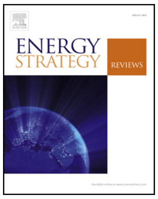
Energy Strategy Reviews 22 (2018) 61–81

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr



An assessment of CCS costs, barriers and potential

Sara Budinis[a,b,*], Samuel Krevor[c], Niall Mac Dowell[b,d], Nigel Brandon[b,c], Adam Hawkes[a,b]

[a] Department of Chemical Engineering, Imperial College London, London, SW7 2AZ, UK
[b] Centre for Process Systems Engineering, Imperial College London, London, SW7 2AZ, UK
[c] Department of Earth Science and Engineering, Imperial College London, London, SW7 2AZ, UK
[d] Centre for Environmental Policy, Imperial College London, London, SW7 2AZ, UK

ARTICLE INFO

Keywords:
Energy
CO_2
CCS
Cost
Integrated assessment model

ABSTRACT

Global decarbonisation scenarios include Carbon Capture and Storage (CCS) as a key technology to reduce carbon dioxide (CO_2) emissions from the power and industrial sectors. However, few large scale CCS plants are operating worldwide. This mismatch between expectations and reality is caused by a series of barriers which are preventing this technology from being adopted more widely. The goal of this paper is to identify and review the barriers to CCS development, with a focus on recent cost estimates, and to assess the potential of CCS to enable access to fossil fuels without causing dangerous levels of climate change.

The result of the review shows that no CCS barriers are exclusively technical, with CCS cost being the most significant hurdle in the short to medium term. In the long term, CCS is found to be very cost effective when compared with other mitigation options. Cost estimates exhibit a high range, which depends on process type, separation technology, CO_2 transport technique and storage site.

CCS potential has been quantified by comparing the amount of fossil fuels that could be used globally with and without CCS. 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 being consumed by 2050, against 37% being consumed 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. It was also shown that the residual emissions from CCS facilities is the key factor limiting long term uptake, rather than cost. Overall, the results show that worldwide CCS adoption will be critical if fossil fuel reserves are to continue to be substantively accessed whilst still meeting climate targets.

1. Introduction

Carbon Capture and Storage (CCS) is a technology aiming at separating, transporting and permanently storing carbon dioxide (CO_2) underground in order to avoid its emission into the atmosphere. CCS is often argued to be a key technology for the decarbonisation of the global energy system and can be applied to both power generation and industrial production. For the industrial sector in particular, when material or process replacement is not technically or economically feasible, CCS is currently the only technology able to drastically reduce carbon emissions.

The pivotal role of CCS as a transitional technology towards a low or zero emission future has been highlighted by a number of recent publications [1,2]. A key tool in the assessment of possible pathways for the decarbonisation of the energy system are global Integrated Assessment Models (IAMs). These models are used to produce scenarios of energy system transition to a low carbon world, providing estimates of the future use of fossil fuels, CCS, and other energy resources that are consistent with climate change mitigation targets. IAMs use a range of methodological approaches that determine which technologies are selected, along with a range of input data assumptions like costs and performance, which all have a strong bearing on outcomes. For example, the IEA [3] has employed an integrated assessment model to support a roadmap assisting governments and industry in integrating CCS in their emissions reduction strategies. Adoption of this roadmap would enable storage of a total cumulative mass of approximately 120 $GtCO_2$ between 2015 and 2050 (according to the Carbon Tracker Initiative, this value would be higher and equivalent to 125 $GtCO_2$ [4]).

In this context, the importance of CCS is evident. This technology could enable countries to continue to include fossil fuels in their energy mix [5] without further exacerbating climate change and therefore could unlock assets that would otherwise be stranded [6,7]. Moreover,

---

[*] Corresponding author. Department of Chemical Engineering, Imperial College London, London, SW7 2AZ, UK.
E-mail address: s.budinis11@imperial.ac.uk (S. Budinis).

https://doi.org/10.1016/j.esr.2018.08.003
Received 9 January 2018; Received in revised form 15 May 2018; Accepted 1 August 2018

Abbreviations

AR	Assessment Report
BECCS	Bio Energy with Carbon Capture and Storage (CCS)
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CO_2e	Equivalent carbon dioxide
COE	Cost Of Electricity
COP	Conference Of the Parties
CPS	Current Policies Scenario
ECBM	Enhanced Coal Bed Methane
ECMR	Enhanced Coal Bed Methane Recovery
EGR	Enhanced Gas Recovery
EMF	Energy Modelling Forum
EOR	Enhanced Oil Recovery
EWS	Efficient World Scenario
FOAK	First Of A Kind
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
LHV	Low Heating Value
NET	Negative Emission Technology
NGCC	Natural Gas Combined Cycle
NGO	Non-Governmental Organization
NOAK	N^{th} Of A Kind
NPS	New Policies Scenario
NPV	Net Present Value
PC	Pulverised Coal
SiMCaP	Simple Model for Climate Policy assessment
TRL	Technology Readiness Level
UKERC	UK Energy Research Centre

meeting climate targets without adopting CCS would mean up to 138% increase in total discounted mitigation costs [8].

Despite the positive estimates on the potential role of CCS reported in the literature, the current number of operating CCS plants is limited. According to the Global CCS Institute, there are currently 39 large-scale CCS projects worldwide in either ‘early development’, ‘advanced development’, ‘in construction’ or ‘operating’ phase [9]. Among the projects currently in operation (17), nine are based in the United States, followed by Canada (3 projects), Norway (2 projects) and Brazil, Saudi Arabia and United Arab Emirates (1 project each). The Boundary Dam Carbon Capture and Storage Project [10] and the Petra Nova Carbon Capture Project [11] are the only two examples of CCS applied to power generation, while the remaining 15 operating projects are on industrial production (ethanol, fertilizers, hydrogen, iron and steel, synthetic natural gas) and natural gas processing [12].

The total number of large scale CCS projects has fallen in the past five years, from 75 (2012) to 39 currently (2017). At the same time the number of projects in the ‘operating’ phase has increased from 8 (2012) to 17 (2017). These trends reflect both the technical feasibility of CCS and its struggle to emerge as a game-changing technology against climate change.

The cost of CCS has been previously identified as a major barrier to its adoption, however there are other potential barriers which are preventing its wider implementation. One of the goals of this article is to identify the barriers to the global adoption of CCS, with a focus on its costs. The second goal of the paper is to quantify CCS potential, in particularly with reference to the concept of ‘unburnable carbon’. This concept points out that known fossil fuel reserves cannot all be converted to CO_2 emitted to the atmosphere (i.e. burned or otherwise) if the world is to avoid dangerous climate change. A number of reports have been published recently on the topic, though it is by no means 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.

Analyses on unburnable carbon exists in the grey literature, produced by banks, consultancies, insurers, think tanks and NGOs (Non-Governmental Organisations). Academic research behind the insights is also available in specific areas, but few studies exist that span the 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 larger than the allowable carbon budget for a 2 °C world. Less compelling evidence exists on likely outcomes with respect to fossil fuel utilisation, where the use of abatement technology such as CCS might unlock fossil fuel reserves whilst meeting carbon emission targets.

This article identifies and reviews potential CCS barriers, with a focus on CCS costs, and reviews the evidence for the potential role of CCS technology in unlocking fossil fuel assets that would otherwise be stranded in a world where CO_2 emissions are severely constrained.

In section 2, the paper covers the evidence on this broad issue including the climate science, global data on fossil fuel reserves and resources and quantification of unabated burnable carbon. Section 3 summarises the potential barriers to the full development of CCS, including costs (which are covered in details in section 4), geo-storage capacity, source-sink matching, supply chain and building rate, policy regulation and market, and public acceptance. Section 4 summarises cost metrics and estimates for CCS energy and efficiency penalty; CO_2 capture, transport and storage; capital and operating costs. Section 5 includes a review of a multi-model IAM comparison study that considered CCS in relation to the unburnable carbon concept, and quantifies the potential of CCS to give access to fossil fuels in the long term while meeting stringent climate targets. Section 6 provides an analysis on the influence of residual CO_2 emissions on the adoption of CCS in the energy scenarios. This leads to recommendations on the treatment of this aspect of CCS in unburnable carbon assessments in future (section 7) and conclusions (section 8).

2. Background

2.1. *The global greenhouse gas budget*

2.1.1. *The need for emissions mitigation*

It is unequivocal that climate change is influencing the planet, with a range of effects already observable [13]. It is also extremely likely that this is caused by emissions of GHG ensuing from human activities, 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 [14], and the rapidly increasing emissions [8], it is pressing that decision makers consider options to mitigate climate change by reducing emissions, and plan adaptation to deal with climate change that does occur.

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 [15]. Peak warming given by cumulative emissions has been adopted by the scientific community as a reliable measure of climate change [16], while 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 [17]. However, even 2 °C cannot be considered completely safe, with "well below" 2 °C emerging from the Paris Agreement [18], and in any case adaptation will still be required.

2.1.2. *Carbon budget estimations*

Carbon budgets that lead to warming of greater than 2 °C have also been produced using climate models such as MAGICC 6.0 [19] [15], HadSCCCM1 [16] [20,21] and SiMCap EQW [22,23]. These models have been employed by different research groups and institutions in order to estimate the carbon budget, which 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. In a range of studies attempting to quantify this budget, the authors 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. Key sources of uncertainty are 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 [24]. 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.

Table 1 summarises the carbon budgets as estimated by reported sources. According to Meinshausen et al. [15], the probability of exceeding 2 °C can be limited to below 25% (50%) by keeping 2000–2049 cumulative CO_2 emissions from fossil sources and land use change to below 1000 (1440) $GtCO_2$. They also estimate that non-CO_2 GHGs (including methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) may constitute 33% of overall emissions. Allen et al. [16] estimate that if total emissions between 1750 and 2500 are 3670 $GtCO_2$, then the most likely peak warming will be 2 °C. However, half of the emissions have already been released to the atmosphere since 1750. Therefore, this would mean a carbon budget of about 1835 $GtCO_2$ in 2009, when the paper was published.

Finally, it is clear that the global carbon budget is being rapidly exhausted. Over the period 2002 to 2011, the global fossil fuel, cement and land use change CO_2 emissions were approximately 34 $GtCO_2$ per year [25]. Therefore the global carbon budget for temperature rise to remain below 2 °C is likely to be exhausted before 2050 unless action is taken quickly.

2.2. *Classification and estimation of fossil fuel reserves and resources*

2.2.1. *Classification*

The methodology for determining fossil fuel reserves is a contested subject. One of the first attempts to classify them is represented by the McKelvey box, which classifies resources as undiscovered, discovered and economic (i.e. reserves) and discovered sub-economic (resources) [26]. Since 1972, various nomenclatures have been proposed and adopted [27–33].

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. The commercial criteria depend on what can be defined as "commercial". In most definitions, commercial is used as being synonymous to "economic", which means that "the project income will cover the cost of development and operations (at zero discount rate)" [35]. Simplistically, fossil fuel price is in turn 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 very volatile quantity. This makes any estimate of reserves open to debate, and indeed the supply curve for each fossil fuel is dynamic in nature.

The extent of reserves is contentious with respect to its link to the 'carbon bubble' concept, which is driven by the fact that if some reserves are unburnable the companies that own those reserves might be overvalued in the stock market [36]. However Mayer and Brinker [37] have argued that the perception of carbon risk has been inflated by the choice of definition for the reserves, in particular that reserves estimated using the SEC (Security and Exchange Commission) method are not as high as some other methods, and also that these reserves 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 i.e. an indirect 'carbon bubble' effect [38].

2.2.2. *Reserves and resources estimations*

In order to evaluate the amount of unburnable fossil fuel reserves in a low carbon scenario, the next step is to evaluate the overall potential carbon emissions within these reserves, and compare this with the global carbon budget. The extent of reserves has been reviewed by Meinshausen et al. [15], who state that the mid-estimate from the literature could produce 2800 gigatonnes (Gt) of CO_2 emissions in a scenario of unabated combustion, with an 80%-uncertainty range of 2541 to 3089 $GtCO_2$. Reserve estimates have also been reported by McCollum et al. [39], which summarised conventional and unconventional fuel estimates. This reported a lower estimate of 3683 $GtCO_2$, which corresponds reasonably to that reported by McGlade and Ekins [40] (3613 $GtCO_2$). McCollum also presented an upper estimate of 7118 $GtCO_2$. Clearly there is great uncertainty regarding estimates of global fossil fuel reserves, particularly where as-yet undiscovered reserves are included.

