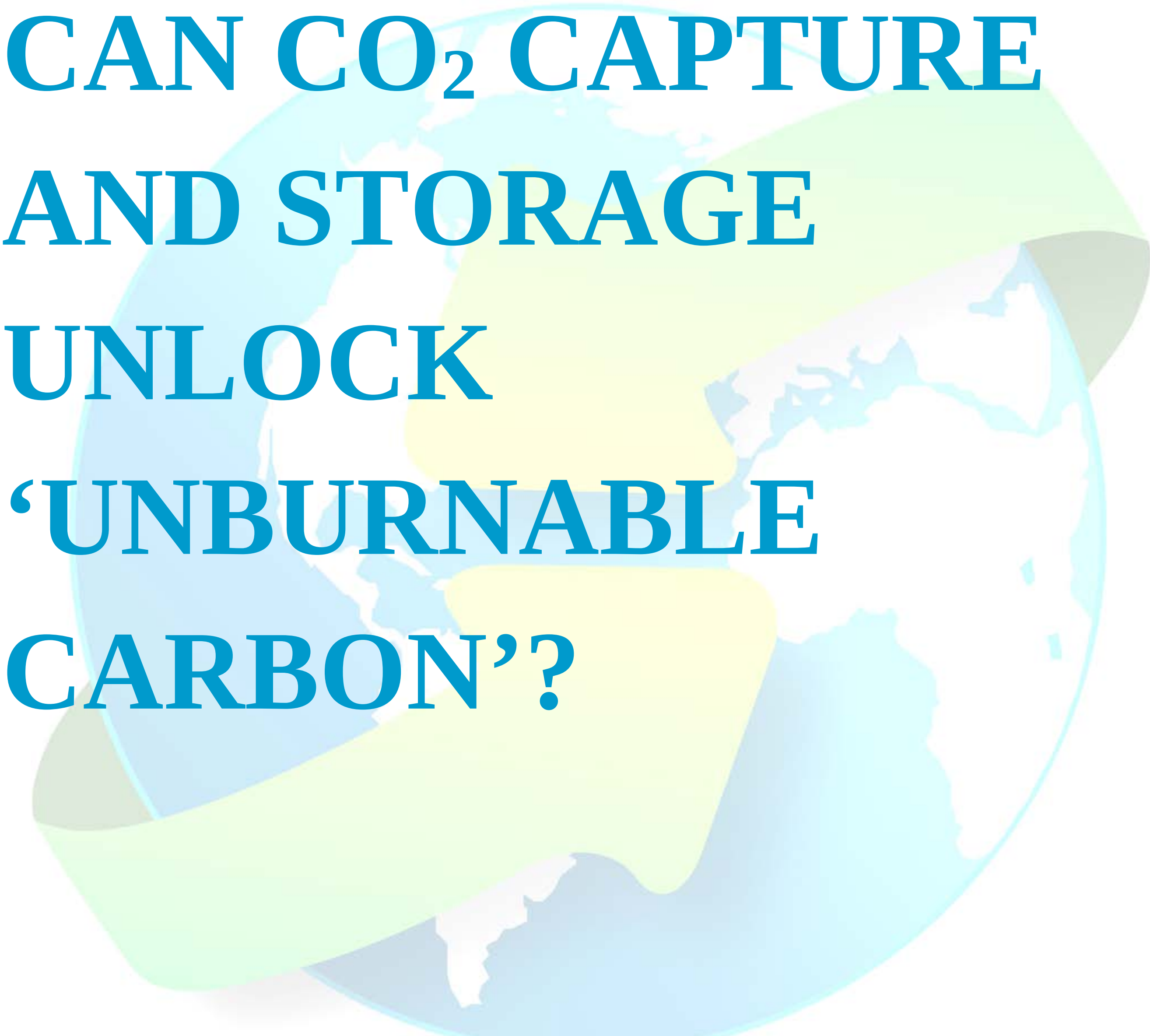


CAN CO_2 CAPTURE AND STORAGE UNLOCK ‘UNBURNABLE CARBON’?

Report: 2016/05

May 2016

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. The IEA fosters co-operation amongst its 28 member countries and the European Commission, and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 40 Implementing Agreements. These agreements cover more than 200 individual items of research, development and demonstration. IEAGHG is one of these Implementing Agreements.

DISCLAIMER

COPYRIGHT

ACKNOWLEDGEMENTS AND CITATIONS

This report describes research commissioned by IEAGHG. This report was prepared by:

Sustainable Gas Institute/Imperial College London

The principal researchers were:

- Sara Budinis
- Adam Hawkes
- Samuel Krevor
- Niall Mac Dowell

To ensure the quality and technical integrity of the research undertaken by IEAGHG each study is managed by an appointed IEAGHG manager. The report is also reviewed by a panel of independent technical experts before its release.

The IEAGHG managers for this report were:

Tim Dixon & Jasmin Kemper

The expert reviewers for this report were:

- Stuart Haszeldine, SCCS/University of Edinburgh
- Chris Hendriks, Ecofys
- David Jones, BG Group
- Olav Kårstad, Kårstad Energiråd AS
- Luke Warren, CCSA
- Paul Zakkour, Carbon Counts

The report should be cited in literature as follows:

'IEAGHG, "Can CO_2 Capture and Storage Unlock 'Unburnable Carbon'?", 2016/05, May, 2016.'

Further information or copies of the report can be obtained by contacting IEAGHG at:

IEAGHG, Pure Offices, Cheltenham Office Park
Hatherley Lane, Cheltenham,
GLOS., GL51 6SH, UK
Tel: +44 (0)1242 802911
E-mail: mail@ieaghg.org
Internet: www.ieaghg.org

CAN CO_2 CAPTURE AND STORAGE UNLOCK ‘UNBURNABLE CARBON’?

Key Messages

- The global ‘carbon budget’ in emission scenarios for climate change mitigation implies that a certain amount of fossil fuel reserves should not be used and their resulting greenhouse gases emitted to atmosphere. This concept is often referred to as ‘unburnable carbon’.
- As carbon capture and storage (CCS) is a technology that prevents or reduces the emissions of CO_2 to the atmosphere, it has the potential to enable use of fossil fuels in carbon-constrained scenarios.
- In order to evaluate the potentially unburnable carbon of fossil fuel reserves, it is necessary to estimate the overall remaining fossil fuel reserves and compare them with the global carbon budget.
- Integrated assessment models (IAMs) are a good means to evaluate carbon budgets as they have a large coverage of technologies, geographical scope, economics and climate data. These models are widely used in publications of the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA) and academia, and most of them cannot achieve a 2°C or lower scenario without CCS. This report selects and investigates a subset of models that focus on technology options and include CCS.
- This study does not aim to assess or provide evidence of the ‘unburnable carbon’ concept but rather to look at the role of CCS technologies in this regard. It will assess the assumptions, methodologies, any contentious subjects and differences related to this topic.
- This study found that the impact of CCS on unburnable carbon appears to be material up to 2050 and further increases up to 2100. This applies especially to coal but also to gas to some extent.
- Model assumptions and cost data availability do generally not limit uptake of CCS in IAMs. However, other reasons seem to limit CCS uptake in models, and the authors of this report hypothesise it could be that residual emissions from CCS, for which CO_2 capture rates of 85-90% are usually assumed, are the reason. It is recommended to investigate this further and to give consideration in R,D&D to increasing capture rates.
- Uncertainties in IAMs and fossil reserve estimates can influence the total amount of carbon considered as unburnable.
- The authors review estimates of global CO_2 geological storage capacity, and find that estimates obtained from volumetric approaches are large and well above the extent of the CO_2 emissions related to fossil fuel reserves.
- Storage capacity estimates from dynamic approaches are likely to be lower, and hence further work on improving dynamic storage efficiency, such as pressure management by brine extraction, is required.
- The related additional costs for pressure and brine management should be considered in IAMs.

Background to the Study

‘Unburnable carbon’ refers to fossil fuel reserves that cannot be used and the resulting greenhouse gases emitted if the world has a limited carbon budget i.e. they would become ‘stranded assets’.

This situation leads to the question: what role does technology have in addressing these concepts and concerns? This study does not aim to assess or provide evidence of the ‘unburnable carbon’ concept but rather to look at the role of CCS technologies in such concepts. This report will also not evaluate other approaches to reduce CO_2 emissions from fossil fuel use besides CCS, such as high efficiency low emission (HELE).

Organisations such as Carbon Tracker Initiative (CTI), the Smith School Stranded Assets Programme (Oxford University) and University College London (UCL) have recently produced papers on these topics. These include assessments of the role of CCS that suggest CCS will have an insignificant impact on the amount of the world's fossil fuel resources that can be utilised in a 2°C climate scenario. Some of these reports view CCS from a resource-limited perspective, for example taking conservative views of the amount of CO_2 storage capacity available and on availability of CCS before 2050.

The International Energy Agency (IEA) has been mentioning the role for CCS in this concept for a couple of years: “CCS therefore promises to preserve the economic value of fossil fuel reserves and the associated infrastructure in a world undertaking the strong actions necessary to mitigate climate change.“ In addition, the recent 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) mentions that the availability of CCS would reduce the adverse effects of mitigation policies on the value of fossil fuel assets.

Scope of Work

This study has undertaken an initial assessment on the relevance of CCS in terms of the unburnable carbon issues. This consisted of the following tasks:

1. Undertake a comprehensive literature review to identify and assess those studies done to date which are relevant to, include or comment upon the role of CCS in the issues of unburnable carbon.

