R,D&D) in order to improve storage efficiency.

- It should also be a high priority to update CCS components in integrated assessment models with costs associated with the need for brine production to relieve pressure with increased rates of CO_2 injection.

- The recent agreement reached during COP21 invites the Intergovernmental Panel on Climate Change to "provide a special report in 2018 on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways" [42]. Therefore, the assessment provided in this White Paper should be revisited in the future in order to take into account the outcomes of the IPCC special report.

9. Conclusions

This White Paper has considered whether carbon capture and storage (CCS) technology has the potential to enable access to more fossil fuel reserves in the future, where these reserves would otherwise be 'unburnable'. The authors have critically reviewed the studies that have considered CCS in the context of unburnable carbon, analysed the status and costs of CCS, studied its impact on fossil fuel consumption across a selection of global climate change mitigation models used in the IPCC Fifth Assessment Report, and examined the extent of global CO_2 geo-storage capacity. Finally, a new analysis has been performed demonstrating the impact of the capture rate of CCS technology on 'unburnable carbon' outcomes.

There have been a number of recent studies reviewing the unburnable carbon topic. These have broadly reached the same conclusion; that some portion of fossil fuel reserves is unburnable in scenarios where climate change induced warming is limited to a reasonable chance of temperature rise less than 2 °C. Only a few of these studies have explicitly considered the impact of the availability of CCS technology. Those studies that did consider this issue explicitly indicated that CCS has a limited impact on the amount of reserves that are burnable. However, none of these studies focused on the potential of CCS, or questioned why their results indicated a less prominent role for the technology than might otherwise be expected.

Our analysis confirms that CCS availability has a large bearing on the extent of fossil fuel consumption in climate-constrained scenarios; approximately 200 EJ more fossil fuel could be used per year in scenarios with CCS, as opposed to a scenario without the technology.

In order to fill this gap, an analysis specifically on CCS and unburnable carbon has been undertaken. Insights were drawn from the EMF27 multi-model comparison, which produced a set of scenarios of energy system change to mitigate climate change. EMF27 includes scenarios with and without CCS, and therefore provides a robust and consistent basis for investigating the impact of CCS on fossil fuel reserve use. Our analysis confirms that CCS availability has a large bearing on the extent of fossil fuel consumption in climate-constrained scenarios; approximately 200 EJ more fossil fuel could be used per year in scenarios with CCS, as opposed to a scenario without the technology. A key difference between this study and previous efforts is that the dynamics of CCS uptake were considered, with the observation that CCS adoption is still ramping up at 2050 (previous studies limited the time horizon to 2050).

The extent to which EMF27 modelling assumptions limit CCS uptake has also been reviewed. Based on the evidence available from EMF27 models, there are few limiting assumptions made on the availability of CCS. Almost all models reviewed reported no capacity or uptake-rate limits for the transport and storage phases of CCS. While less evidence is available for the capture phase, it is unlikely that such constraints are preventing uptake substantially, particularly later in the time horizon (i.e. 2040 onwards).

Also, the cost of CCS technology assumed in the models does not appear to be a significant barrier. The key observation is that the capital and operating costs of CCS technology are generally much lower than the marginal abatement costs[5] observed in the models. Therefore, if CCS is available (and not unfavourable for other reasons) further adoption should be observed in the models. The only plausible explanation that such adoption is not observed is that there is another factor in the models preventing uptake.

The result of this study was that capture rate is indeed very important for the role of natural gas, in particular, in future energy systems.

This report investigated the possibility that residual emissions from CCS installations, usually modelled as approximately 10–15% of emissions from the source in question, is the reason further uptake is not observed. The TIAM-Grantham model was applied to consider this question, running a scenario constrained to 2 °C warming across a range of capture rates from 64% to 98%. The result of this study was that capture rate is indeed very important for the role of natural gas, in particular, in future energy systems. From 2050, onwards very high capture rates lead to natural gas retaining market share while the other fossil fuels consistently decline. A further multi-model comparison on this issue would be able to explore the issue more fully.

This report also tested the assumption that global CO_2 storage capacity is large. This was found to be true from a volumetric standpoint in that the pore space available is sufficient to accommodate CO_2 from all fossil fuel reserves in virtually any scenario imaginable. However, more recent dynamic studies of geo-storage capacity found that reservoir pressurisation could significantly limit saline aquifer storage capacity in some cases. Pressure management strategies are needed to alleviate this issue, and the impact of this on costs and deployment requires further assessment. This issue is not likely to be material in the short to medium term, given that adequate storage capacity is available in depleted oil and gas fields, and in higher quality saline aquifers.