Reserves and resources estimates by fossil fuel type have been summarised in Table 2. Three different units have been reported to represent the amount of reserves and resources: gigatonnes (Gt), their energetic content (EJ) and the amount of CO_2 they would release to the

Table 1
Global emissions budgets from selected sources.

Budget (Gt)	Gases	Scope	Timeframe	Probability statement	Model	Reference
886	CO_2	fossil sources, land use change	2000–2049	20% chance of exceeding 2 °C	MAGICC 6.0	[15]
1000	CO_2	fossil sources, land use change	2000–2049	25% chance of exceeding 2 °C	MAGICC 6.0	[15]
1437	CO_2	fossil sources, land use change	2000–2049	50% chance of exceeding 2 °C	MAGICC 6.0	[15]
1356	Kyoto gases	fossil sources, land use change	2000–2049	20% chance of exceeding 2 °C	MAGICC 6.0	[15]
1500	Kyoto gases	fossil sources, land use change	2000–2049	26% chance of exceeding 2 °C	MAGICC 6.0	[15]
1678	Kyoto gases	fossil sources, land use change	2000–2049	33% chance of exceeding 2 °C	MAGICC 6.0	[15]
2000	Kyoto gases	fossil sources, land use change	2000–2049	50% chance of exceeding 2 °C	MAGICC 6.0	[15]
3670	CO_2	fossil sources, land use change	1750–2500	50% chance of exceeding 2 °C (according to [34])	HadSCCCM1	[16]
1635–1752[a]	Kyoto gases	fossil sources, land use change	2000–2050	50% chance of exceeding 2 °C (low aerosol scenario)	SiMCaP EQW and MAGICC	[23]
1631–1897	Kyoto gases	fossil sources, land use change	2000–2050	50% chance of exceeding 2 °C (high aerosol scenario)	SiMCaP EQW and MAGICC	[23]

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

Table 2
Estimation of reserves and resources of oil, gas and coal [41–47].

	Fossil fuel type	Gigatonnes (Gt)	Exajoules (EJ)	Carbon ($GtCO_2$)
Reserves	**Oil**	219–240	9264–10145	679–744
Resources	**Oil**	334–847	14128–35845	1036–2627
Reserves	**Gas**	125–155	6016–7461	338–453
Resources	**Gas**	427–540	20518–25921	1151–1454
Reserves	**Coal**	892–1004	25141–28313	2378–2678
Resources	**Coal**	21208–22090	598066–622924	56577–58929
Reserves	**Total**	1236–1399	40421–45919	3395–3876
Resources	**Total**	21969–23477	632712–684690	58764–63010

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 3395–3876 $GtCO_2$.

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 reserves surplus 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 a number of sources, some of which have been reported in Table 3, summarising 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 [41], which estimates overall reserves to be equal to 2860 $GtCO_2$. Without CCS, less than a third (i.e. less than 953 $GtCO_2$) can be burnt in the 2DS. 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 regarding its pace of deployment.

2.3.1. Sensitivity to temperature rise targets

The amount of burnable carbon (i.e. the carbon budget) reported in Table 3 shows a wide variability which depends on factors such as the reference, the modelling methodology and assumptions, the timeframe under analysis and the temperature rise target.

The 2 °C target has received a lot of attention since it was introduced as an EU climate target back in 1996 [48]. However, other targets have been taken into account as well, which were more or less stringent with respect to the 2 °C target. For example, at 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" [18] (this report is currently under review). 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 [15], other less stringent targets include temperature rises up to 5.3 °C. The analysis of scenarios that would bring about similar targets are motivated by the desire to show what would happen without an emission reduction framework in place.

Table 4 shows four different scenarios proposed by IEA [41], which correspond to four different temperature rise targets (with a probability of 50% to meet the target). CO_2 emissions have been reported for the years 2020 and 2035, showing how a reduction in global emissions could still bring the temperature rise to 3 °C. According to the IEA [41], having a more relaxed temperature rise target increases the carbon budget by 2–16% in 2020 and by 38–100% in 2035.

Cumulative emission budgets have been reported in Table 5 for temperature rise targets between 1.5 °C and 4 °C. 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 1610–1790 $GtCO_2$ (3 °C) to 2660–3440 $GtCO_2$ (4 °C) in 2100. Carbon budgets having different likelihoods to meet 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.

2.3.2. Circumstances that could 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 would include a potent global agreement to mitigate climate change; the implementation of an effective policy, regulatory and market mechanism; the adoption of technology approaches avoiding or limiting emissions. The agreement reached during COP21 in 2015 [18] indicates that it is possible to achieve a potent global agreement on climate change, however further more ambitious binding commitments will be required. Implementing effective policy, regulatory and market mechanisms at national and international levels in order to meet the agreed commitments would be likely to include carbon trading or taxation mechanisms similar to those already included in the ETS [49]. Finally, 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.

Some sources have confirmed the possibility of unburnable carbon becoming a reality [41,50,51], while others have denied the 'carbon bubble' as a real problem, such as Mayer and Brinker [37]. While climate change is generally acknowledged by oil and gas companies [52], their position on the 'carbon bubble' is cautious and highlights how the outcome depends on many factors and is therefore difficult to predict. This paper 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 in the grey literature there are controversial opinions regarding the likelihood of unburnable carbon becoming a major issue in the global energy system.

3. Barriers to CCS development

Many abatement technologies affect the use of fossil fuels. The range of options is large, and includes both direct approaches, affecting the use of fossil fuels or their emissions into the atmosphere (e.g. enhanced energy efficiency and conservation; replacement of coal by natural gas; greater use of nuclear power; carbon capture, utilisation and storage) [53,54]; and indirect approaches, increasing the remaining carbon budget (such as the development of mass market renewable energy technologies, afforestation and reforestation). In

Table 3
Estimates of unburnable and burnable carbon from selected sources.

Unburnable carbon ($GtCO_2$)	Burnable carbon ($GtCO_2$)	Overall remaining reserves ($GtCO_2$)	Timeframe	Reference
1360	1440	2800	2000–2050	[15]
"more than 2/3" > 1907	less than 1/3 < 953	2860	until 2050	[41]
2230	565	2795	2010–2050	[36]
1960	900	2860	2013–2049	[4]
2565	1049	3613	until 2050	[40]

Table 4
IEA scenarios and corresponding CO_2 emissions for different temperature rise targets (modified from Ref. [41]).

Scenario	Temperature rise target (^{0}C)	CO_2 emissions (Gt, 2020)	CO_2 emissions (Gt, 2035)
450 Scenario (or 2DS)	2	31.4	22.1
Efficient World Scenario (EWS)	3	32	30.5
New Policies Scenario (NPS)	3.6	34.6	37
Current Policy Scenario (CPS)	5.3	36.3	44.1

Table 5
Fossil fuel carbon budget for different maximum temperature rises [4] IPCC [8]. Timeframes: 2011–2050; 2011–2100.

Fossil fuel carbon budget ($GtCO_2$)			
Temperature target (°C)[a]	Until 2050 ($GtCO_2$)	Until 2100 ($GtCO_2$)	Probability (%)
1.5	550–1300	630–1180	14–51
2	860–1600	960–1550	39–68
3	1310–1750	2570–3340	57–74
4	1570–1940	3620–4990	61–86

[a] Relative to 1850–1900.

extremely emissions constrained scenarios (e.g. net zero emissions in the second half of this century as put forward in COP21), indirect measures will be ineffective simply because there will be no carbon budget left to open up.

Carbon capture and storage 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 which are the separation of CO_2 from the gas stream, its compression and transportation (via pipeline or shipping) and its storage in a suitable geological site (e.g. saline aquifers, 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) [54–56]. While post-combustion and pre-combustion capture technologies are widely used (between TRL 1 and 5), oxy-combustion capture is still under development and not yet commercial, while pre-combustion is likely to be “decades away from commercial reality” [57].

Carbon capture and storage can be integrated in processes which therefore can be 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 [58]. An example of carbon-negative processes is Bio-Energy with CCS (BECCS) processes, which usually include either electricity [59] or biofuel production [60]. 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 fertilization [61]. BECCS and reforestation would arguably be the most attractive options to create negative emissions [61]. According to McLaren [62], 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.

The review presented in this section has identified as main challenges to the uptake up of CCS its cost and energy penalty, followed by location and capacity of storage sites. There are several non-technical barriers, including the lack of market mechanisms and incentives, fewer effective mechanisms to penalise major CO_2 emitting sources, inadequate legal framework allowing transport and storage (both inland and offshore) and public awareness and perception [53,63,64].

At the current CO_2 capture rate (which represents the percentage of CO_2 emitted by the process that will be captured and ultimately sequestered), no major purely technological barriers exist for capture, transport and storage of CO_2. Indeed, 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.

Regarding location and capacity of storage sites, the main factors to take into account include cumulative capacity of carbon storage, rates of release and uptake, connection from source to store and climate impact of storage timescale [65].

3.1. Cost of CCS

Cost of CCS has been identified as the major challenge preventing the widespread adoption of this technology, and has been investigated more in detail in section 4. Estimating actual CCS cost and expressing it in a clear way is challenging. This is mainly due to lack of empirical data (currently, in the power sector there are only two full scale CCS plant in operation [11,66]), difficulty in choosing the baseline when comparing different CCS plants, a variety of currencies and currency base years in the reported literature, cost differences due to unavailability of transport and storage infrastructure and a variety of processes, operating conditions and capture processes. Section 4 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. The results of the analysis show a great variability among sources, with a lack of data for specific processes or capture technologies, and identify the capture step as the most expensive step of the CCS chain.

3.2. Geo-storage capacity

Global demand for CO_2 storage in climate scenarios maintaining CO_2 concentrations at 400–500 ppm are estimated at an accumulated store of 600–2000 $GtCO_2$ by 2100 [67–69]. A number of studies have compiled regional estimates of CO_2 storage resources to suggest that cumulative resources to be in the range of 10,000–30,000 $GtCO_2$ including 1000 Gt in depleted oil and gas reservoirs [67]. This suggests an abundance of storage capacity relative to demand over the century.

The regional studies vary widely in their approach to estimation [70,71]. More recently, efforts by the Society of Petroleum Engineers and the United Nations Economic Commission for Europe have developed storage resource classification systems that will allow for comparable regional estimates to be made, with classifications indicative of the certainty around commercial viability [72,73]. The global storage availability estimates are classified as prospective under these schemes, with little to no physical reservoir characterisation performed for the vast majority of potential locations. This leaves a high degree of uncertainty as to their ultimate potential. The development of scores of projects will be required before this uncertainty can be significantly reduced.

In saline aquifers (i.e. fields without hydrocarbon production) reservoir pressurisation will limit the accessible CO_2 geo-storage capacity in the absence of pressure management strategies [68]. Recent work using reservoir simulation has found that only 0.01–1% of the pore volume of saline aquifers will be available for storage over timescales of around 50 years of injection, 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 induce fractures or reactivate faults in a sealing caprock. However, the first generation of storage capacity is underpinned by the potential use of existing oil and gas fields, and high quality saline aquifer reservoirs. As a result, reservoir pressurisation is unlikely to present major barriers for the first generation of commercial CO_2 storage.

Only a few studies evaluate the impact of a potential limit on storage capacity on the deployment of CCS in integrated assessment models [74–77]. In Koelbl et al. [76] 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 3500 to 20,000 Gt. The maximum cumulative storage demand was 3000 $GtCO_2$ 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. [77] also showed that the deployment of CO_2 storage until 2050 was not sensitive to a regional storage capacity estimates ranging from 4500 to 10,000 $GtCO_2$. The primary reason was again because the capacity in most regions was not approached 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 [75] analysed the impact of more severe constraints on CO_2 storage capacity until 2100, comparing a baseline scenario 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, are 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.