2. Assess the assumptions, methodologies, any contentious subjects, and understand differences in these studies.

3. Identify and assess sources of information on the global potential for CCS deployment, including storage potential.

4. Potential issues that would contribute to better understanding and assessment of this topic (which are of a technical nature and thus IEAGHG could address), will be identified and recommendations made for further work, including whether any work is necessary relating to global storage capacity and CCS global potential.

Findings of the Study

Unburnable carbon and CCS

Global greenhouse gas (GHG) budgets and fossil fuel reserves

Several studies have estimated global carbon and greenhouse gas (GHG) budgets, such as by the Potsdam Institute for Climate Impact Research, the University of Oxford and the IPCC. Each study also gives the probability of exceeding a global temperature increase of 2°C. Some studies consider CO_2 only, whereas others include the full range of GHGs under the Kyoto Protocol (i.e. CO_2, CH_4, N_2O, HFCs, PFCs, SF_6). The timeframe is usually 2000 to 2050 but one study reports the carbon budget for the period 1750 to 2500. Carbon budgets usually include fossil sources as well as land use change. Figure 1 summarises the results.

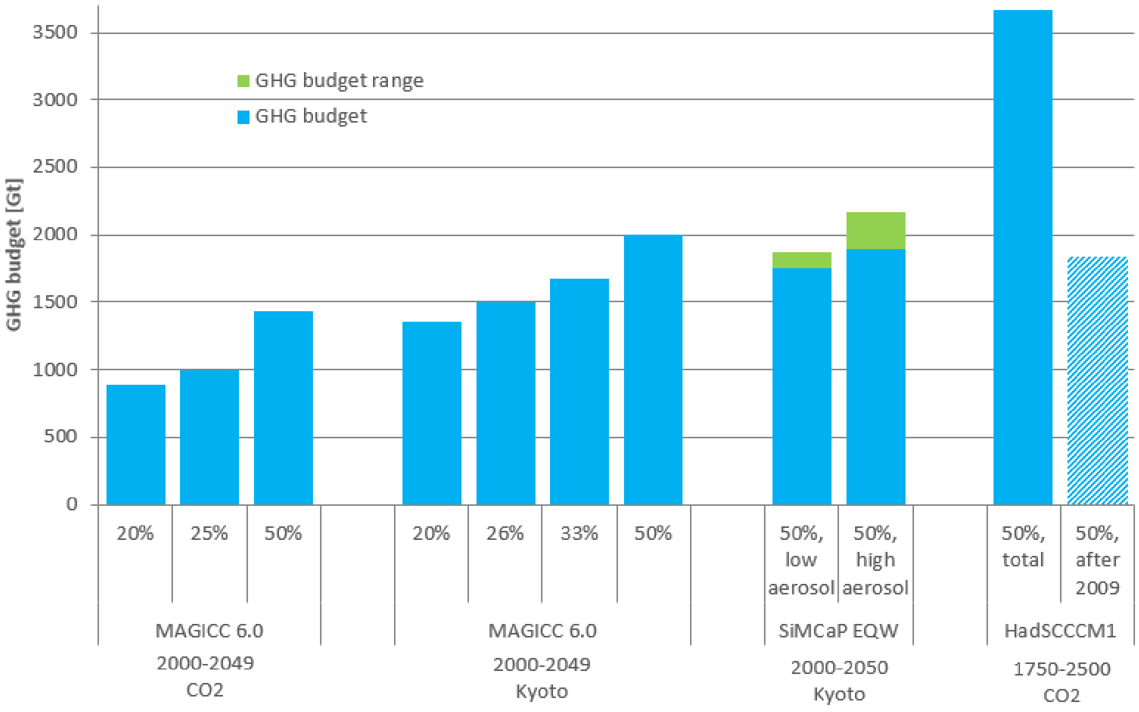


Figure 1 Global emissions budgets from different models for 2000-2050 timeframe for either CO_2 or all Kyoto gases. HadSCCCM1 timeframe is 1750-2500. % = chance of exceeding 2°C scenario.

The study using MAGICC 6.0 by Meinshausen et al. 2009 further estimates that non-CO_2 GHGs contribute up to 33% to overall emissions. Allen et al. calculated a total carbon budget between 1750 and 2500 of 3670 $GtCO_2$. It is important to note that we have already used up around half of this budget from 1750 to 2009, leaving less than 1800 $GtCO_2$ for the future. The IPCC and CTI both assessed available literature and data on carbon budgets and arrive at a best estimate of around 960-975 $GtCO_2$ until 2100 (with a 68-80% probability).

The results from those studies on carbon budgets of course contain several sources of uncertainty, such as the level of climate sensitivity, carbon cycle feedbacks, aerosol emissions and unmodelled processes. IPCC and CTI also point out that the remaining carbon budget after 2050 will be only in the region of 7-10% of the total budget. The future global carbon budget erodes quickly at currently approximately 40 $GtCO_2$/yr, underlining the importance of timely action on climate change mitigation.

In order to evaluate the potentially unburnable carbon of fossil fuel reserves, it is necessary to estimate the overall remaining fossil fuel reserves and compare them with the global carbon budget. However, determining global fossil fuel reserves is a function of price that is subject to significant volatility and different methods exist. Thus, the resulting estimates can vary and contain different levels of uncertainty. This will also be influenced by whether reporting standards and best practices are used, e.g. coal reserves are often reported under the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC Code). Figure 2 contains data on overall reserves as well as burnable and unburnable carbon. Most of the selected studies agree on fossil fuel reserves of around 2800 $GtCO_2$ leading up to 2050, with the most recent study reporting a significantly higher amount of 3613 $GtCO_2$. However, they report different shares of unburnable carbon, ranging from 49-80%, translating into a range of 1360-2565 $GtCO_2$. IEA assessments on global carbon reserves further reveal that usually coal contributes around 63%, oil 22% and gas 15% to these carbon reserves.

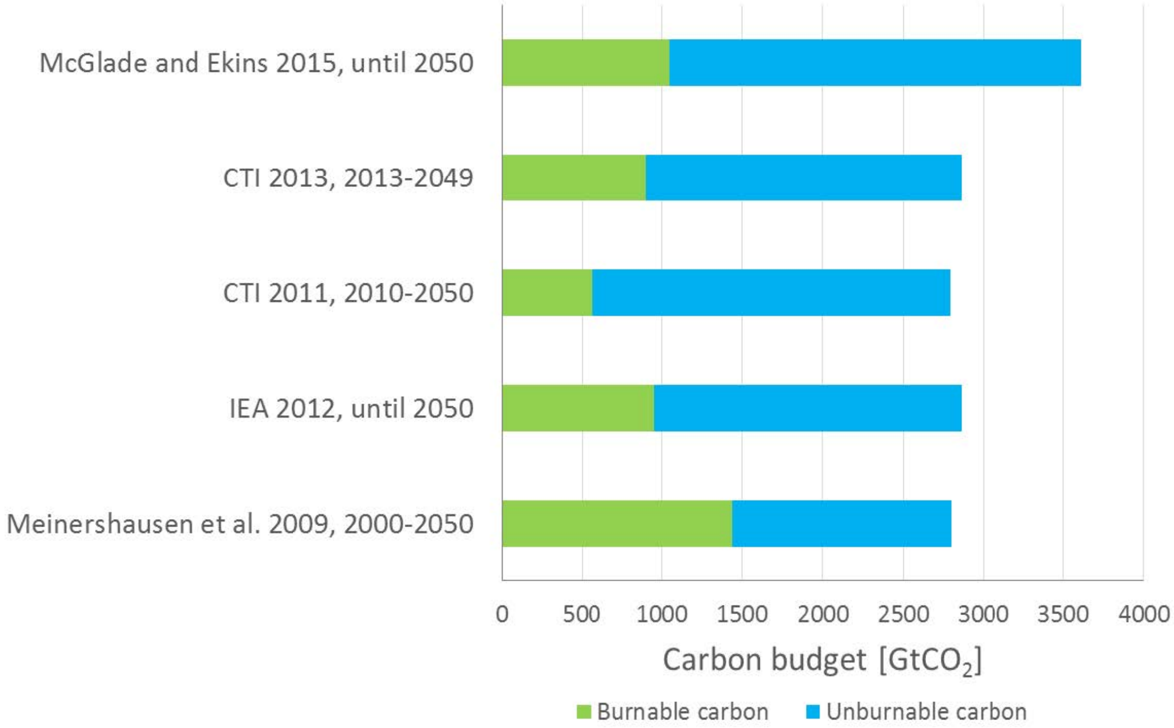


Figure 2 Burnable and unburnable carbon of fossil fuel reserve estimates.

Recent assessments on CCS' effect on unburnable carbon

As CCS is a technology that prevents or reduces the emissions of CO_2 to the atmosphere, it has the potential to enable continued use of fossil fuels in carbon-constrained scenarios. Many studies have analysed the role of CCS in future energy scenarios, however only a small number in the context of unburnable carbon. Sources that have explicitly included this issue are:

- CTI
- Institute for Sustainable Resources (UCL)
- IPCC

CTI concludes that CCS would increase the percentage of burnable fossil fuel reserves in the power sector. Their most recent analysis estimates fossil fuel reserves to be 2860 $GtCO_2$ and that almost 70%

of these reserves are unburnable. Applying CCS as in IEA's 2°C scenario could extend the carbon budget by around 14%, i.e. 125 $GtCO_2$ but would require nearly 3800 CCS projects operating by 2050 and full investment in the technology.