5. Marginal abatement cost observed in the model corresponds to the abatement cost of the most expensive mitigation technology adopted for that time period. These are from hundreds to thousands of US$ per tonne across the models, which is substantially higher than the cost of CCS.

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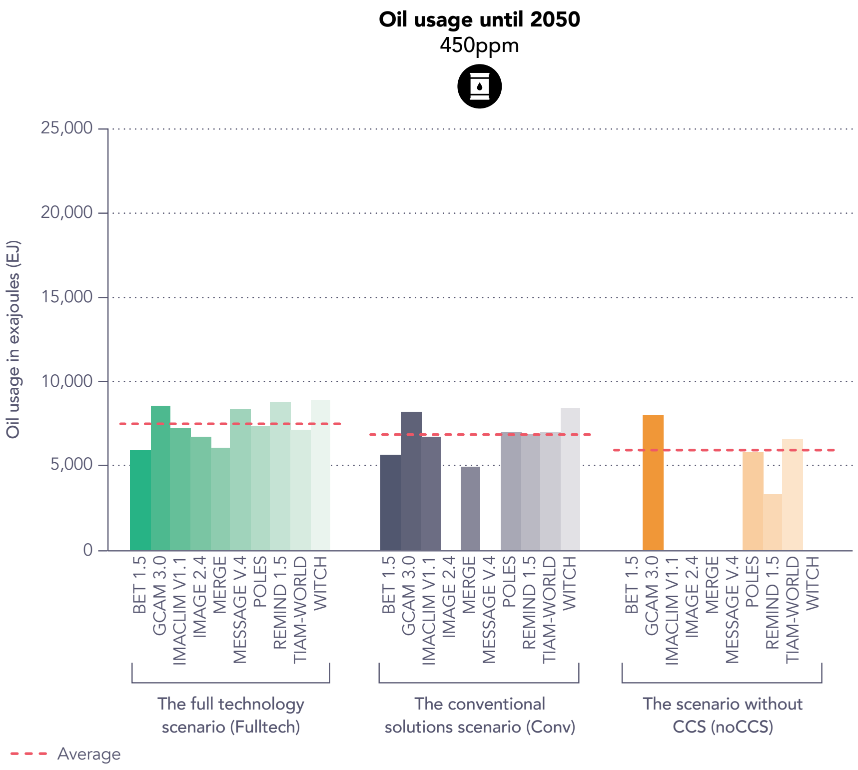
Appendix

Annex 1. EMF27 primary energy by fuel (all models)

FIGURE 26
Emissions from oil usage according to the EMF27 models (scenario 450 ppm timeframe 2005–2050 above, 2005–2100 below).