An estimated 1000 Gt of storage capacity is available in oil and gas reservoirs alone. The analysis of integrated assessment models in Koelbl et al. [76] 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 to 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 oil and gas fields.

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 [78] for North America, and by Dahowski et al. [79] for China. A commonly used regionally distributed supply cost curve for the rest of the globe was developed by Hendriks and Graus [80]. Notably, these datasets were developed prior to the work done by Birkholzer and Zhou [81], 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, it is clear that regional pressurisation of the storage resource may not [82]. 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 [83], or by interviews with relevant oilfield operators.

3.3. 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 [75,77]. Koelbl et al. [77] addresses the issue of regional distribution of storage. In their study, storage supply was found to be limiting 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 sufficient supply for at least decades [84]. In the case of China, the model appears to use values for storage capacity a factor of three less than those reported in the source data of Dahowski et al. [79] and CCS is being actively pursued as a large scale mitigation technology [85].

In general, where regional storage supply estimates are most developed (e.g. North America, Europe including Scandinavia, 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 there will be few locations where local storage availability will be a limiting factor.

3.4. 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. [86]), 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 [57].

In 2012, IEAGHG commissioned a study on potential supply and capacity constraints associated with equipment for CCS plants [87]. 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 IEA [2] could meet major barriers due to supply or capacity constraints. The results of the study have identified as major potential supply chain constraints hydrogen turbines for the capture step, pipelines for the transport step, availability of geo-engineers and drilling rigs for the storage step and finally availability of petroleum engineers across the full CCS chain. The conclusion of the study did not identify any insurmountable obstacles to the deployment of CCS as suggested by IEA [2]. However, 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 focussing on the UK market [88].

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; availability of skilled labour; and regulatory shortfalls. 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 (these timelines are representative for a plant based in EU or USA but could vary for developing countries such as China). 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. The availability of sufficient skilled labour could represent a bottleneck in the long term. However in the short term, there may be a higher workforce availability due to the recently depressed oil and gas prices resulting in a number of job losses [89]. As an example, the White Rose project in the UK was estimated to need on-average 4000–5000 people over approximately five years, with a peak of 9000 people. Finally, at present the regulatory environment for CCS infrastructure is not well developed, leading 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, meaning that the risk is largely non-technical in nature, which could mean that financial environments and/or regulation will change significantly over the construction period.

3.5. Policy, regulations and market

As previously mentioned, the cost of CCS has been identified as a major barrier to its wider adoption. 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 in fact have been employed for many decades. Without effective mechanisms to underpin uptake, the deployment of CCS to a level that would be adequate to meet the climate change targets will remain implausible.

Possible policy options include 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 carbon floor price; low-carbon portfolio standard with tradable certificates; minimum standards, such as a CCS obligation for new installations after 2020 [90].

Some low-carbon initiatives that could encourage CCS include the Clean Energy Future Package in Australia, the Regional Greenhouse Gas Initiative in 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, just to cite a few [91]. According to Lohwasser and Madlener [92], 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 US$ 587 M), 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 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” [93]. This would encourage reduction of CO_2 emissions by means of increased efficiency, fossil fuel switch (from coal to gas) and investment in CCS, renewable energy, smart buildings and grids and 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”.

3.6. 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 public acceptance of new technology, however a framework has been proposed that includes a range of different factors affecting acceptance. These factors include acceptance and attitude, knowledge, experience, trust, fairness, affect, perceived costs, risk and benefits, outcome efficacy and problem perception [94].

This framework has been adapted to CCS by Seigo et al. [95], who has reviewed the analyses on public perception. According to Seigo et al. [95], 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.

Furthermore, a further concern is that public investments in CCS would reduce the budget for renewable alternatives [95–97]. A survey with 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 [98]. 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 et al. [95] and other publications. For example van Alphen et al. [96] 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 towards CCS, including the previously cited 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 [97]. This suggests a need for a closer collaboration between experts from engineering and communications in order to inform the public.

4. CCS cost estimates

4.1. Cost metrics for CCS plants

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:

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

$$\mathit{Efficiency\ penalty} = \mathit{Efficiency\ without\ CCS}\ (\%) - \mathit{Efficiency\ with\ CCS}\ (\%) \tag{2}$$

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” [99].

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 [100]:

$$COE = \frac{(TCC)(FCF) + (FOM)}{(CF)(8766)(MW)} + VOM + (HR)(FC) \tag{3}$$

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), 8766 = 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 ($/tCO$_2$), which may refer to the CO$_2$ avoided, captured or abated, as reported in equations (4)–(6) [5,100]. The equations refer to the power generation sector, where COE is the cost of electricity generation ($/MWh) while NPV is the Net Present Value of the specified scenarios. The subscripts "CCS", "ref" and "cc" refer respectively to plants with CCS, plant 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 more appropriate for Integrated Assessment Models as it enables comparison of different energy systems. The subscripts "ref" and "low-C" refer to values respectively before and after a specified carbon reduction scenario [100].

$$Cost\ of\ avoided\ CO_2 = \frac{(COE)_{CCS} - (COE)_{ref}}{(tCO_2/MWh)_{ref} - (tCO_2/MWh)_{CCS}} \tag{4}$$

$$Cost\ of\ captured\ CO_2 = \frac{(COE)_{CC} - (COE)_{ref}}{(tCO_2/MWh)_{captured}} \tag{5}$$

$$Cost\ of\ abated\ CO_2 = \frac{(NPV)_{low-C} - (NPV)_{ref}}{(tCO_2)_{ref} - (tCO_2)_{low-C}} \tag{6}$$

Finally the cost of CCS can be reported in the literature in a more traditional way which includes estimation of capital and operating costs.

4.2. Energy and efficiency penalty

According to Clark and Herzog [6], the major barrier to CCS in the power industry is the high capital cost and energy penalty compared to traditional fossil fuel fired generators. As an example, the net efficiency penalty (LHV) of CCS for coal-fired power generation is about 10% [101]. 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. [102], 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. [99], energy penalty values for PC plants with capture range from 15% to 28% while efficiency penalties range from 8% to 15.4%. For Natural Gas Combined Cycle (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% (Table 6).

4.3. Capture, transport and storage costs

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 the operating conditions of the capture step, which in turn depend on how carbon dioxide is transported to the storage site, together with its location and type.

Table 7 reports the cost of captured CO$_2$ depending respectively on 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. The reported costs present a wide variety, 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 Recover (EOR/EGS) has a smaller range characterised by a higher minimum cost but a lower maximum cost when compared to CCS storage.

Table 8 reports the cost of CO$_2$ transport depending on the pipeline capacity (MtCO$_2$/yr) and location (onshore or offshore). As expected, the lowest cost of transport refers to the onshore pipelines having higher capacity (1.3–2.2 $2015/tCO$_2$/250 km with capacity 30 MtCO$_2$/yr).

Table 9 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.

Table 10 reports the cost of avoided CO$_2$ depending respectively on 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.

4.4. Cost of electricity

Table 11 reports the cost of electricity ($2015/MWh) depending on process plant, capture technology and storage solution, respectively. The lowest cost corresponds to gas-fired power generation (54 $2015/MWh) while the highest cost corresponds to Integrated Gasification Combined Cycle (278 $2015/MWh). The cost of electricity does not vary with different capture technologies (111–265 $2015/MWh) but may be much higher when CCS is adopted instead of EOR or EGR for the storage of CO$_2$.

4.5. Capital and operating costs

Capital and operating costs are reported in Table 12 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) rather than gas fired power generation (around 8 $2015/kW-yr).

4.6. 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 $2015/tCO$_2$ 20–110. Transport cost ranges between 1.3 and 15.1 $2015/tCO$_2$/250 km, depending on 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

Table 6
Energy and efficiency penalty for Pulverised Coal (PC), Natural Gas Combined Cycle (NGCC) and Integrated Gasification Combined Cycle (IGCC) power plants [99,101,102].

	Pulverised Coal	Natural Gas Combined Cycle	Integrated Gasification Combined Cycle
Energy penalty	15–28%	15–16%	4.9–20%
Efficiency penalty	8–15.4%	6–11.3%	5–10.3%

Table 7
Cost of captured CO_2 for different process plants, capture technologies and storage solutions.

	Cost ($2015/$tCO_2$)		References
	Min	Max	
Process plant			
Coal-fired power	41	62	[103–106]
Gas-fired power	52	100	[103,107]
Iron and steel	57	69	[106,108]
Refineries and natural gas processing	20	79	[106,108]
Cement production	35	110	[106,108]
Natural gas combined cycle	75	95	[104–106]
Oxyfuel combustion	45	50	[106]
Capture technology			
Post-combustion (amine)	50	110	[108]
Chemical looping	35	52	[108]
Oxy-combustion	45	66	[106,108]
Storage			
CCS	20	110	[103–108]
EOR/EGR	52	62	[107]

Table 8
Cost of CO_2 transport for onshore and offshore pipelines with different capacities (modified from Ref. [109]).

Methods	Capacity (MtCO_2/yr)	Transport cost ($2015/t$CO_2$/250 km)	
		Min	Max
Onshore pipelines	3	4.4	11.1
	10	2.2	3.8
	30	1.3	2.2
Offshore pipelines	3	7.3	15.1
	10	3.5	4.9
	30	1.9	2.4

Table 9
Cost of CO_2 storage for various storage sites (modified from Ref. [109]).

Properties	Storage cost ($2015/t$CO_2$)	
	Min	Max
Depleted oil and gas field – reusing wells onshore	1.6	11
Depleted oil and gas field – no reusing wells onshore	1.6	15.7
Saline formations onshore	3.1	18.8
Depleted oil and gas field – reusing wells offshore	3.1	14.1
Depleted oil and gas field – no reusing wells offshore	4.7	22
Saline formations offshore	9.4	31.4

Table 10
Cost of avoided CO_2 for different process plants, capture technologies and storage solutions.

	Cost ($2015/t$CO_2$)		References
	Min	Max	
Process plant			
Coal-fired power	24	110	[103–106,109–112]
Gas-fired power	67	115	[103,107,110–112]
Iron and steel	52	120	[103,106,113]
Refineries	6	160	[103,106,113]
Pulp and paper	47	93	[113]
Cement production	27	146	[103,106,113]
NGCC	10	146	[104–106,109]
Oxyfuel combustion	48	99	[106,109]
IGCC	3	140	[106,109]
Chemicals + bio or synfuel	20	111	[103,113]
Capture technology			
Post-combustion (amine)	63	87	[110]
Pre-combustion	47	60	[110]
Storage			
CCS	20	113	[106]
EOR/EGR	71	84	[107]

Table 11
Cost of electricity for different process plants, capture technologies and storage solutions.

	Cost ($2015/ MWh)		References
	Min	Max	
Process plant			
Coal-fired power	59	167	[57,104,105,110–112,114–116]
Gas-fired power	54	231	[104,107,110–112,114,115]
NGCC	61	102	[105,115]
Oxyfuel combustion	111	271	[110,114,117]
IGCC	111	278	[57,114,117]
Capture technology			
Post-combustion (amine)	111	266	[114] [110],
Oxy-combustion	111	265	[114] [110],
Storage			
CCS	59	271	[57,104,105,107,110–112,114–116]
EOR/EGR	68	87	[107]

Table 12
Capital and operating costs for coal and gas fired power plants (modified from Refs. [104,111,112,118]).

Process plant	Capital costs ($2015/kWel.net)	Operating fixed costs ($2015/kW-yr)	Operating variable costs ($2015/MWh)
Coal-fired power	3552–6816	69–84	9–10
Gas-fired power	2313–5088	14–33	11–16

1.6 and 31.4 $2015/t$CO_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 $2015/t$CO_2$. These numbers are comparable to those reported in Table 10, which report the cost of carbon for the avoided CO_2.