A study by McGlade and Ekins (UCL) found CCS had the largest effect of any technology on cumulative fossil fuel production levels. However, overall the effect is modest, allowing for an increase in oil use by 1%, in gas use by 3% and in coal use by 7% until 2050. According to the authors, reasons for the limitation of the amount of burnable carbon that CCS can unlock are maximum rate of construction, delayed implementation and costs.

Current projections of biomass in combination with CCS (Bio-CCS or BECCS) estimate a potential of this negative emissions technology (NET) of up to 10 $GtCO_2$/yr by 2050. This would translate to an extension of the carbon budget of ~1%. Potential of Bio-CCS in the longer term could be more significant but its estimation is subject to high uncertainties at present.

Integrated Assessment Models (IAMs)

IAMs are a good means to analyse unburnable carbon, as they have a large coverage of technology options and geographical scope, as well as economic and climate data. To understand the role CCS plays in the context of unburnable carbon better it is important to determine the factors that potentially limit its rollout in IAMs. Several studies in the literature have reported the following limitations so far:

- Costs
- Energy penalty
- Locations
- Storage capacity
- Water availability
- Regulatory environment
- Project development timeframes across the CCS chain

As some studies named limitations related to storage capacity as potential major challenges, this work will undertake a further investigation of this topic in the next chapter.

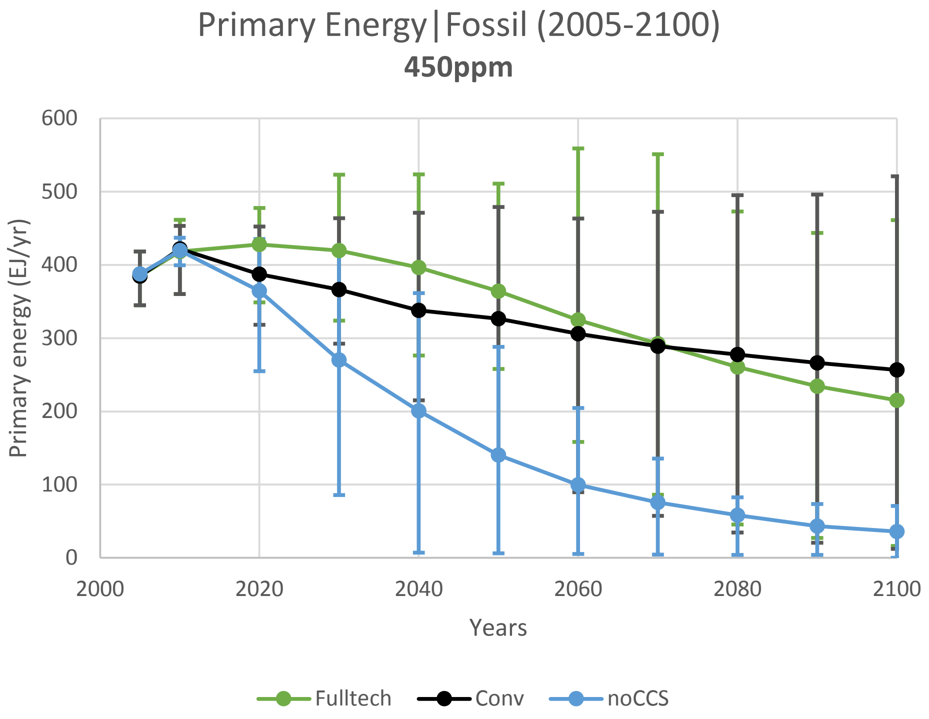
Case study: Energy Modelling Forum (EMF27)

The scenario database of IPCC's AR5 includes 31 different models and a total of 1184 scenarios, which all have to meet certain criteria (i.e. peer-reviewed publication, minimum set of variables, full energy representation and at least a 2030 time horizon). Several model inter-comparison exercises exist, one of which is the Energy Modelling Forum (EMF) at Stanford University. EMF27 compares 18 different IAMs, covering different equilibrium concepts, solution dynamics, time horizons, land use sector representations and GHGs. EMF27 was chosen over other modelling comparison exercises due to its focus on technology and representation of CCS in the models. In addition, EMF27 figures prominently in the IPCC's 5th Assessment Report. The assessment of the role of CCS uses the following three technology scenarios:

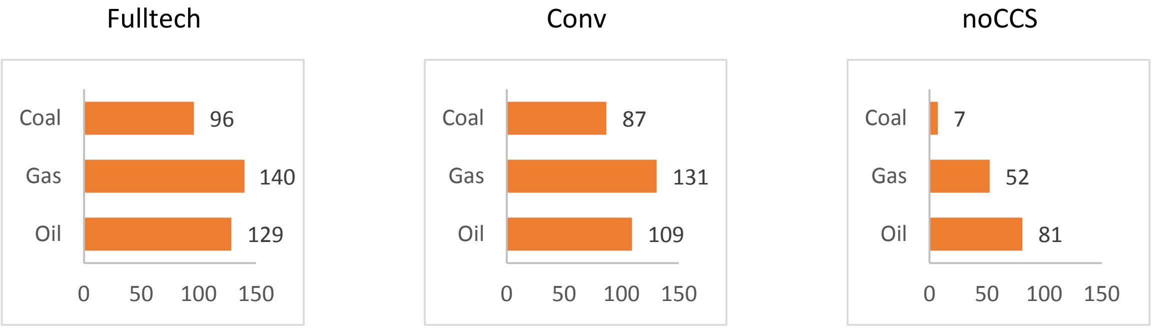
- Fulltech: Full portfolio of technologies available and future scale-up possible
- Conv: Solar and wind limited to 20%, biomass limited to 100 EJ/yr and non-traditional biomass
- noCCS: CCS excluded from technology portfolio in all sectors

More information about the models, scenarios and assumptions is available in the main report and the cited literature.

The climate mitigation scenarios are either a 450 or 550 ppm target for atmospheric CO_2 concentration and the analysis focusses on the models that can produce a 2100 timeframe. Many models do not include a limitation of storage rate and/or capacity. Almost all model scenarios with full technology availability deploy CCS at significant scale and only four models could achieve a 450 ppm target without CCS. This highlights the importance of CCS in adhering to the 2°C scenario by providing flexibility and the scope for negative emissions through bio-CCS. However, it is important to note that not all models were able to give an output for specific scenarios, likely due to a lack of either technical or economic feasibility. Kriegler et al. 2014 provide a detailed review of the EMF27, including technical and economic uncertainties/feasibilities of the models.



2050



2100

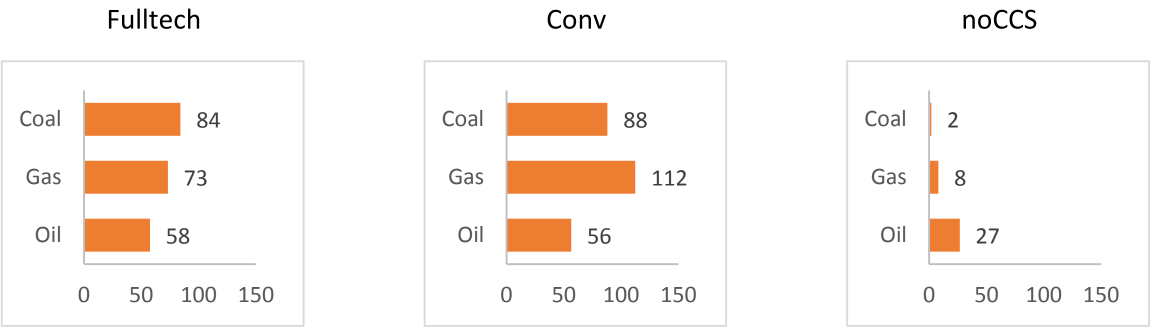


Figure 3 Primary energy from fossil fuels and fuel type shares in 2050 and 2100

Figure 3 shows the fossil fuel usage for the three scenarios for a 450 ppm target and presents the shares for each fossil fuel in 2050 and 2100. A key message is that the utilisation of fossil fuels decreases in all scenarios over time. From 2030, the availability of CCS has significant impact on the continued use of fossil fuels, especially for coal but also for gas to some extent. However, it is important to note that the range of outcomes from the different models is large (see error bars in Figure 3).

Koelbl et al. 2014 reviewed the EMF27 exercise as well and pointed out the main reasons for variations in the model results with respect to CCS:

- Fuel prices
- Baseline emissions
- Model type
- Representation of technology change
- Representation of CCS

The authors suggest further research into this area, as they could not clearly associate a specific model assumption with the amount of CO_2 captured. They did not cite any limits on uptake of technologies and further personal communications of the contractor with the relevant modellers confirmed that any such limits were likely to be non-binding, particularly in later model years. Thus, this report hypothesises that the constraint on CCS is not cost or supply chain related. One possibility is that the residual emissions from CCS could make it an unfavourable option in climate change mitigation scenarios. Even such low levels of emissions could be sufficiently high to conflict with extremely constrained global carbon budgets. Testing of this hypothesis is outside the scope of this report but could be investigated in future work.