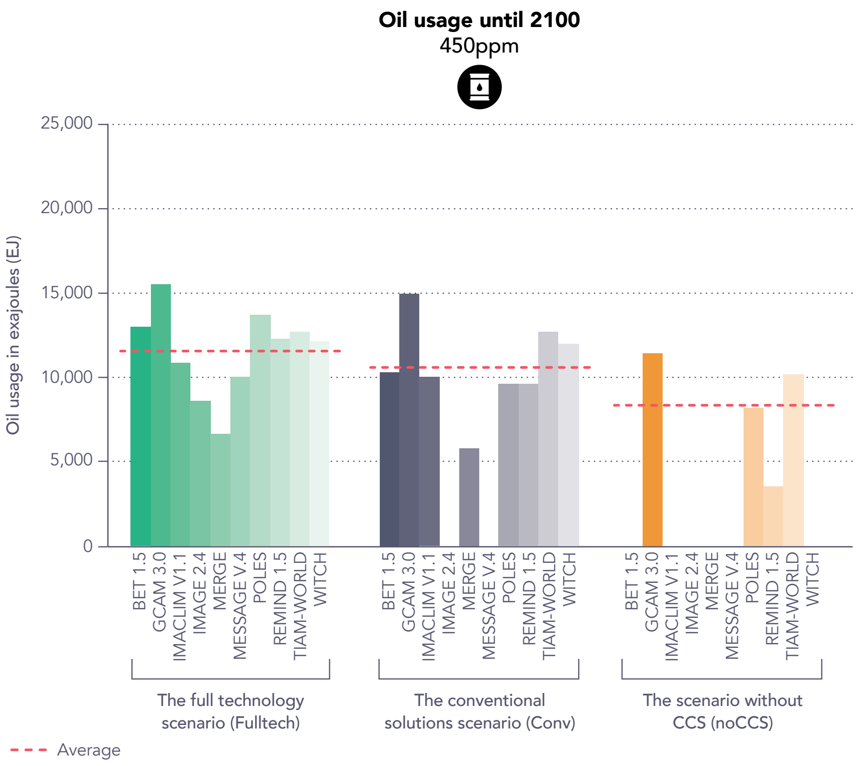


FIGURE 27
Emissions from gas usage according to the EMF27 models (scenario 450 ppm timeframe 2005–2050 above, 2005–2100 below).