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. For instance at the moment there are only two examples of full scale CCS applied to power generation [11,66] and therefore they represent First Of A Kind (FOAK) projects. 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, as discussed in the next section. According to the Global CCS Institute [106], the cost reduction of CCS from FOAK to NOAK varies between 3.4% and 8.1% for the power generation sector, while 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 cost uncertainties, cost baseline and limited operating experience.

5. CCS potential in the context of unburnable carbon

5.1. Selected industrial and academic outlooks

The role of CCS in future energy scenarios has been analysed by industrial and academic sources. For instance, 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 [42], Shell and ExxonMobil explicitly mention CCS as a technology able to reduce carbon emissions. While ExxonMobil says that the development of CCS could be significantly limited by "economic and practical hurdles" [119], Shell propose energy scenarios in which CCS plays a key role, helping to decarbonise electricity by 2060 and to reduce world CO_2 emission to zero by 2100 [120].

Although many academic publications cover a range of aspects related to CCS, only few have explicitly investigated this technology in the context of unburnable carbon in their projections. This is the case for the UCL Institute for Sustainable Resources, who has released two publications on the topic. The first publication [34] focused on the volumes of oil that cannot be used up to 2035, and the results estimate that 500–600 billion barrels (Gb) of current 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 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 [34], 40–55% (with CCS-without CCS) of yet to be found deepwater 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 low CO_2 energy system.

The second UCL publication on the topic of unburnable carbon [40] considers all fuels and their geographical location. 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 13, which presents the overall reserves, divided by fossil fuel type, and the unburnable/burnable carbon in the two technology scenarios. CCS enables use of 1% more oil, 3% more gas and 7% more coal by 2050. According to McGlade and Ekins [40], 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 publications from 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.

5.2. Integrated assessment models

Integrated assessment models are models that can depict scenarios of global change related to climate change. They are inherently multidisciplinary, 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. 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 [117]. 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 [121]. In this context, the importance of CCS is evident, being applicable to power generation and industrial production. Moreover, BECCS and other NETs would be able to extend the 2050 carbon budget by 11–13% (for a 50–80% probability to remain below 2 °C temperature increase [122]).

5.3. Review of the model comparison exercise EMF27

5.3.1. Description of the project and models involved

The IPCC Fifth Assessment Report Database includes 31 models and 1184 scenarios [123]. 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 Energy Modelling Forum centred at Stanford University since 1976 is 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 [124], which have also been analysed in the projects AMPERE2 [125] and AMPERE 3 [126].

One of the main purposes of EMF27 is to analyse the role of technology for achieving climate policy objectives. According to Kriegler et al. [124], CCS is deployed at a substantial scale in almost all the EMF27 mitigation scenarios with full technology availability. 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 [127].

5.3.2. Investigated climate and technology scenarios

The analysis presented in this paper includes all the models that were part of EMF27 that have been employed for generating the scenarios included in the AR5 database and that were able to run up to the year 2100 (therefore the models AIM-Enduse, DNE21 +, ENV-Linkages and Phoenix have been excluded from the analysis). It is important to highlight that not all the models 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. [124]. In particular, both Kriegler et al. [124] and Krey et al. [127] reported that most of the models were not able to meet the most stringent climate target without CCS. While 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 [128], for the remaining models the availability or otherwise of CCS has the strongest impact on carbon prices [129] and on the variation of mitigation costs [124,125].

The scenarios selected for the analysis reported in this paper are characterised by climate mitigation target and technological availability. The climate mitigation scenarios include the scenarios "450 ppm" (reported in the main body of the paper) and "550 ppm" (reported in Appendix), aiming to reach atmospheric GHG

Table 13
Unburnable reserves before 2050 for the 2 °C scenarios with and without CCS (modified from Ref. [40]).

Fossil fuel	Overall reserves	With CCS		Without CCS	
		Unburnable	Burnable	Unburnable	Burnable
Oil (Gb)	1306	431 (33%)	875 (67%)	449 (34%)	857 (66%)
Gas (Tm^3)	194	95 (49%)	99 (51%)	100 (52%)	94 (48%)
Coal (Gt)	999	819 (82%)	180 (18%)	887 (89%)	112 (11%)
Oil ($GtCO_2$)	531	175 (33%)	356 (67%)	183 (34%)	349 (66%)
Gas ($GtCO_2$)	418	205 (49%)	213 (51%)	215 (51%)	202 (48%)
Coal ($GtCO_2$)	2664	2185 (82%)	480 (18%)	2366 (89%)	299 (11%)
Overall ($GtCO_2$)	3613	2565 (71%)	1049 (29%)	2764 (77%)	850 (24%)

concentration at levels of respectively 450 ppm CO_2e and 550 ppm CO_2e by 2100 [126]. The selected technology scenarios include the full technology scenario ("Fulltech"), the conventional solutions scenario ("Conv") and the scenario without CCS ("noCCS"). The full technology scenario has a full portfolio of technologies which may scaled up in the future in order to meet the climate targets; in the conventional solution scenario 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; finally in the scenario without CCS carbon capture and storage never becomes available [124,125,127].

5.3.3. CCS modelling assumptions

As part of the EMF27 project, Koelbl, et al. [76] looked at the way CCS was characterised in each model, focussing on assumptions such as fuel prices, baseline emissions, type of model, modelling technology change and CCS modelling approach. However, 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. According to what reported by Koelbl et al. [76], most of the models are not including any limitation to either storage rate or capacity, while only one model includes all the types of storage sites (on and offshore EOR, depleted gas, undepleted gas, depleted oil, as well as Enhanced Coal Bed Methane (ECBM) onshore, and two types of aquifers). The assumptions on the availability of CCS cover today (4 models), 2020 (7 models) and 2030 (1 model).

Among the 64 references listed in the AR5 database webpage, only one reference [130] reports the marginal abatement cost of CCS. Annex III of the IPCC report "Climate Change 2014: Mitigation of Climate Change" [1] reports, for CCS combined with power generation, the overnight capital expenditure to be between 2000 and 4000 $2010/kW, construction time around 4–5 years, fixed annual operation and maintenance cost between 13 and 58 $2010/kW and variable operation and maintenance cost between 8.3 and 15 $2010/kW.

Investment costs and efficiencies for power generation combined with CCS have been estimated by Koelbl et al. [77] 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. When comparing the costs reported by Koelbl et al. [77] with the costs reported in the literature (section 4), the following considerations apply. CCS investments costs reported in Table 14 for 2020 are lower than the capital costs reported in the literature (Table 12) for both coal-fired ($2015/kWe 1181–4942 vs. 3552–6816) and gas-fired ($2015/kWe 856–2394 vs. 2313–5088) power generation. The efficiency penalties reported in Table 14 are similar to the penalties reported in Table 6 (6–11% for CCGT, 5–11% for IGCC).

The transport costs reported in the literature (Table 8) varies between 1.3 (onshore pipelines, capacity 30 $MtCO_2$/yr) and 15.1 (offshore pipelines, capacity 3 $MtCO_2$/yr) $2015/$tCO_2$/250 km against figures reported in Table 15, where the transport costs varies between 0.5 and 42.5 $2015/$tCO_2$/250 km. 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 (Table 16). According to Rubin et al. [109], it varies between 1.6 and 22 $2015/$tCO_2$ (as reported in Table 9), while according to Koelbl et al. [77] it varies between 1 and 35.1 $2015/$tCO_2$. Negative storage costs represent an income, coming from fossil fuel recovery.

5.4. CCS and unburnable carbon up to 2100

5.4.1. Emissions and capture of carbon dioxide

Fig. 1 reports the emissions of the three selected technology scenarios (Fulltech, Conv, noCCS) for 450 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. The shapes of the profiles are slightly different, reflecting the impact of technology options and constraints on the abatement pathway chosen by the models.

Fig. 2 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. Fig. 2 shows that 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 (reported in Appendix). 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. Moreover, comparing 'Conv' and 'Fulltech' scenarios in the 450 ppm case, 'Conv' utilises 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, to name a few, which are important topics for further research. The residual emissions challenge is discussed further in section 6.

5.4.2. Fossil fuel consumption with and without CCS

Fig. 3 reports the total fossil fuel use for the three technology scenarios for the 450 ppm scenario. There is a large variation of model results (reported in Appendix), and this variation increases for the timeframe 2005–2100, highlighting the increased uncertainty that characterises the model outputs after 2050. With regard to the top chart in Fig. 3, it is clear that 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 [43] and also by BHP Billiton [131], who still forecast a growing fossil fuel demand in the future. However, the range of model outcomes for consumption of fossil fuels is large, with some models indicating a stabilisation or increase of fossil use in the 'Conv' and 'Fulltech' scenarios. The range of outcomes from the models for the 'noCCS' case are much tighter towards the end of the time horizon, and

Table 14
Ranges of investment costs, efficiency and efficiency loss (p.p. percentage points of capture efficiency loss) for power plants and capture unit (modified from Ref. [77]). Investment costs are expressed in $2015 per kWe.

	Investment costs		Efficiency	
	2020	2050	2020	2050
	no CCS		no CCS (%)	
IGCC Coal	914–3464	643–3300	38–52	40–58
IGCC Biomass	1416–3966	997–3780	32–50	35–54
CCGT	532–1158	432–1055	48–64	50–67
	2020	2050	2020	2050
	Capture		Capture (p.p.)	
IGCC Coal	267–1479	107–1353	4–11	3–9
IGCC Biomass	669–1100	333–1007	5–11	3–7
CCGT	325–1236	156–1058	6–11	5–9

Table 15
Ranges of CO_2 transport costs per distance category (modified from Ref. [77]).

Distance in 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

fossil fuel use drops rapidly 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.

Gas and coal are the fuels where increased consumption is observed through the availability of CCS. While coal has the most significant difference between Conv and noCCS scenarios, gas is the only fossil fuel that increases its utilisation between 2005 and 2050, and also almost maintains its contribution in absolute terms between 2050 and 2100. Results referring to use of single fuels have been reported in Appendix.

The results referring to the 550 ppm scenario are similar to those reported in Fig. 3 in the way they report the projections of fossil fuel usage for the three technology scenarios. As expected, the presence of CCS in these scenarios unlocks more fossil fuel reserves than 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 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 also sees significant gains due to CCS, 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 and for each fossil fuel are presented in Appendix and show the range of outcomes observed.

In summary, Table 18 shows the average cumulative consumption of fossil fuels over two timeframes (2005–2050 and 2005–2100) observed across the models. This consumption has been express in gigatonnes of equivalent carbon dioxide ($GtCO_2$), exajoules (EJ) and percentages of reserves as reported by McCollum et al. [39](low estimate value). Clearly 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 still delivering climate targets.

5.4.3. Discussion

A primary point of interest when considering the potential of CCS as seen by integrated assessment models is an understanding of what factors in the models are limiting its uptake. While the presented results 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 is CCS not adopted in greater quantities.

Akimoto et al. [130] suggests that the marginal cost of CCS across the entire possible range of fossil fuel reserves (i.e. up to ~4000 $GtCO_2$) is less than US\$100/tCO_2. However, as shown in Fig. 4, 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 Fig. 4 for the 450 ppm scenario is well above the cost of carbon assumed by the IEA [132] for the 450 Scenario (\$140/tCO_2 in most OECD countries in 2040). Therefore the cost of CCS in future is highly competitive with the other available abatement options, if climate change is to be limited to less than 2 °C. It is worth noting that the costs reported here are not an assumption of the EMF models, but rather an output of the models (i.e. they are the marginal abatement cost, which can be interpreted as the cost of the most expensive measure that was used to meet the climate target in each year, or alternatively as the global carbon price required to achieve the climate target).