Figure 4 summarises the role CCS can play in unlocking unburnable carbon for the timeframes from 2005 to 2050 and 2100. Especially in the longer term, CCS could enable access to significant amount of fossil fuels, i.e. under a 2°C scenario 65% of reserves could be consumed, compared to only 33% without CCS technologies.

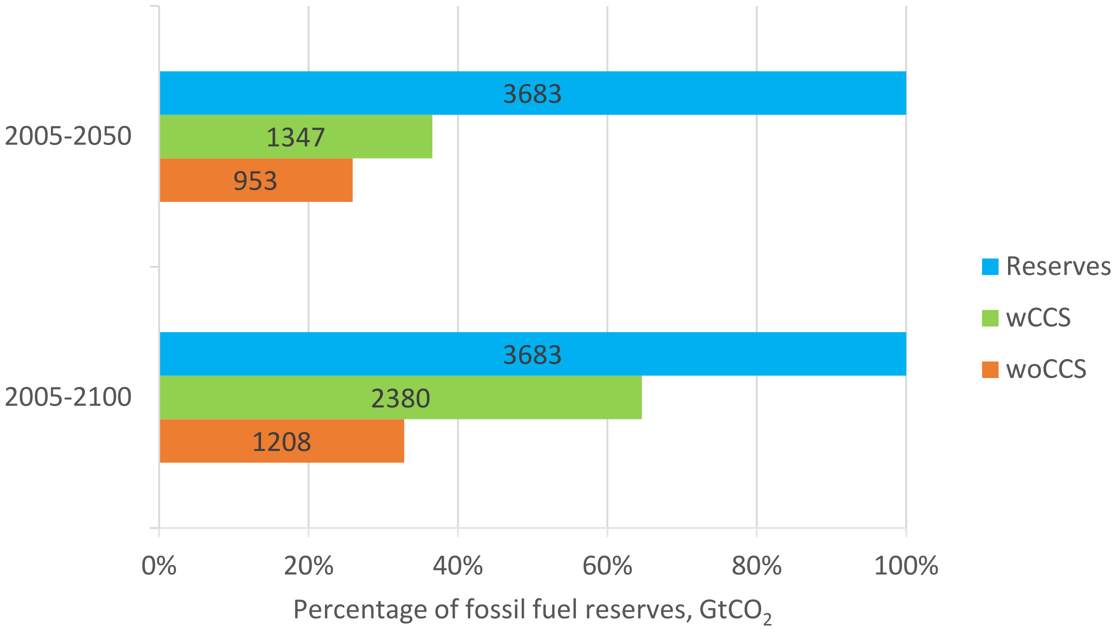


Figure 4 Cumulative fossil fuel consumption in a 2°C scenario with and without CCS. Reserves estimates from McCollum et al. 2014.

Status of CO_2 storage potential

Global potential

Current efforts assessing CO_2 storage resources use evaluation methods that fall into two general categories, i.e. static or dynamic. Static techniques use a product of the total pore volume available in a given storage site, region, etc. with an efficiency that can take into account a number of variables, and form the basis for most national storage assessment. More recently, static estimates incorporating impacts of pressure build-up have become available. Dynamic methods encompass those techniques that model the time-transient movement of CO_2 injected into a storage site. They provide time-varying resource estimates, accounting for the limitations that pressure build-up and dissipation in the reservoir will place on allowable injection rates. They also provide the most realistic estimates of a true storage capacity, while demanding more information about the storage site than is generally required by the volumetric evaluations. Unlike the static techniques, there is no standard procedure for producing a dynamic estimate. In general, static estimates incorporating pressure constraints are systematically lower than volumetric estimates ignoring limitations imposed by pressure build-up. Former IEAGHG work also estimates that static pressure limited estimates are at least an order of magnitude lower than volumetric capacity estimates. This suggests that useful capacity estimates cannot readily be derived from volumetric estimates, i.e. volumetric estimates cannot be appropriately corrected for pressurization effects. In general, it appears that dynamic simulation, whether using reservoir simulation or a simpler model, even at the regional scale, should be applied for a realistic assessment of the storage resource availability on the decadal timescale. Engineering strategies for pressure management, and particularly the production of brine from the reservoir, are effective at mitigating the impact of local and regional pressurization. A pressure management strategy using brine production wells will have a noteworthy impact on the overall cost of CO_2 storage. Costs will include further reservoir characterization needed to choose the placement of wells, the construction of the wells, and the management of the produced water. The technology for pressure management and handling produced water is mature and information for producing cost estimates for use in techno-economic models of CCS, or IAMs that use CCS should be readily available. The extent to which pressure management will be required to reach near term storage injection targets, however, will not be clear until more national and regional scale assessments of storage capacity using dynamic modelling are performed.

Geographical distribution

Studies covering international regions using a consistent assessment methodology have thus far employed volumetric estimates of capacity, and have only been performed for North America and OECD Europe. The global resource availability estimate ranges from 5,000 to 33,000 $GtCO_2$. Figure 5 summarises the regional breakdown from these compilations. For oil and gas fields, capacity ranges 1-2 orders of magnitude lower than the total storage capacity, i.e. between 400 and 1000 $GtCO_2$. In some regions, particularly in the Middle East, capacity in oil and gas fields is a majority of the total capacity, as the regional breakdown in Figure 6 shows.