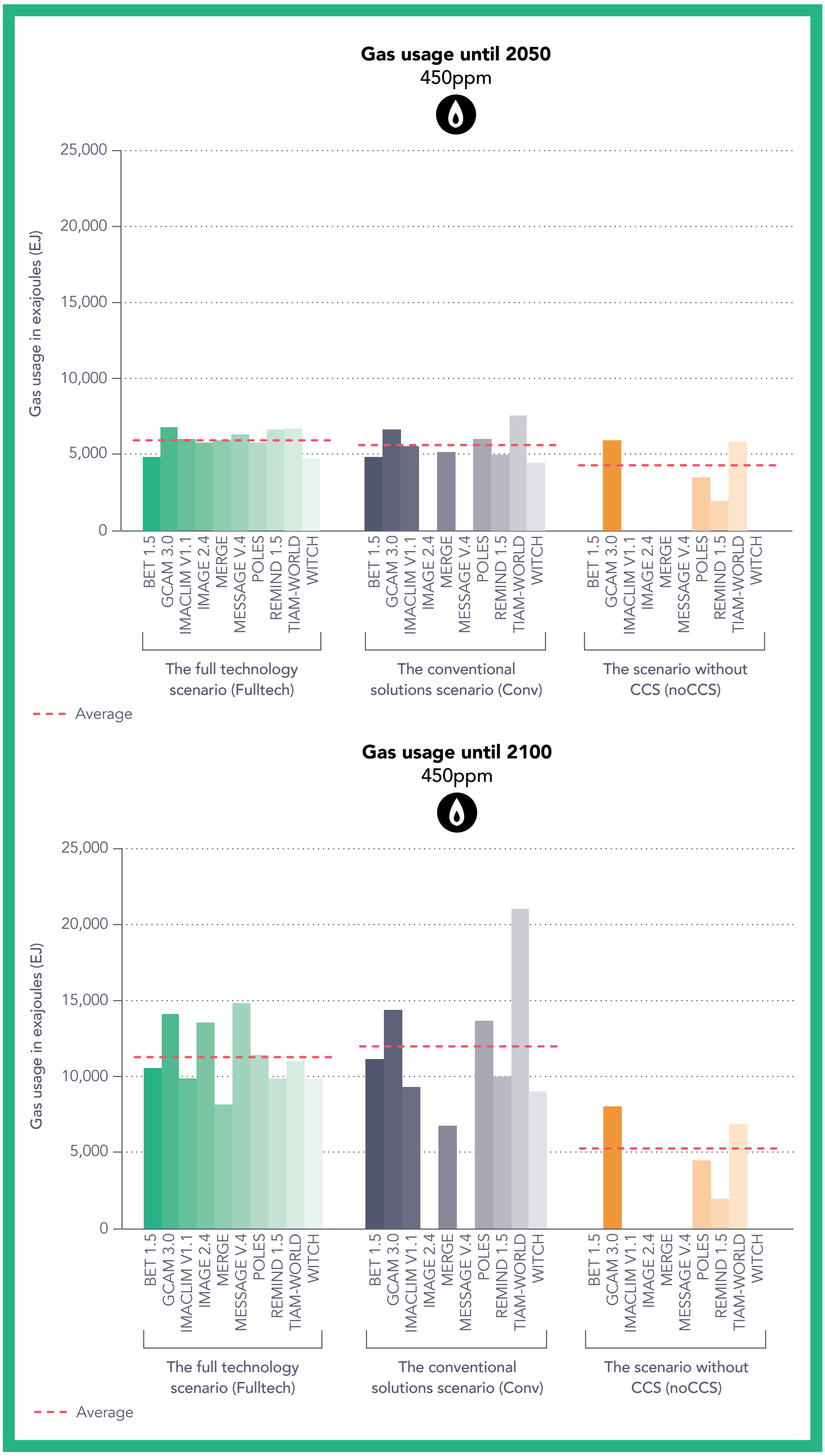
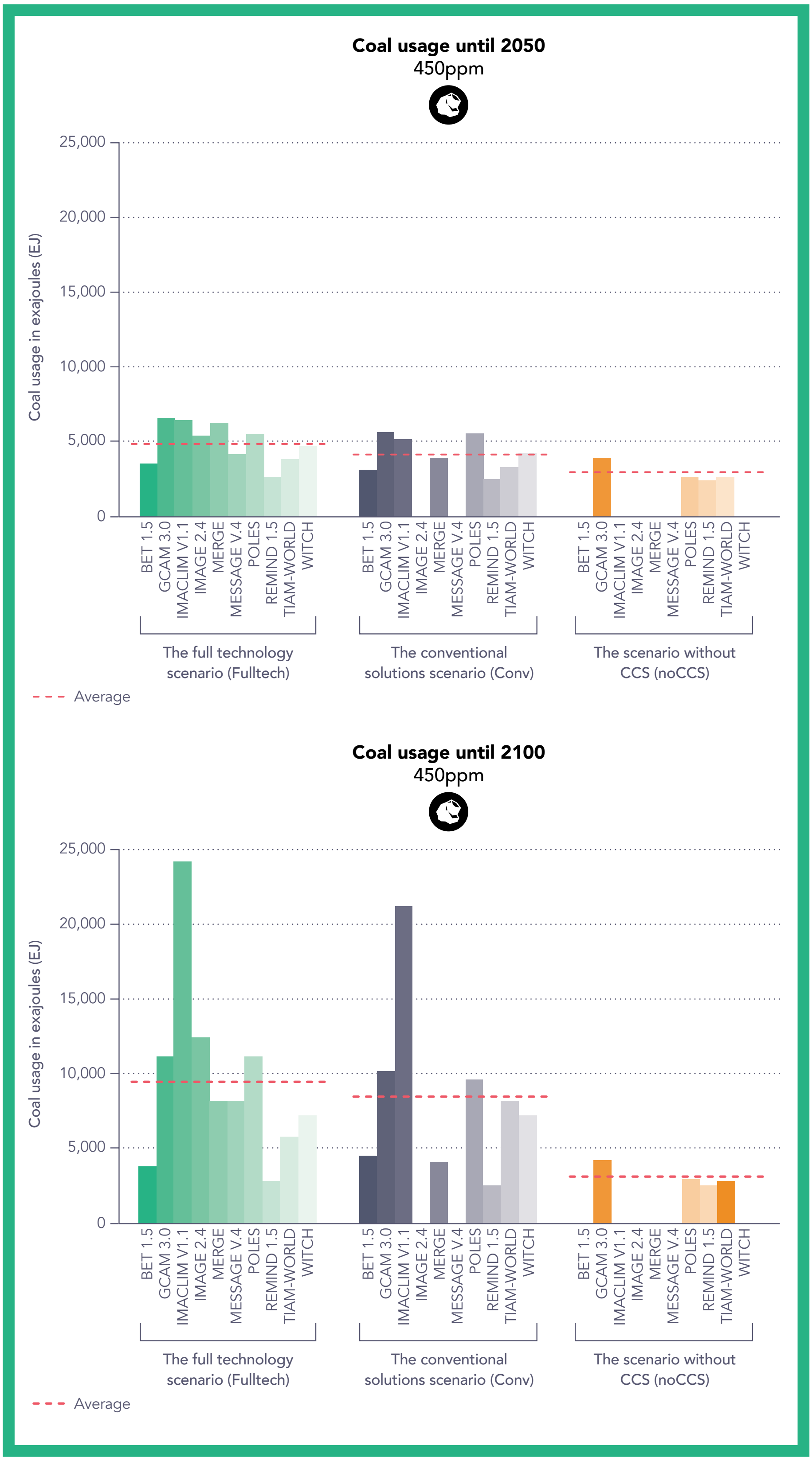


FIGURE 28
Emissions from coal usage according to the EMF27 models (scenario 450 ppm timeframe 2005–2050 above, 2005–2100 below).



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