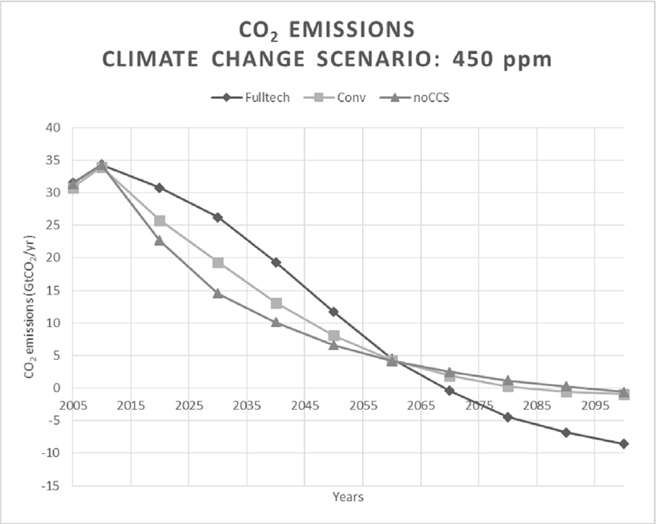


Fig. 1. Average global emissions of CO_2 ($GtCO_2$/yr) for the 450 ppm scenario across EMF27 models.

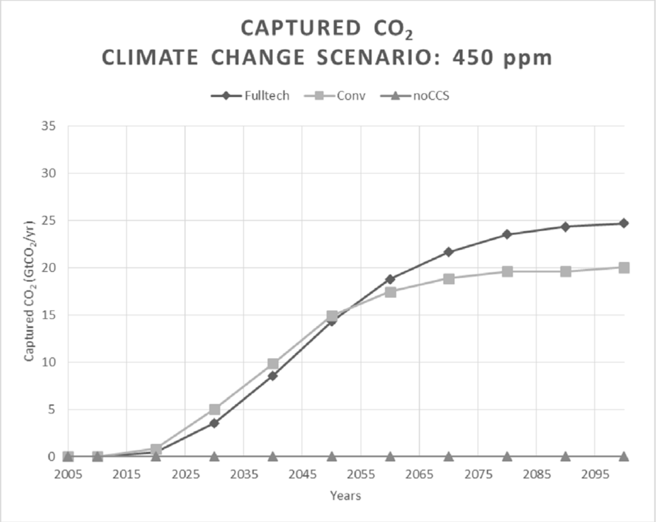


Fig. 2. Average capture of CO_2 ($GtCO_2$/yr) for the 450 ppm scenario across EMF27 models.

One possible explanation for this phenomenon is that the rate of uptake of CCS-equipped facilities is limited in the models. From what reported by Koelbl et al. [76], we can conclude that CCS uptake is not limited by storage capacity or growth thereof. Therefore, another

Table 16
CO_2 storage cost ranges per storage type (modified from Ref. [77]).

\$2015/tCO_2 stored	Enhanced 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

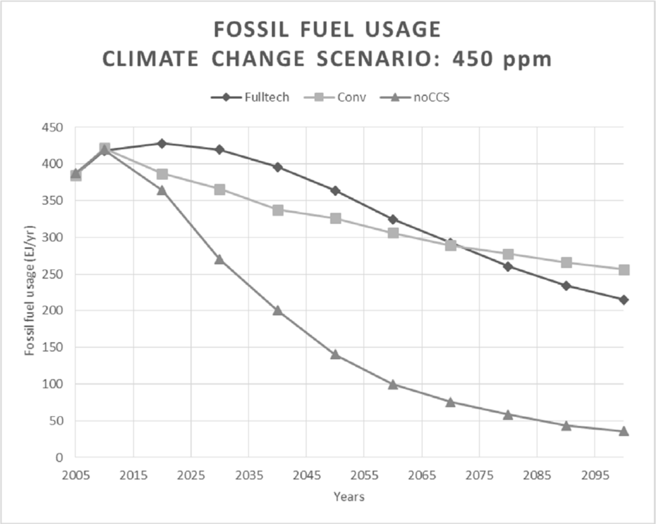


Fig. 3. Average total primary energy from fossil fuel use (EJ/yr) for the 450 ppm scenario across EMF27 models.

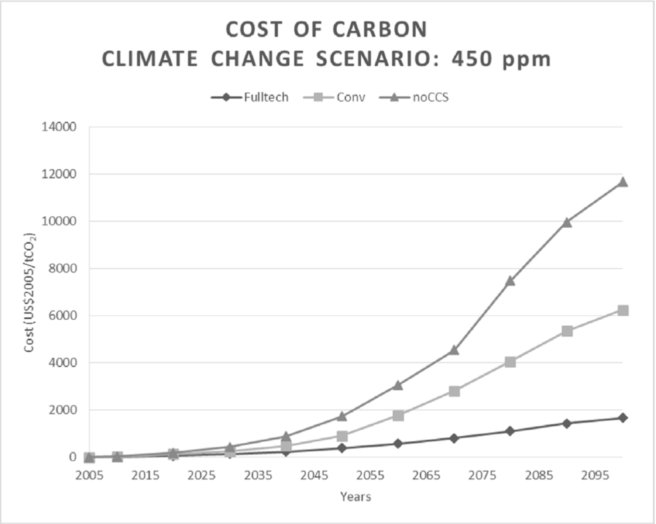


Fig. 4. Average cost of carbon (CO_2) for the 450 ppm scenario across EMF27 models.

Table 17
Average total primary energy from fossil fuel use (EJ/yr) in 2050 and 2100 for the 450 ppm scenario across EMF27 models.

Climate mitigation scenario	450 ppm		
Technology scenario	Conv	Fulltech	noCCS
Primary Energy (fossil, EJ) - 2050	326	364	140
Primary Energy (fossil, EJ) - 2100	256	215	36

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 [76] 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 paper hypothesises that the constraint on CCS is therefore not cost related or supply chain related (i.e. build rate limited), particularly in later years, but rather 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) [133] and IEAGHG [134], who both report a capture rate of 90% for coal based power generation with CCS. IEAGHG [134] 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 paper. However, it will be the subject of further investigation in future research.

6. 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 emitted 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 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 [135], 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 66%–96% in 2% increments, with results for global gas primary energy supply as shown in Fig. 5. While neither coal nor oil experience significant changes across the capture rate sensitivity examined, gas sees the strongest impact 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. Further research is required, including multi-model

Table 18
Cumulative fossil fuel consumption in the timeframes 2005–2050 and 2005–2100. Reserves ‘low’ estimate from McCollum et al. [39]. “without CCS” scenario corresponds to the noCCS scenario while “with CCS” scenario corresponds to the Fulltech scenario.

	$GtCO_2$		Exajoules (EJ)		% of reserves	
	without CCS	with CCS	without CCS	with CCS	without CCS	with CCS
Up until 2050	953	1347	13,166	18,356	26	37
Up until 2100	1208	2380	16,823	32,376	33	65

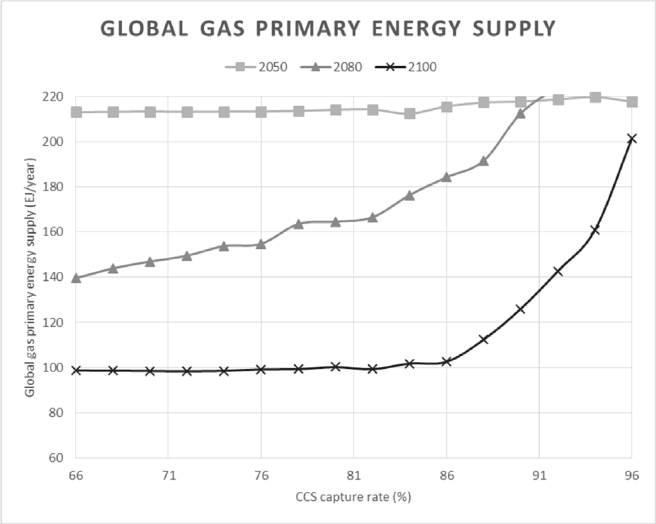


Fig. 5. Sensitivity of primary energy supply of natural gas in 2050, 2080 and 2100 to CCS capture rate, produced by means of the TIAM-Grantham model.

comparison studies, in order to fully explore the capture rate issue. Such a study is out of the scope of this paper, but will be pursued in future research.

The result produced here is dependent on a range of assumptions in the model, including the relative fossil fuel extraction costs, bioenergy cost, CCS technology cost, performance and availability, 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 herein is likely to be observed.

7. Recommendations for further research

The reported results 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 include sensitivity analysis of design and operational parameters on CCS capture rate, regional dynamic assessment of CO_2 storage resources and CCS modelling in integrated assessment models.

This paper has performed an initial investigation into the impact of the CCS capture rate on the use of fossil fuels in the long term, with the key finding being that it is indeed an important factor. Further modelling studies are required to clarify the nuances of this point, and specifically what the impact of fossil fuel prices, CCS technology cost, performance and availability, and competition with other low carbon technologies has on outcomes. These studies should not only perform sensitivity analysis on these parameters, but should also examine results across multiple models to determine robustness of results to modelling approach.

The analysis of 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 [134] 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 may be needed in order 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 CO_2 storage resource. This will provide important information on the future prevalence 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 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” [18]. Therefore, the assessment provided in this Paper should be revisited in the future in order to take into account the outcomes of the IPCC special report.

8. Conclusions

This paper has reviewed potential barriers to the worldwide adoption of CCS and also considered whether this 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 5th 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 results indicated a less prominent role for the technology than might otherwise be expected.

In order to fill this gap, an analysis specifically on CCS and unburnable carbon has been undertaken. Insights are drawn from the EMF27 multi-model comparison, which produced a set of scenarios of energy system change to mitigate climate change. EMF27 included scenarios with and without CCS, and therefore provides a robust and consistent basis for investigation of the impact of CCS on fossil fuel reserve utilisation. Analysis of results confirm that CCS availability has a large bearing on the extent of fossil fuel consumption in climate-constrained scenarios; approximately 200 EJ per year more fossil fuel is utilised 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 of consideration 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 was 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 observed in the models (these are from hundreds to thousands of US$ per tonne across the models, which is substantially higher than the cost of CCS). 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.

This paper 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 66% to 96%. 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.

Acknowledgements

Part of this paper has been developed in collaboration with the IEA Greenhouse Gas R&D Programme (IEAGHG), who are gratefully acknowledged for their funding and intellectual contribution. The authors would like to especially thank Tim Dixon and Dr Jasmin Kemper for their advice and inputs.

The authors would also like to acknowledge the funding from the Sustainable Gas Institute, which was founded by Imperial College London and BG Group (now part of Royal Dutch Shell). Funding for the Sustainable Gas Institute is gratefully received from Royal Dutch Shell, Enagas SA and the Newton/NERC/FAPESP Sustainable Gas Futures project NE/N018656/1. Note that funding bodies were not involved in the design, implementation or reporting of this study.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.esr.2018.08.003.

Appendices. A. Projections for the climate change scenario: 550 ppm

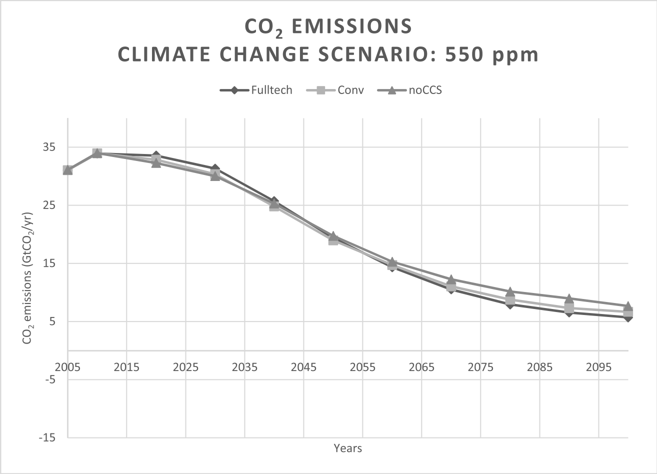


Fig. A.1. Average global emissions of CO2 (GtCO2/yr) for the 550 ppm scenario across EMF27 models.