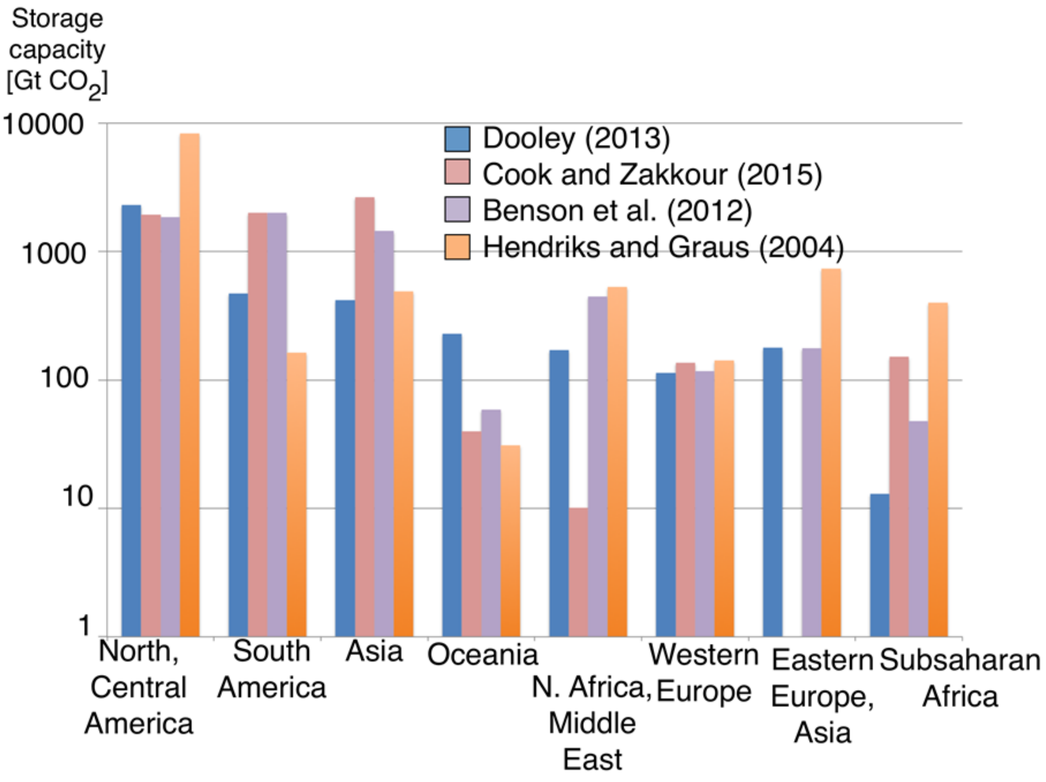


Figure 5 Regional CO_2 storage capacity estimates

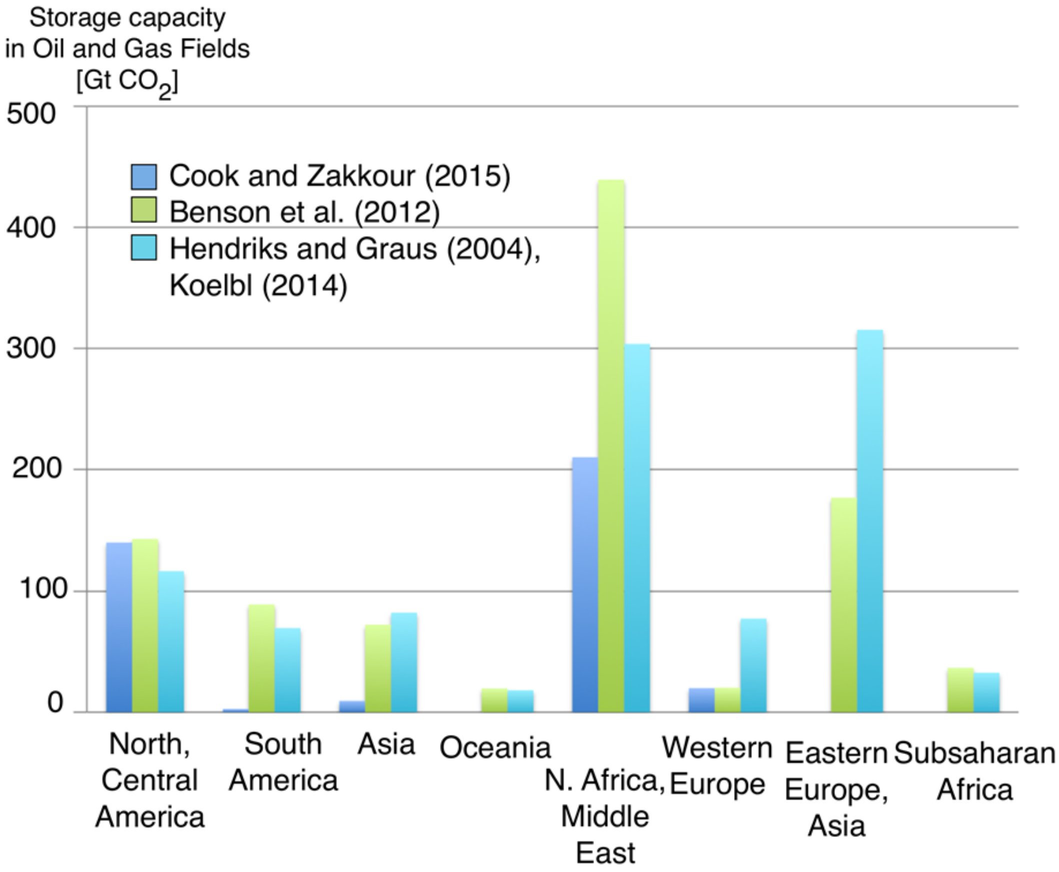


Figure 6 Regional CO_2 storage capacity estimates in oil and gas fields

Limitations to CCS deployment

The previous section implies that sufficient storage capacity is available for CCS. There will likely be no significant storage capacity limits for the first generation of CCS deployment, as oil and gas fields could meet all demand. However, the estimates are mostly volumetric, and thus the extent to which pressure and brine management strategies are necessary is the major uncertainty in this context. In conclusion, IAMs should consider the additional costs for such methods.

Expert Review Comments

Seven experts from different backgrounds (academia, industry and NGOs) reviewed the report. Most reviewers commented the report was well written, timely and would be a useful resource. Some of the more specific comments, which the authors addressed in the final version, included a better comparability/consistency of number in EJ and $GtCO_2$, improvement of the graphical presentation of the results and making the conclusions clearer and more accessible. Requests for testing the hypothesis of residual emissions and for resolving the debate around fossil fuel reserves and resources estimates are outside the scope of this work and have not been addressed. A few reviewers disagreed with the numbers presented for CO_2 storage and Bio-CCS potential. However, the authors and IEAGHG consider them reasonable and sufficiently backed up by literature.

Conclusions

A number of recent studies have reviewed the unburnable carbon topic. These have broadly reached the same conclusion: that some portion of fossil fuel reserves is unburnable in scenarios where global temperature rise must be less than 2°C. A few studies explicitly considered the impact of CCS on unburnable carbon and found a modest impact of CCS 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, this study undertook an EMF27 multi-model comparison, which produced a set of scenarios of energy system change to mitigate climate change. Analysis of results confirms that CCS availability has a large impact on the extent of fossil fuel consumption in climate-constrained scenarios, as scenarios with CCS lead to a fossil fuel use that is ~200EJ/yr higher. A key difference between this study and previous efforts is that the dynamics of CCS uptake were considered herein, with the observation that CCS adoption is still ramping up at 2050 (previous studies limited the time horizon of consideration to 2050).

Based on the evidence available from EMF27 models, there are few limiting assumptions made on the availability of CCS. Almost all models reviewed had 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).

In addition, the cost of CCS technology in the models does not appear to be a significant barrier. Therefore, if CCS is available (and not unfavourable for other reasons) further adoption should be observed in the models. One explanation that such adoption does not occur is that there are other factors in the models preventing uptake, e.g. the residual emissions from CCS installations. Though small, they could be significant enough to prevent further technology deployment. However, testing this hypothesis is outside the scope of this work.

CO_2 geological storage capacity is large from a volumetric standpoint, i.e. the pore space available is sufficient to accommodate CO_2 from all fossil fuel reserves in virtually any scenario. However, reservoir pressurisation and uncertainties in volumetric estimates could significantly limit storage capacity. Pressure and brine management strategies would be necessary to alleviate this issue and the impact on costs and deployment requires further assessment and inclusions in IAMs. This constraint is probably not binding in the short to medium term, as adequate storage capacity is available in depleted oil and gas fields, and in higher quality saline aquifers.

IEAGHG is aware of the different opinions that exist on the concepts around unburnable carbon. This study did not attempt to provide a full analysis of these concepts. The report started out with the assumption that the unburnable carbon hypothesis does exist and subsequently evaluated the role CCS could have in enabling continued access to fossil fuel reserves under different climate change mitigation scenarios. Other means of reducing CO_2 emissions from the use of fossil fuels, e.g. HELE for coal-fired power plants, were not part of this study.

Recommendations

Recommendations for future work on the topic include:

- Testing of the hypothesis that residual emissions from CO_2 capture can limit uptake of CCS in IAMs, and if so then increased R,D&D on improving capture rates is necessary.

- More work on dynamic estimates of global CO_2 storage capacity.

- Work on improving dynamic storage efficiency through pressure management and other techniques.

- Inclusion of pressure and brine management strategies and their costs in IAMs.

A forthcoming SGI White Paper will looked at some of the issues identified in this study in more detail.

Can carbon capture and storage unlock ‘unburnable carbon’?

Sara Budinis

Niall Mac Dowell

Sam Krevor

Adam Hawkes

Executive Summary

'Unburnable carbon' is a phrase used to describe a long-standing problem; the fact that if all fossil fuel reserves were burned (unabated), the world would experience very significant climate change. Several recent reports have highlighted the scale of this challenge, drawing on selected scenarios of climate change mitigation and their implications for the projected consumption of fossil fuels. They universally find that some portion of reserves is unburnable if global temperature rise is to be limited to 2°C. However, while some of these studies have considered the potential role of carbon capture and storage (CCS) in enabling access to more fossil fuels, no detailed analysis on this issue has been undertaken.

This report focuses on this topic with the specific overarching question; "to what extent can carbon capture and storage technology unlock fossil fuel reserves that would otherwise be unused in a carbon-constrained world?" It presents a review and analysis of evidence on this topic, including introduction to the key issues of carbon budgets and fossil fuel reserves, analysis of the status of CCS, review of a multi-model comparison study on global climate change mitigation strategy, and a deep-dive on the extent of global CO_2 geo-storage capacity available. Key findings as follows:

The availability of CCS underpins access to significant quantities of fossil fuels under pathways of global climate change mitigation. Recent studies considering the extent to which CCS impacts unburnable carbon have considered the timeframe to 2050 only, and shown a small impact. However, models used in the IPCC 5th assessment report find that on-average almost 200EJ per year more fossil fuels are consumed in a scenario with CCS versus a scenario where CCS is not available by 2050 (Figure ES1). This margin continues to 2100. Therefore, while the difference in cumulative fossil fuel consumption between a CCS and no CCS scenario is only approximately 3,500-5,000EJ in 2050, by 2100 this has increased to 14,000-16,000EJ.

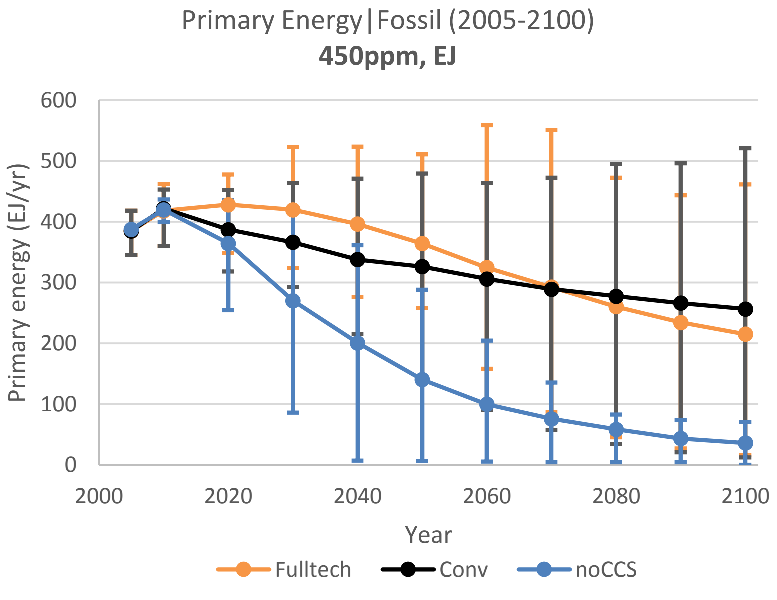


Figure ES1. Average consumption of fossil fuels (oil, coal, gas) across a range of integrated assessment model outputs. Scenarios plotted are Fulltech (all technologies available), Conv (renewables constrained), and noCCS (no CCS available). Error bars represent the maximum and minimum model result observed.

The role of CCS in unlocking unburnable carbon is greater in the second half of this century. In modelled energy system transition pathways that limit global warming to less than 2°C, scenarios without CCS available result in 26% of fossil fuel reserves being consumed by 2050. This rises to 37% where CCS is available. However, by 2100 the scenarios with no CCS have only consumed slightly more fossil fuel reserves (33%), whereas scenarios with CCS available end up consuming 65% of reserves. This is shown in Figure ES2, and demonstrates the significance of CCS in enabling access to fossil fuel reserves post 2050. Among the three key fossil fuels (oil, gas and coal), gas and coal are the most strongly affected by the adoption of CCS, with an increase in coal use of 82-86 EJ/yr and of gas use of 65-104EJ/yr by 2100, while oil consumption could increase by 29-31EJ/yr.