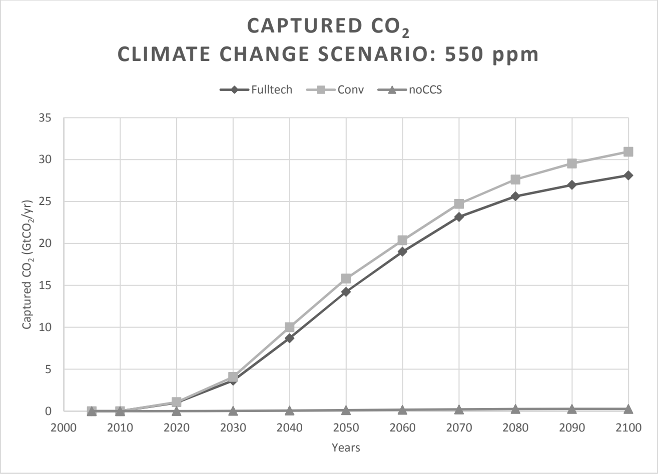


Fig. A.2. Average capture of CO2 (GtCO2/yr) for the 550 ppm scenario across EMF27 models.

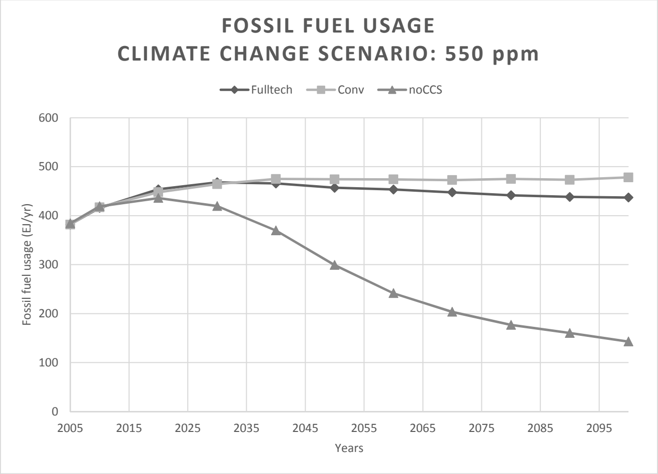


Fig. A.3. Average total primary energy from fossil fuel use (EJ/yr) for the 550 ppm scenario across EMF27 models.

Table A.1
Average total primary energy from fossil fuel use (EJ/yr) in 2050 and 2100 for the 550 ppm scenario across EMF27 models.

Climate mitigation scenario	550 ppm		
Technology scenario	Conv	Fulltech	noCCS
Primary Energy (fossil, EJ) - 2050	474	457	299
Primary Energy (fossil, EJ) - 2100	478	437	143

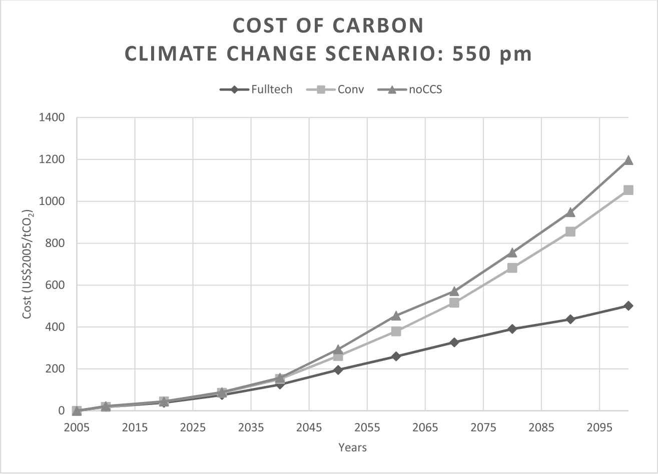


Fig. A.4. Cost of carbon (CO2) for the 550 ppm scenario. Timeframe 2005–2100, B. Projections for single EMF27 models.

B. Projections for single EMF27 models

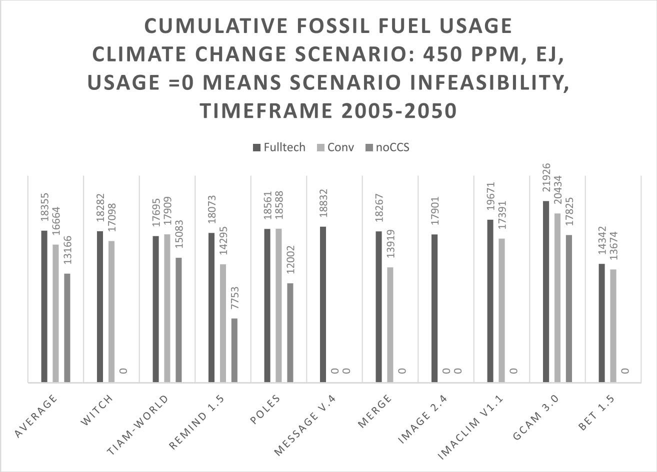


Fig. B.1. Emissions from fossil fuel usage in the timeframe 2005–2050 according to the EMF27 models. Usage = 0 means scenario infeasibility.

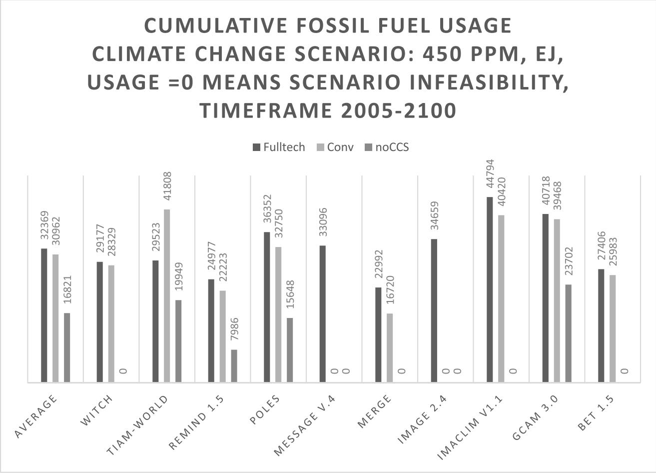


Fig. B.2. Emissions from fossil fuel usage in the timeframe 2005–2100 according to the EMF27 models. Usage = 0 means scenario infeasibility, C. Projections for single fuels use.

C. Projections for single fuels use

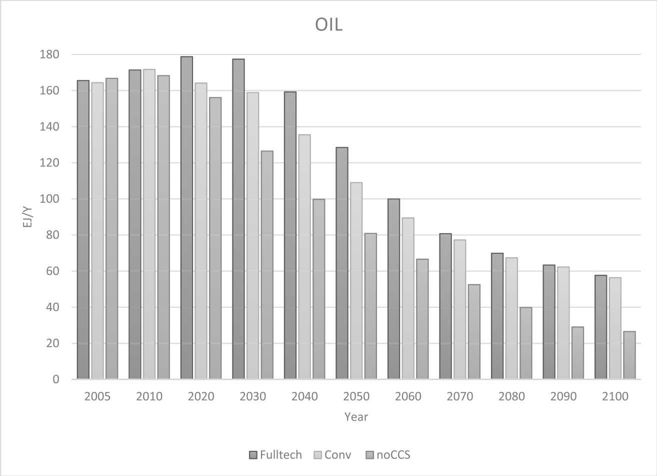


Fig. C.1. Total primary energy from oil use (EJ/yr) for the 450 ppm scenario across EMF27 models.

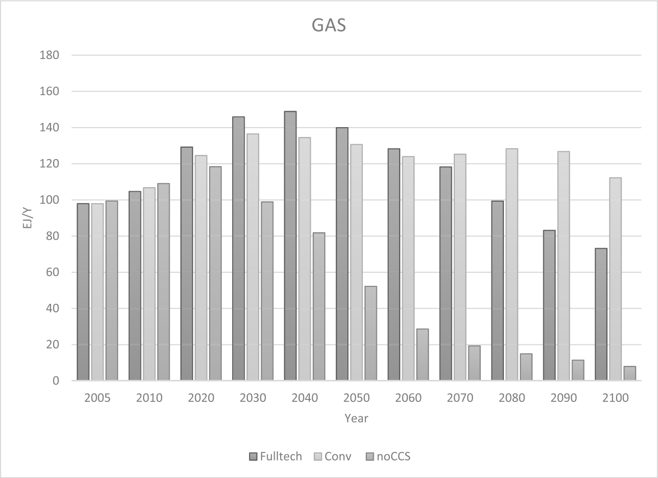


Fig. C.2. Total primary energy from gas use (EJ/yr) for the 450 ppm scenario across EMF27 models.

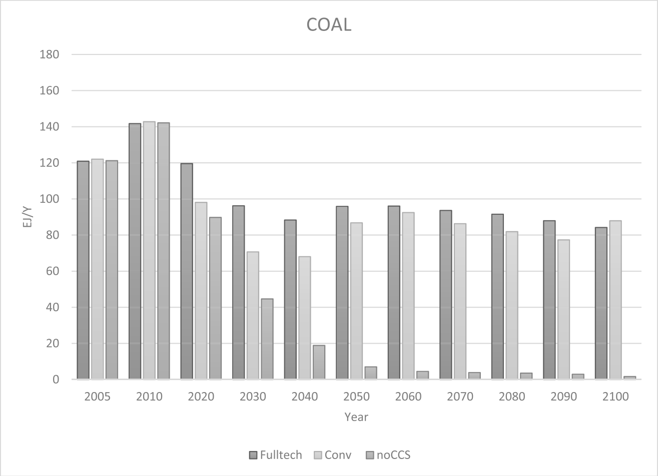


Fig. C.3. Total primary energy from coal use (EJ/yr) for the 450 ppm scenario across EMF27 models.

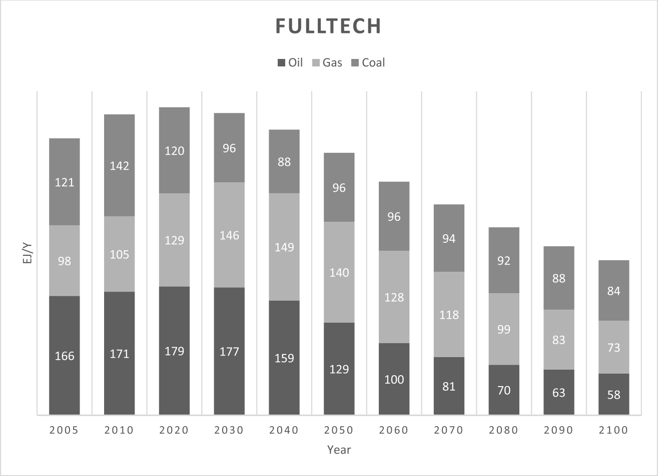


Fig. C.4. Average distribution of total primary energy from fossil fuel use (EJ/yr) by type of fuel for the 450 ppm scenario across EMF27 models for the Fulltech scenario.

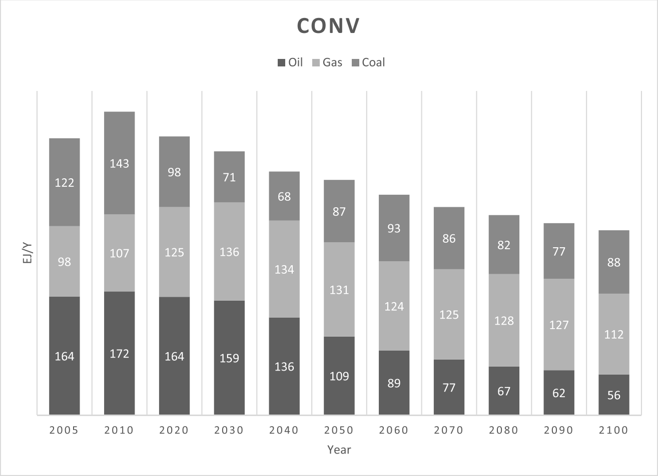


Fig. C.5. Average distribution of total primary energy from fossil fuel use (EJ/yr) by type of fuel for the 450 ppm scenario across EMF27 models for the Conv scenario.

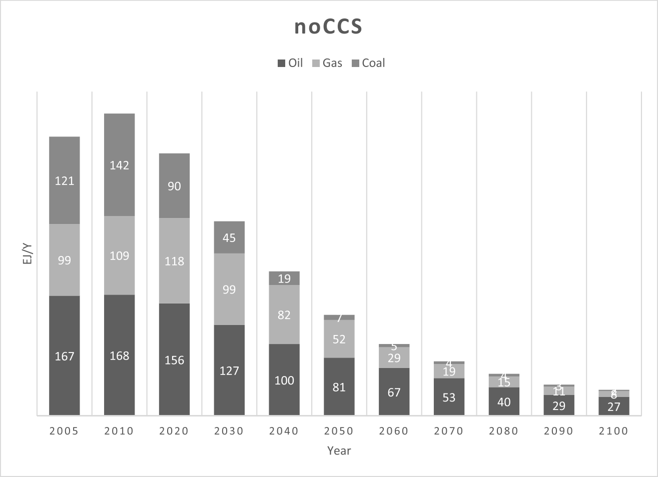


Fig. C.6. Average distribution of total primary energy from fossil fuel use (EJ/yr) by type of fuel for the 450 ppm scenario across EMF27 models for the noCCS scenario.

References

[1] IPCC, Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.
[2] IEA, Technology roadmap: carbon capture and storage 2011, in: IEA (Ed.), Technology RoadmapOnline, 2011.
[3] IEA, Technology roadmap: carbon capture and storage 2013, in: IEA (Ed.), Technology RoadmapOnline, 2013.
[4] Carbon Tracker Initiative, Unburnable carbon 2013: wasted capital and stranded assets, C.T. Initiative, 2013.
[5] IPCC, IPCC Special Report: Carbon Capture and Storage, (2005).
[6] V.R. Clark, H.J. Herzog, Can “stranded” fossil fuel reserves drive CCS deployment? Energy Procedia 63 (2014) 7261–7271.
[7] J.J. Gale, T. Dixon, CCS as a Critical Part of the Carbon Budget, (2014).
[8] IPCC, Climate change 2014: summary for policy makers. Mitigation of climate change, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.
[9] Global CCS Institute, The Global Status of CCS: 2016 summary report, Global CCS Institute, 2016.
[10] SaskPower, Boundary Dam Carbon Capture Project, (2017).
[11] NRG, Petra Nova, (2017).
[12] Global CCS Institute, Large Scale CCS Projects, (2017).
[13] IPCC, Climate change 2013: summary for policy makers. The physical science basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.
[14] IPCC, Climate Change 2014: Summary for Policy Makers. Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.
[15] M. Meinshausen, N. Meinshausen, W. Hare, S.C.B. Raper, K. Frieler, R. Knutti, D.J. Frame, M.R. Allen, Greenhouse-gas emission targets for limiting global warming to 2^{0}C, Nature 458 (2009) 1158–1162.
[16] M.R. Allen, D.J. Frame, C. Huntingford, C.D. Jones, J.A. Lowe, M. Meinshausen, N. Meinshausen, Warming caused by cumulative carbon emissions towards the trillionth tonne, Nature 458 (2009) 1163–1166.
[17] IPCC, Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland, 2007.
[18] COP21, Adoption of the Paris agreement, COP21, 2015.
[19] M. Meinshausen, S.C.B. Raper, T.M.L. Wigley, Emulating IPCC AR4 atmosphere-ocean and carbon cycle models for projecting global-mean, hemispheric and land/ocean temperatures: MAGICC 6.0, Atmos. Chem. Phys. Discuss. 8 (2008) 6153–6272.
[20] P. Friedlingstein, P. Cox, R. Betts, L. Bopp, W. Von Bloh, V. Brovkin, P. Cadule, S. Doney, M. Eby, I. Fung, G. Bala, J. John, C. Jones, F. Joos, T. Kato, M. Kawamiya, W. Knorr, K. Lindsay, H.D. Matthews, T. Raddatz, P. Rayner, C. Reick, E. Roeckner, K.G. Schnitzler, R. Schnur, K. Strassmann, A.J. Weaver, C. Yoshikawa, N. Zeng, Climate-carbon cycle feedback analysis: results from the (CMIP)-M-4 model intercomparison, J. Clim. 19 (2006) 3337–3353.
[21] C. Huntingford, J.A. Lowe, B.B.B. Booth, C.D. Jones, G.R. Harris, L.K. Gohar, P. Meir, Contributions of carbon cycle uncertainty to future climate projection spread, Tellus B 61 (2009) 355–360.
[22] M. Meinshausen, B. Hare, T.M.L. Wigley, D. Van Vuuren, M.G.J. Den Elzen, R. Swart, Multi-gas emissions pathways to meet climate targets, Climatic Change 75 (2006) 151–194.
[23] A. Bowen, N. Ranger, Mitigating Climate Change through Reductions in Greenhouse Gas Emissions: the Science and Economics of Future Paths for Global

Annual Emissions, (2009).
[24] J. Rogelj, M. Schaeffer, P. Friedlingstein, N.P. Gillett, D.P. van Vuuren, K. Riahi, M. Allen, R. Knutti, Differences between carbon budget estimates unravelled, Nat. Clim. Change 6 (2016) 245–252.
[25] IPCC, Climate change 2013: technical summary, The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.
[26] V.E. McKelvey, Mineral Resource Estimates and Public Policy: better methods for estimating the magnitude of potential mineral resources are needed to provide the knowledge that should guide the design of many key public policies, Am. Sci. 60 (1972) 32–40.
[27] Society of Petroleum Engineers (SPE), Petroleum Reserves & Resources Definitions, (2018).
[28] SPE, Petroleum resources management system, S.S.o.P. Engineers, 2008 Online.
[29] USA Government, U.S. Securities and Exchange Commssion, (2018).
[30] USGS, World Petroleum Assessment, (2018).
[31] Norwegian Petroleum Directorate, Resource Accounts & Analysis, (2018).
[32] The Russian Government, Ministry of Natural Resources and Environment of the Russian Federation, (2018).
[33] Oil and Gas Reserves Committee, Comparison of selected reserves and resource classifications and associated definitions, SPE, 2005.
[34] C. McGlade, P. Ekins, Un-burnable oil: an examination of oil resource utilisation in a decarbonised energy system, Energy Pol. 64 (2014) 102–112.
[35] Society of Petroleum Engineers, Comparison of Selected Reserves and Resource Classifications and Associated Definitions, (2005).
[36] Carbon Tracker Initiative, Unburnable Carbon – are the world's financial markets carrying a carbon bubble? in: C. Tracker (Ed.), Carbon Tracker Initiative, 2011.
[37] N. Mayer, L. Brinker, Deflating the "carbon bubble, I. Energy, 2014.
[38] P. Spedding, K. Mehta, N. Robins, Oil & carbon revisited, H.G. Research, 2013.
[39] D. McCollum, N. Bauer, K. Calvin, A. Kitous, K. Riahi, Fossil resource and energy security dynamics in conventional and carbon-constrained worlds, Climatic Change 123 (2014) 413–426.
[40] C. McGlade, P. Ekins, The geographical distribution of fossil fuels unused when limiting global warming to 2^0C, Nature 517 (2015) 187–190.
[41] IEA, World energy outlook 2012, IEA, 2012 Online.
[42] BP, BP statistical review of world energy, BP, 2015.
[43] IEA, World energy outlook 2014 - executive summary, IEA, 2014 Online.
[44] World Energy Council, World Energy Resources: 2013 Survey, (2013).
[45] BGR, Reserves, Resources and Availability of Energy Resources, (2014).
[46] Oil & Gas Journal, Worldwide look at reserves and production, Oil Gas J. 112 (1) (2014) [104] is an online report: http://www.zeroemissionsplatform.eu/library/publication/165-zep-cost-report-summary.html.
[47] L. Herrmann, E. Dunphy, J. Copus, Oil and Gas for Beginners, Deutsche Bank, 2010.
[48] European Council, Communication on community strategy on climate change: council conclusions, European Council, 1996 Brussels.
[49] European Commission Climate Action, The EU Emissions Trading System, EU ETS, 2016.
[50] D. Hone, The carbon bubble reality check, Shell, 2013.
[51] BP, Climate change, BP, 2014.
[52] CarbonBrief, What the Fossil Fuel Industry Thinks of the 'carbon Bubble', (2014).
[53] D.Y.C. Leung, G. Caramanna, M.M. Maroto-Valer, An overview of current status of carbon dioxide capture and storage technologies, Renew. Sustain. Energy Rev. 39 (2014) 426–443.
[54] S.D. Kenarsari, D.L. Yang, G.D. Jiang, S.J. Zhang, J.J. Wang, A.G. Russell, Q. Wei, M.H. Fan, Review of recent advances in carbon dioxide separation and capture, RSC Adv. 3 (2013) 22739–22773.
[55] M.E. Boot-Handford, J.C. Abanades, E.J. Anthony, M.J. Blunt, S. Brandani, N. Mac Dowell, J.R. Fernandez, M.C. Ferrari, R. Gross, J.P. Hallett, R.S. Haszeldine, P. Heptonstall, A. Lyngfelt, Z. Makuch, E. Mangano, R.T.J. Porter, M. Pourkashanian, G.T. Rochelle, N. Shah, J.G. Yao, P.S. Fennell, Carbon capture and storage update, Energy Environ. Sci. 7 (2014) 130–189.
[56] J.C.M. Pires, F.G. Martins, M.C.M. Alvim-Ferraz, M. Simões, Recent developments on carbon capture and storage: an overview, Chem. Eng. Res. Des. 89 (2011) 1446–1460.
[57] E.S. Rubin, H. Mantripragada, A. Marks, P. Versteeg, J. Kitchin, The outlook for improved carbon capture technology, Prog. Energy Combust. Sci. 38 (2012) 630–671.
[58] J. Gibbins, H. Chalmers, Is all CCS equal? Classifying CCS applications by their potential climate benefit, Energy Procedia 4 (2011) 5715–5720.
[59] M. Fajardy, N. Mac Dowell, Can BECCS deliver sustainable and resource efficient negative emissions? Energy Environ. Sci. 10 (2017) 1389–1426.
[60] J. Koornneef, P.v. Breevoort, C. Hamelinck, C. Hendriks, M. Hoogwijk, K. Koop, M. Koper, T. Dixon, A. Camps, Global potential for biomass and carbon dioxide capture, transport and storage up to 2050, Int. J..Greenh.gas. Contr. 11 (2012) 117–132.
[61] D. van Vuuren, S. Deetman, J. van Vliet, M. van den Berg, B. van Ruijven, B. Koelbl, The role of negative CO_2 emissions for reaching 2 °C—insights from integrated assessment modelling, Climatic Change 118 (2013) 15–27.
[62] D. McLaren, A comparative global assessment of potential negative emissions technologies, Process Saf. Environ. Protect. 90 (2012) 489–500.
[63] IEAGHG, Barriers to Overcome in Implementation of CO_2 Capture and Storage (2): Rules and Standards for the Transmission and Storage of CO_2, (2003).
[64] J. Gibbins, H. Chalmers, Carbon capture and storage, Energy Pol. 36 (2008) 4317–4322.
[65] V. Scott, R.S. Haszeldine, S.F.B. Tett, A. Oschlies, Fossil fuels in a trillion tonne world, Nat. Clim. Change 5 (2015) 419–423.
[66] C.C.S. SaskPower, Boundary Dam carbon capture project, SaskPower, 2016 Online.
[67] IEAGHG, Can Carbon Capture and Storage Unlock 'unburnable Carbon'? (2016).
[68] M.L. Szulczewski, C.W. MacMinn, H.J. Herzog, R. Juanes, Lifetime of carbon capture and sorage as a climate-change mitigation technology, Proc. Natl. Acad. Sci. Unit. States Am. (2012) 5185–5189.
[69] J.J. Dooley, Estimating the supply and demand for deep geologic CO_2 storage capacity over the course of the 21st Century: a meta-analysis of the literature, Ghgt-11 37 (2013) 5141–5150.
[70] C.-T. Liu, B.-Z. Hsieh, C.-C. Tseng, Z.-S. Lin, Modified classification system for estimating the CO_2 storage capacity of saline formations, Int. J..Greenh.gas. Contr. 22 (2014) 244–255.
[71] S.M. Frailey, O. Tucker, G.J. Koperna, The genesis of the CO_2 storage resources management system (SRMS), Energy Procedia 114 (2017) 4262–4269.
[72] Society of Petroleum Engineers (SPE), CO_2 Storage Resources Management System, (2018).
[73] Task force on application of UNFC - 2009 to injection projects specifications for the application of the united Nations classification for fossil energy and mineral reserves and resources 2009 (UNFC-2009) to injection projects for the purpose of geological storage, UNECE, 2016.
[74] N. Bauer, Carbon Capturing and Sequestration: an Option to Buy Time? Doctoral Thesis University Potsdam Faculty of Economics and Social Sciences, 2005.
[75] I. Keppo, B. van der Zwaan, The impact of uncertainty in climate targets and CO_2 storage availability on long-term emissions abatement, Environ. Model. Assess. 17 (2012) 177–191.
[76] B.S. Koelbl, M.A. van den Broek, A.P.C. Faaij, D.P. van Vuuren, Uncertainty in Carbon Capture and Storage (CCS) deployment projections: a cross-model comparison exercise, Climatic Change 123 (2014) 461–476.
[77] B.S. Koelbl, M.A. van den Broek, B.J. van Ruijven, A.P.C. Faaij, D.P. van Vuuren, Uncertainty in the deployment of Carbon Capture and Storage (CCS): a sensitivity analysis to techno-economic parameter uncertainty, Int. J..Greenh.gas. Contr. 27 (2014) 81–102.
[78] J.J. Dooley, S.J. Friedman, A Global but Regionally Disaggregated Accounting of CO_2 Storage Capacity: Data and Assumptions for Compiling Regional CO_2 Storage Capacity Supply Curves for Incorporation within ObjECTS - > MiniCAM, Lawrence Livermore National Laboratory, 2005 UCRL-SR-209663.
[79] R.T. Dahowski, X. Li, C.L. Davidson, N. Wei, J.J. Dooley, Regional opportunities for carbon dioxide capture and storage in China, P.N.N.L. PNNL-19091, 2009.
[80] C. Hendriks, W. Graus, Global carbon dioxide storage potential and costs, E. EEP-02001, 2004.
[81] J.J. Birkholzer, Q. Zhou, Basin-scale hydrogeologic impacts of CO_2 storage: capacity and regulatory implications, Int. J..Greenh.gas. Contr. 3 (2009) 745–756.
[82] W.G. Allinson, Y. Cinar, P.R. Neal, J. Kaldi, L. Paterson, CO_2 storage capacity – combining geology, engineering and economics, SPE Econ. Manag. 6 (2014) 15–27.
[83] IEAGHG, Extraction of Formation Water from CO_2 Storage, (2012).
[84] T. Ogawa, S. Nakanishi, T. Shidahara, T. Okumura, E. Hayashi, Saline-aquifer CO_2 sequestration in Japan – methodology of storage capacity assessment, Int. J..Greenh.gas. Contr. 5 (2011) 318–326.
[85] Asian Development Bank, Roadmap for Carbon Capture and Storage Demonstration and Deployment in the People's Republic of China, (2015).
[86] B. Söderbergh, K. Jakobsson, K. Aleklett, European energy security: an analysis of future Russian natural gas production and exports, Energy Pol. 38 (2010) 7827–7843.
[87] IEAGHG, Barriers to Implementation of CCS: Capacity Constraints, (2012).
[88] N. Odeh, Assessing the domestic supply chain barriers to the commercial deployment of carbon capture and storage within the power sector, AEA, 2012.
[89] J. Miller, Life after oil: can Aberdeen rise again? B. News, 2016.
[90] H. Groenenberg, H. de Coninck, Effective EU and member state policies for stimulating CCS, Int. J..Greenh.gas. Contr. 2 (2008) 653–664.
[91] A. Kossoy, P. Guigon, State and trends of the carbon market 2012, W. Bank, 2012 Washington DC.
[92] R. Lohwasser, R. Madlener, Relating R&D and investment policies to CCS market diffusion through two-factor learning, Energy Pol. 52 (2013) 439–452.
[93] BG Group plc, BP plc, ENI SpA, Royal Dutch Shell Plc, Statoil ASA, Total SA, Paying for Carbon Letter, (2015).
[94] N.M.A. Huijts, E.J.E. Molin, L. Steg, Psychological factors influencing sustainable energy technology acceptance: a review-based comprehensive framework, Renew. Sustain. Energy Rev. 16 (2012) 525–531.
[95] S.L. Seigo, S. Dohle, M. Siegrist, Public perception of carbon capture and storage (CCS): a review, Renew. Sustain. Energy Rev. 38 (2014) 848–863.
[96] K. van Alphen, Q.V.T. Voorst, M.P. Hekkert, R. Smits, Societal acceptance of carbon capture and storage technologies, Energy Pol. 35 (2007) 4368–4380.
[97] L. Wallquist, V.H.M. Visschers, M. Siegrist, Impact of knowledge and misconceptions on benefit and risk perception of CCS, Environ. Sci. Technol. 44 (2010) 6557–6562.
[98] L.A. Fleishman, W.B. de Bruin, M.G. Morgan, Informed public preferences for electricity portfolios with CCS and other low-carbon technologies, Risk Anal. 30 (2010) 1399–1410.
[99] S.C. Page, A.G. Williamson, I.G. Mason, Carbon capture and storage: fundamental thermodynamics and current technology, Energy Pol. 37 (2009) 3314–3324.
[100] E.S. Rubin, Understanding the pitfalls of CCS cost estimates, Int. J..Greenh.gas. Contr. 10 (2012) 181–190.
[101] K. Goto, K. Yogo, T. Higashii, A review of efficiency penalty in a coal-fired power