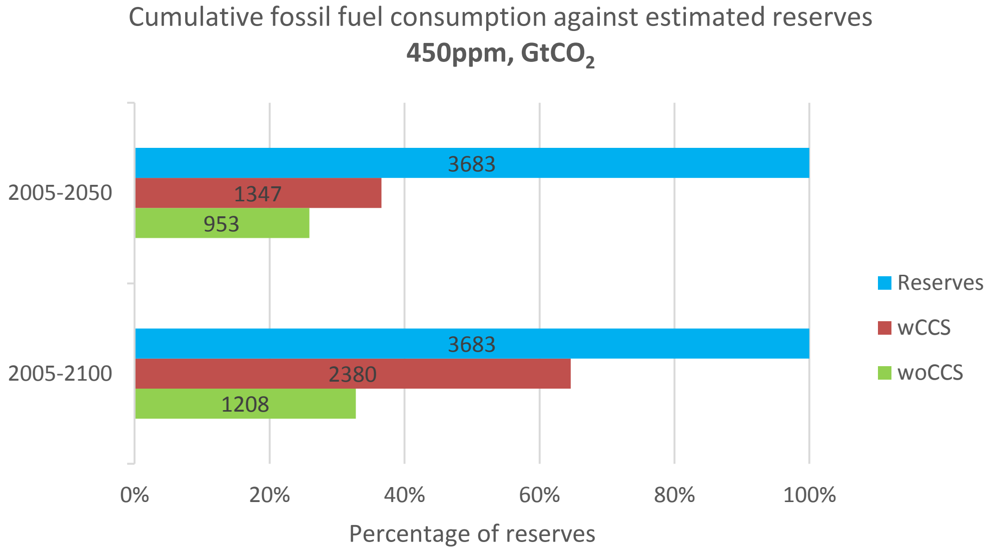


Figure ES2. Cumulative fossil fuel consumption in the timeframes 2005-2050 and 2005-2100 in a 2°C scenario. $GtCO_2$ includes both emitted and abated CO_2. Reserves estimate is the ‘low’ value from McCollum et al. (2014). “woCCS” scenario corresponds to the noCCS scenario while “wCCS” scenario corresponds to the Fulltech scenario.

The global carbon budget is being rapidly eroded. In order for fossil fuels to play a major role in future energy systems prompt action on CCS is required. In the first decade of this century anthropogenic CO_2 emissions were approximately $34GtCO_2$ per year. The remaining global carbon budget to limit warming to 2°C is of the order of $1000GtCO_2$ (with some uncertainty). Therefore, if current rates of emissions are not decreased, the global carbon budget will be exhausted before 2050. In order for fossil fuels to play a role in a low carbon world, activity to speed the commercialisation and scale up of CCS is required promptly.

In general the availability and cost assumptions made when modelling CCS in global climate change mitigation do not greatly limit the uptake of CCS seen in the model outputs. This is because based on the best available information there are few binding constraints limiting the rate of uptake in capture, transport or storage stages of the CCS chain. Furthermore, the cost of CCS assumed in the models is less than the marginal abatement cost observed in model outputs. Therefore, the only explanation that the observed adoption of CCS in model outputs is not higher is that another factor is blocking further uptake. Systematic identification of this factor is out of the scope of this report, but the following hypothesis is made:

This report hypothesises that the residual emissions produced by CCS-enabled facilities are of a sufficient magnitude to prevent the technology being adopted more broadly in studies of global mitigation strategy. Even the relatively small residual emissions level may be sufficient to make the technology unfavourable in a highly carbon constrained world. Testing of this hypothesis is beyond the scope of this report. However, should the hypothesis prove to be correct it would send a strong R&D message to capture technology developers; improvement of capture rates to closer to 100% could make the technology much more relevant to the fossil fuel supply chain.

This report has tested and confirmed the assumption that global CO_2 geo-storage capacity is large, in the range of 10,000-30,000GtCO_2 including 1000 Gt in oil and gas reservoirs. This is well above the extent of known fossil fuel reserves, by approximately an order of magnitude. These figures have been have estimated in a number of studies through compilations of regional or national storage potential assessments. These compilations generally use a volumetric approach.

Recent work using detailed reservoir simulation and other modelling approaches has found that over decadal timescales, 50-100 years from the start of commercial deployment, only .01 – 1% of the pore volume of saline aquifers will be available for storage, in the absence of brine production from the reservoir. This is due to the requirement that pressures in the reservoir remain below that which would fracture sealing caprock. The exact fraction of available pore space has complex dependencies on reservoir, rock, and fluid properties and is only reasonably estimated using dynamic modelling. At the time of writing only one such dynamic estimate has been made for an entire region – the U.S. in Szulczewski et al. (2012). However, due to storage capacity in oil and gas fields, and high quality saline aquifer reservoirs, the impact of this issue will not be felt until after at least the first generation of CCS plants has been deployed, i.e. post 2050.

Therefore it should be a high priority for any jurisdiction considering large-scale deployment of CO_2 storage to perform regional dynamic assessments of the resource. Considering farther, to 2100, there is significant uncertainty in national and regional estimates, particularly when considering the issue of limits to injection imposed by pressurization of the reservoir.

An additional constraint should be built into integrated assessment models in which regional pressurization may trigger the deployment of pressure management strategies with associated higher costs. 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. The limitations to deployment created by the costs of pressure management will provide a more accurate estimate of the potential role of CCS in future energy technology scenarios.

This report has made some targeted recommendations for future research. The key recommendation is to check of the hypothesis on residual emissions, where an increase of capture rate of CCS technology could enable access to more fossil fuel reserves. Also, research aimed at developing CCS technology with lower residual emissions should be prioritised. In terms of geo-sequestration of emissions, countries with aspirations for large scale deployment of CCS should undertake regional dynamic assessments of storage resource.

1 Introduction

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

A number of recent reports have been published on the unburnable carbon 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.

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

A key resource in unburnable carbon assessments are global integrated assessment models[1] (IAMs), which are used to produce scenarios of energy system transition to a low carbon world, thereby providing estimates of the future use of fossil fuels that is consistent with climate change mitigation. These models use a range of methodological approaches that determine what technologies are selected, along with a range of input data assumptions like costs and performance, which all have a strong bearing on outcomes. A good example of the outcomes that can be produced is the IEA's Energy Technology Perspectives 2012 scenario which allows CCS to unlock $125GtCO_2$ until 2050 (Carbon Tracker Initiative, 2013).

This report reviews the evidence on 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 it introduces the evidence on the broad issue including the climate science, specifics of fossil fuel reserves and resources, leading to quantification of unabated burnable carbon. It then presents a review of a multi-model IAM comparison study that considered carbon capture and

---

[1] Integrated Assessment Models (IAMs) "include representations of climate, using models and data generated by the climate modeling and research community, and Earth systems, using models and data generated by the impacts, adaptation, and vulnerability (IAV) modeling and research community. In turn, IAMs provide to the climate modeling community emissions scenarios of greenhouse gases (GHGs) and short-lived species (SLS) and land-use projections. IAMs provide to the IAV modeling community projections of socioeconomic states, general development pathways, and the multiple stressors of climate change" (Janetos, A. C. (2009). Science challenges and future directions: Climate Change Integrated Assessment Research. *In:* US DOE (ed.)).

storage (CCS) in relation to the unburnable carbon concept, including their results, methodologies and assumptions where available. Finally, a deep dive on the quantification of global storage capacity is undertaken. This leads to conclusions and recommendations on the treatment of this aspect of CCS in unburnable carbon assessments in future.

2 Background

2.1 The global greenhouse gas budget

It is unequivocal that climate change is influencing the planet, with a range of effects already observable (IPCC, 2013a). It is also extremely likely that this is caused by emissions of greenhouse gases ensuing from human activities, either directly (e.g. fossil fuel combustion, cement production) or indirectly (e.g. deforestation). Given the observed impacts to date, the extreme nature of potential future impacts on natural and human systems (IPCC, 2013d), and rapidly increasing emissions (IPCC, 2014b), it is pressing that decision makers consider options to mitigate climate change by reducing emissions, and to plan adaptation for changes that are already committed.

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^{o}C (M. Meinshausen et al., 2009). Peak warming given by cumulative emissions has been adopted by the scientific community as a reliable measure of climate change (Allen et al., 2009). It should be noted that the 2^{o}C limit was chosen because the best evidence on projected impacts and damages indicate that they are more limited and more certain below this level (IPCC, 2007). As such, even 2^{o}C cannot be considered completely safe, and adaptation will still be required.

It is worth noting at carbon budgets that lead to warming of greater than 2^{o}C have also been produced. For example, the IEA described two scenarios, the 4DS and the 6DS, which project a long-term temperature rise of respectively 4°C and 6°C. The 6°C Scenario (6DS) is largely an extension of current trends and is characterised by the absence of efforts to stabilise atmospheric concentrations of GHGs (Greenhouse Gases). The IEA also include (IEA, 2015b) a 2°C Scenario (2DS), which describes an energy system consistent with an emissions trajectory that would give an 80% chance of limiting average global temperature increase to 2°C.