plant with post-combustion CO_2 capture, Appl. Energy 111 (2013) 710–720.
[102] G.P. Hammond, S.S.O. Akwe, S. Williams, Techno-economic appraisal of fossil-fuelled power generation systems with carbon dioxide capture and storage, Energy 36 (2011) 975–984.
[103] G. Simbolotti, CO_2 capture and storage, IEA ETSAP, 2010 Technology Brief.
[104] European technology platform for zero emission fossil fuel power plants (ZEP), the costs of CO_2 capture, Transport and Storage (2011).
[105] T. Fout, A. Zoelle, D. Keairns, M. Turner, M. Woods, N. Kuehn, V. Shah, V. Chou, L. Pinkerton, Cost and Performance Baseline for Fossil Energy Plants - Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity - Revision 3, (2015).
[106] Global CCS Institute, Economic assessment of carbon capture and storage technologies - 2011 update, WorleyParsons, Schlumberger, GCCS, 2011.
[107] N. Kuehn, K. Mukherjee, P. Phiambolis, L.L. Pinkerton, E. Varghese, M. Woods, Current and Future Technologies for Natural Gas Combined Cycle (NGCC) Power Plants, (2013).
[108] D. Leeson, J. Fairclough, C. Petit, P. Fennell, A Systematic Review of Current Technology and Cost for Industrial Carbon Capture - Grantham Report 7, (2015).
[109] E.S. Rubin, J.E. Davison, H.J. Herzog, The cost of CO_2 capture and storage, Int. J..Greenh.gas. Contr. 40 (2015) 378–400.
[110] M. Finkenrath, Cost and performance of carbon dioxide capture from power generation, International Energy Agency, 2011.
[111] Global CCS Institute, The Costs of CCS and Other Low-carbon Technologies, (2011).
[112] L. Irlam, The costs of CCS and other low-carbon technologies in the United States - 2015 update, GCCS, 2015.
[113] J. Davison, CCS costs and economics, in: IEAGHG (Ed.), IEAGHG-OPEC Workshop on CCS CDM,Vienna, 2013.
[114] Department of Energy & Climate Change, The Potential for Reducing the Costs of CCS in the UK, (2013).
[115] EIA, Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2015, (2015).
[116] Congressional budget office, federal efforts to reduce the cost of capturing and storing carbon dioxide, Congress Of the United States, 2012.
[117] S. Bassi, R. Boyd, S. Buckle, Fennell Paul, N. Mac Dowell, Z. Makuch, I. Staffell, Bridging the gap: Improving the Economic and Policy Framework for Carbon Capture and Storage in the European Union, (2015).
[118] EIA, Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants, (2013).
[119] ExxonMobil, The outlook for energy: a view to 2040, ExxonMobil, 2015.
[120] Shell, New lens scenarios, Shell, 2013.
[121] IPCC, climate change 2014: Synthesis report, Contribution of Working Group I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.
[122] B. Caldecott, G. Lomax, M. Workman, Stranded carbon assets and negative emissions technologies, S.A.P.a.t.U.o.O.s.S.S.o.E.a.t. Environment, 2015 Working Paper SeriesOnline.
[123] IPCC, Integrated assessment modelling consortium (IAMC) AR5 scenario database (working group III), I.I.f.A.S.A. 2014, 2014 Online.
[124] E. Kriegler, J. Weyant, G. Blanford, V. Krey, L. Clarke, J. Edmonds, A. Fawcett, G. Luderer, K. Riahi, R. Richels, S. Rose, M. Tavoni, D. van Vuuren, The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies, Climatic Change 123 (2014) 353–367.
[125] K. Riahi, E. Kriegler, N. Johnson, C. Bertram, M. den Elzen, J. Eom, M. Schaeffer, J. Edmonds, M. Isaac, V. Krey, T. Longden, G. Luderer, A. Méjean, D.L. McCollum, S. Mima, H. Turton, D.P. van Vuuren, K. Wada, V. Bosetti, P. Capros, P. Criqui, M. Hamdi-Cherif, M. Kainuma, O. Edenhofer, Locked into Copenhagen pledges — implications of short-term emission targets for the cost and feasibility of long-term climate goals, Technol. Forecast. Soc. Change 90 (Part A) (2014) 8–23.
[126] E. Kriegler, K. Riahi, N. Bauer, V.J. Schwanitz, N. Petermann, V. Bosetti, A. Marcucci, S. Otto, L. Paroussos, S. Rao, T. Arroyo Currás, S. Ashina, J. Bollen, J. Eom, M. Hamdi-Cherif, T. Longden, A. Kitous, A. Méjean, F. Sano, M. Schaeffer, K. Wada, P. Capros, D.P. van Vuuren, O. Edenhofer, Making or breaking climate targets: the AMPERE study on staged accession scenarios for climate policy, Technol. Forecast. Soc. Change 90 (Part A) (2014) 24–44.
[127] V. Krey, G. Luderer, L. Clarke, E. Kriegler, Getting from here to there – energy technology transformation pathways in the EMF27 scenarios, Climatic Change 123 (2014) 369–382.
[128] J. van Vliet, A. Hof, A. Mendoza Beltran, M. van den Berg, S. Deetman, M.J. den Elzen, P. Lucas, D. van Vuuren, The impact of technology availability on the timing and costs of emission reductions for achieving long-term climate targets, Climatic Change 123 (2014) 559–569.
[129] V. Krey, K. Riahi, Implications of delayed participation and technology failure for the feasibility, costs, and likelihood of staying below temperature targets—-greenhouse gas mitigation scenarios for the 21st century, Energy Econ. 31 (Supplement 2) (2009) S94–S106.
[130] K. Akimoto, F. Sano, T. Homma, K. Wada, M. Nagashima, J. Oda, Comparison of marginal abatement cost curves for 2020 and 2030: longer perspectives for effective global GHG emission reductions, Sustain Sci 7 (2012) 157–168.
[131] B.H.P. Billiton, Climate change: portfolio analysis, B. Billiton, 2015.
[132] IEA, World Energy Model Documentation - 2014 Version, (2014).
[133] G. Anandarajah, N. Strachan, P. Ekins, K. Ramachandran, N. Hughes, Pathways to a low carbon economy: energy systems modelling - working paper, UKERC, 2008.
[134] IEAGHG, CO_2 capture at coal based power and hydrogen plants, IEAGHG, 2014.
[135] T. Napp, A. Gambhir, R. Thomas, A. Hawkes, D. Bernie, J. Lowe, Exploring the Feasibility of Low-carbon Scenarios Using Historical Energy Transitions Analysis (C3), (2015).