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

Table 1: Global emissions budgets from a variety of sources

Budget (Gt)	Gases	Scope	Timeframe	Probability statement	Model	Ref
886	CO_2	fossil sources, land use change	2000-2049	20% chance of exceeding 2C	MAGICC 6.0	M. Meinshausen et al. (2009)
1000	CO_2	fossil sources, land use change	2000-2049	25% chance of exceeding 2C	MAGICC 6.0	M. Meinshausen et al. (2009)
1437	CO_2	fossil sources, land use change	2000-2049	50% chance of exceeding 2C	MAGICC 6.0	M. Meinshausen et al. (2009)
1356	Kyoto gases	fossil sources, land use change	2000-2049	20% chance of exceeding 2C	MAGICC 6.0	M. Meinshausen et al. (2009)
1500	Kyoto gases	fossil sources, land use change	2000-2049	26% chance of exceeding 2C	MAGICC 6.0	M. Meinshausen et al. (2009)
1678	Kyoto gases	fossil sources, land use change	2000-2049	33% chance of exceeding 2C	MAGICC 6.0	M. Meinshausen et al. (2009)
2000	Kyoto gases	fossil sources, land use change	2000-2049	50% chance of exceeding 2C	MAGICC 6.0	M. Meinshausen et al. (2009)
3670	CO_2	fossil sources, land use change	1750-2500	50% chance of exceeding 2C (according to McGlade and Ekins (2014))	HadSCCCM 1	Allen et al. (2009)
1635-1752[2]	Kyoto gases	fossil sources, land use change	2000-2050	50% chance of exceeding 2C (low aerosol scenario)	SiMCaP EQW and MAGICC	Bowen and Ranger (2009)
1631-1897	Kyoto gases	fossil sources, land use change	2000-2050	50% chance of exceeding 2C (high aerosol scenario)	SiMCaP EQW and MAGICC	Bowen and Ranger (2009)

---

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

Table 1 summarises the carbon budgets as estimated by the reported sources. Each carbon budget has an associated probability to not exceed the 2°C temperature rise and has been estimated for a specific timeframe. Three timeframes have been considered, including time horizons until 2050, until 2100 and total emissions. Resources for estimation of carbon budgets include the Potsdam Institute for Climate Impact Research (M. Meinshausen et al., 2009), the University of Oxford (Allen et al., 2009), the IPCC Fifth Assessment Report (AR5) and the contribution given by the Working Group I (IPCC, 2013c) and III (IPCC, 2014a). Those who have received most attentions are M. Meinshausen et al. (2009) for the budget until 2050 and Allen et al. (2009) for the budget until 2100.

M. Meinshausen et al. (2009) related the emissions and climate system response by means of the coupled climate-carbon cycle model MAGICC. They delivered a probabilistic analysis in order to quantify cumulative GHG emission budgets for the time period 2000-2050. According to the authors, the probability of exceeding 2°C can be limited to below 25% (50%) by keeping 2000–49 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 SF6) may constitute the 33% of overall emissions.

Allen et al. (2009) present idealized carbon dioxide emission scenarios by means of the coupled climate carbon-cycle model HadSCCCM1. They 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 emission 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.

Other sources reporting evaluations of the carbon budget include IPCC (960 $GtCO_2$ until 2100 for 68% probability to remain below 2°C increase) and Carbon Tracker Initiative (975 $GtCO_2$ until 2100 for 80% probability to remain below 2°C increase) also based on the MAGICC model. It is worth noting that most of the references report a quite small carbon budget remaining after 2050 (7.7% according to Carbon Tracker, 9.4% according to IPCC). This further highlights the importance of early actions on climate change mitigation.

There are many sources of uncertainty in greenhouse gas budgets, and no single author claims to be able to predict climate change precisely. Key sources of uncertainty are the level of climate sensitivity, carbon cycle feedbacks, aerosol emissions scenarios and unmodelled processes. Climate science is a rich and active area of research and as such estimates of the global carbon budget are likely to be refined over time.

Finally, it is clear that the global carbon budget is being rapidly eroded: Over the period 2002 to 2011 the global fossil fuel, cement and land use change CO_2 emissions were approximately 34$GtCO_2$ (IPCC, 2013b) per year. 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 Fossil fuel reserves

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 exact quantity of reserves is a contentious subject, as it depends on prevailing commodity price, prices for asset developments, and many other factors. A large range of estimates exist in the literature.

The extent of reserves has been reviewed by Meinshausen et al. (M. Meinshausen et al., 2009), who state that the mid-estimate from the literature could produce 2,800 Gt of CO_2 emissions in a scenario of unabated combustion, with an 80%-uncertainty range of 2,541 to 3,089 Gt CO_2. Reserve estimates have also been reported by McCollum et al. (2014), 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 (2015) (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.

The methodology of determination of fossil fuel reserves is a contested subject; See Box 1 for a description of the range of approaches. 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 specific project favourable. 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 also contentious with respect to its link to the “carbon bubble” concept. This concept is driven by the fact that if some reserves are unburnable, the companies that own those reserves might be overvalued in the stock market (Carbon Tracker Initiative, 2011). However Mayer and Brinker (2014) have argued that the perception of carbon risk has been inflated by choice of the definition of reserves, in particular that reserves estimated using the SEC 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 companies 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 to the degree that company value will also impacted; an indirect carbon bubble effect (Spedding et al., 2013). This report does not attempt to assess the carbon bubble issue directly, but focuses on the technical realities of “unburnable carbon” rather than the financial aspect of the problem.

Box 1: Classification of fossil fuel resources and reserves

One of the first attempts to classify resources and reserves is represented by the McKelvey box, which classifies resources as undiscovered, discovered and economic (i.e. reserves) and discovered sub-economic (McKelvey, 1972). Since 1972, various nomenclatures have been proposed and adopted and the most common ones include (Mayer and Brinker, 2014):

Petroleum Reserves Management System (PRMS) of the Society of Petroleum Engineers (SPE)

US Security and Exchange Commission (SEC)

United States Geological Survey (USGS)

Norwegian Petroleum Directorate (NPD)

Russian Ministry of Natural Resources (RF).

The PRMS of the Society of Petroleum Engineers defines proved reserves as those resources that meet all the technical requirements for commercialization and have 90% probability of been recovered (OGRC (Oil and Gas Reserves Committee), 2005). Probable and possible reserves have respectively 50% and 10% probability of being recovered (Mayer and Brinker, 2014). Proved reserves are also called 1P, while proved plus probable are called 2P and proved plus probable plus possible are called 3P (OGRC (Oil and Gas Reserves Committee), 2005).

Reserve databases include numerous sources, which have been employed in both academic and grey literature in order to estimate the carbon content of overall reserves. Some examples include BP (BP, 2012), IEA (IEA, 2012), German Federal Institute for Geosciences and Natural Resources (Rempe et al., 2007), Deutsche Bank (Herrmann et al., 2010), Energy Watch Group (Schindler and Zitell, 2008), World Energy Council (World Energy Council, 2007) and BGR (BGR, 2012).

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 that is then released to the atmosphere if the world is to avoid temperature rise greater than 2C. 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 it refers to the amount of fossil fuel that cannot be burnt in a mitigated climate change scenario. Though the issue is not new, unburnable carbon has been recently investigated by the Carbon Tracker Initiative (Carbon Tracker Initiative, 2011) and later by other institutions such as the International Energy Agency (IEA, 2013) and the Environmental Audit Committee of the UK Government (Environmental Audit Committee, 2014) and banking and other organisations such as HSBC (Channel et al., 2015, Lewis et al., 2014, Robins et al., 2014, Spedding et al., 2013).

Table 2 reports 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.

Table 2. Unburnable and burnable carbon. Note large range in reserves between sources.

Unburnable carbon ($GtCO_2$)	Burnable carbon ($GtCO_2$)	Overall remaining reserves ($GtCO_2$)	Timeframe	Reference
1360	1440	2800	2000-2050	M. Meinshausen et al. (2009)
"more than 2/3" >1907	less than 1/3 <953	2860	until 2050	IEA (2012)
2230	565	2795	2010-2050	Carbon Tracker Initiative (2011)
1960	900	2860	2013-2049	Carbon Tracker Initiative (2013)
2565	1049	3613	until 2050	McGlade and Ekins (2015)

A prominent example is the World Energy Outlook 2012 (IEA, 2012), which estimates overall reserves to be equal to 2860$GtCO_2$. Without CCS, less than a third (that would be 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.

3 Can CCS unlock unburnable carbon?

Given that CCS is a technology that prevents the emission of CO_2 to the atmosphere, it follows that its application could enable more fossil fuels to be utilised in carbon-constrained scenarios. This section reviews the status of the technologies of interest and reviews a range of studies using IAMs that have considered the issue.

3.1 The status and potential of CCS

3.1.1 Current status of CCS

The current status of CCS has been reported by e.g. the Global CCS Institute and the London School of Economics and Political Science jointly with the Grantham Institute. According to the Global CCS Institute (2014), there are currently 55 large-scale CCS projects worldwide in either ‘identify’, ‘evaluate’, ‘define’, ‘execute’ or ‘operate’ stage. Nineteen of these projects are based in United States, followed by China (12 projects) and Europe (8 projects). Ten of the operating projects are based in US (Bassi et al., 2015) and all of these are part of industrial applications where CO_2 separation is already employed for other purposes.

3.1.2 Outlooks produced by industry including CCS

Reduction of atmospheric emissions has been taken into account also in some scenarios produced by industry. Examples include BP (2015), Shell (2013) and ExxonMobil (2015). While BP highlights the role of gas as a cleaner fossil fuel for power generation in future projections, encouraging research and development toward higher energy efficiency routes, Shell and ExxonMobil explicit 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”, Shell propose energy scenarios in which CCS plays a key role, having a world capacity of 20GW by 2020 and capturing 10GtCO_2/yr by around 2045. This would help to decarbonise electricity by 2060 and to reduce world CO_2 emission to zero by 2100 (Shell, 2013).

3.1.3 CCS development limitations

A primary point of interest when considering the potential of CCS as seen by IAMs is in understanding what factors in the models are limiting its uptake. Various sources have reported on this, with the main limitations including cost and energy penalty of CCS plants, and location and capacity of storage sites.

According to Clark and Herzog (2014), 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 efficiency penalty of CCS for coal-fired power generation is about 10% (Goto et al., 2013). This penalty does not depend on the type of power plant or coal but rather on the capture process, which contributes to about two thirds of the overall energy penalty. According to Hammond et al. (2011), the energy penalty of a pulverised–coal 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 plants (about 7%) when combined with carbon capture and storage.

Moreover new power plant station should be CCS-ready for the future and this would require a suitable space for the construction of the CCS unit, reasonable proximity to a storage site and local water in sufficient quantities (IEA, 2015a).

The main factors determining the global scale feasibility for storing CO_2 as a method for climate management include (V. Scott et al., 2015):

- Cumulative capacity of carbon storage (see Section 4 for detailed assessment of this issue)
- Rates of release and uptake
- Connection from source to store
- Climate impact of storage timescale.

Box 2: What is CCS (Carbon Capture and Storage)?

CCS refers to a process that separates carbon dioxide from a gas stream and stores it underground. CCS can be applied to power generation and industrial facilities.

CCS includes three main steps:

1. The separation of carbon dioxide from the gas stream
2. Its compression and transportation (vie pipeline or shipping)
3. Its storage in a suitable geological site (some examples include saline aquifers and depleted oil and gas reservoirs).

CCS is categorised according to the type of separation process:

1. Post-combustion CCS involves the separation of carbon dioxide from a flue stream after a fossil fuel has been combusted.
2. Pre-combustion CCS separates CO_2 from a hydrogen-rich gas called syngas prior to combustion. The syngas is obtained by gasification of a fuel.
3. Oxy-combustion CCS is characterised by the combustion of a fossil fuel with pure oxygen. This generates a flue stream without impurities, where carbon dioxide can be separated more easily by condensing the water vapour.

According to V. Scott et al. (2015), rates of storage creation cannot balance current and expected rates of fossil fuel extraction and CO_2 consequences. Therefore the identification of a suitable storage space was identified as one of the major challenges to the future development of CCS. This topic is further investigated in Section 4.

This issue was also put forward during discussions with CCS developers undertaken in this project, where the following issues were cited to be important when considering barriers to CCS:

- The geological appraisal of a store takes 3 - 4 years. Power station build takes 3-4 years for gas turbines and 5-6 years for solid-fuelled systems, so if appraisal and power station build are simultaneous the CCS aspect *may* be on the critical path. However, if power station build is dependent suitability of the store, appraisal may need to proceed prior to power station build. Furthermore, if national CO2 transportation infrastructure were present, any dependency between store identification and power station build would be largely eliminated.

- The availability of sufficient skilled labour could represent a bottleneck. For example, White Rose in the UK is estimated to need on-average 4000-5000 people over approximately five years, with a peak of 9000 people.
- At present the regulatory environment for CCS infrastructure is not well developed, leading to uncertainty regarding development timeframes and price models.

It should be noted that the process of the 3-4 year appraisal period for a CCS site is not a new technology, and is already regularly undertaken by the oil and gas industry. Also, availability of storage sites is very unlikely to be an issue; within any region there will be suitable fields, which can be characterised by standard practices within the 3-4 year timeframe. Overall, construction-related barriers to CCS development appear to be a minor issue, meaning that risk is largely non-technical in nature, much more relating to the possibility that financial environments and/or regulation will change significantly over the construction period.

3.2 Selected recent analyses of CCS and unburnable carbon

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

- Carbon Tracker Initiative: http://www.carbontracker.org/
- UCL Institute for Sustainable Resources: http://www.bartlett.ucl.ac.uk/sustainable
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/.

According to Carbon Tracker Initiative (Carbon Tracker Initiative, 2011), CCS would increase the percentage of burnable fossil fuel reserves. However this would apply only to the power generation sector, where coal and gas are employed, and would not directly affect the transportation sector that is mainly based on oil. Carbon Tracker Initiative initially referred to the carbon budget estimated by M. Meinshausen et al. (2009) (565GtCO_2 by 2050) and estimated the total known fossil fuels reserves to be equal to 2795 GtCO_2, composed by 65% coal, 22% oil and 13% gas. Carbon Tracker Initiative has estimated fossil fuels reserves by looking at data from Raw Materials Group (coal) and from Evaluated Energy (oil and gas). CO_2 emission factors have been estimated by means of IPCC guidelines. They conclude that because the carbon content of the known reserves is almost five times higher than the carbon budget, then 80% of fossil fuel reserves will be "unburnable".

Carbon Tracker Initiative then released a second report on the topic of unburnable carbon in 2013. In this second report, the carbon budget is higher (900GtCO_2 for an 80% probability to stay below 2°C and 1075GtCO_2 for a 50% probability) as greater reductions in non-CO_2 emissions (e.g. methane and nitrous oxide) have been assumed. Various emissions pathways have been employed in the analysis, and the climate outcome for each of them has been validated by means of the model MAGICC. Negative emissions were not considered while CO_2 emissions from land use were assumed to be 7.3% of total CO_2 emissions. According to Carbon Tracker Initiative, applying the scenario proposed by IEA on CCS (IEA, 2013) would extend the budget by 125GtCO_2 between 2015 and 2050. Moreover, under that scenario a total of nearly 3800 CCS projects would need to be operating by 2050. According to Carbon Tracker Initiative, with full investment in CCS, this technology would extend the carbon budget for the 2DS by 12-14%. These results have been confirmed in a more recent report (Carbon Tracker Initiative, 2015).

The UCL Institute for Sustainable Resources released two publications focussing on unburnable carbon. While the first paper focused on oil only (McGlade and Ekins, 2014), the second paper considered all types of fuels and their geographical distribution (McGlade and Ekins, 2015).

The first UCL publication on the topic of unburnable carbon (McGlade and Ekins, 2014) focused on the volumes of oil that cannot be used up to 2035. The emissions of CO_2 have been limited to 425 ppm in all years up to 2100. According to IEA, this is equivalent to 450 ppm GHG with 50% probability to stay below 2 °C raise. Two scenarios have been simulated. In the first scenario a global effort to mitigate emission is assumed and CCS is widely adopted while the second scenario assumes that CCS never becomes available. The results estimate that 500-600 billion barrels (Gb) of current 2P reserves should not be burnt. The lower estimate (500Gb) excludes CCS from the energy scenario while the higher estimate (600Gb) 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 (2014), 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 (McGlade and Ekins, 2015) considers all fuels and their geographical location. The model employed was TIAM-UCL in combination with the oil-field model BUEGO, while the MAGICC model has been used to estimate the approximate temperature rise trajectories. The climate module of TIAM-UCL module is used to restrict the temperature rise to certain levels and is calibrated to the MAGICC model. The proposed scenarios include three mitigation scenarios (2, 3 and 5°C increase of temperature) and two technology scenarios (with and without CCS). The results for the 2°C scenario are summarised in Table 3, 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 (2015), 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.

Table 3. Unburnable reserves before 2050 for the 2°C scenarios with and without CCS (modified from McGlade and Ekins (2015). Energy units.

		With CCS		Without CCS	
Fossil fuel	**Overall reserves**	**Unburnable**	**Burnable**	**Unburnable**	**Burnable**
Oil (Gb)	1306	431 (33%)	875 (67%)	449 (34%)	857 (66%)
Gas (Tm3)	194	95 (49%)	99 (51%)	100 (52%)	94 (48%)
Coal (Gt)	999	819 (82%)	180 (18%)	887 (89%)	112 (11%)

Table 4. Unburnable reserves before 2050 for the 2°C scenarios with and without CCS (modified from McGlade and Ekins (2015). Unit: GtCO2

$GtCO_2$		With CCS		Without CCS	
Fossil fuel	**Overall reserves**	**Unburnable**	**Burnable**	**Unburnable**	**Burnable**
Oil	531	175	356	183	349
Gas	418	205	213	215	202
Coal	2664	2185	480	2366	299
Overall	**3613**	**2565 (71%)**	**1049 (29%)**	**2764 (77%)**	**850 (23%)**

In essence both the Carbon Tracker Initiative and McGlade/Ekins suggest that CCS makes little difference to the extent of unburnable carbon. However, these scenarios are not the only resource that can be used to assess the impact of CCS on fossil fuel use. As part of the Fifth Assessment Report, the International Panel on Climate Change (IPCC) made an open call to collect energy projections coming from various integrated assessment models. A detailed analysis on the scenarios included in AR5 Database as part of the EMF27 project is presented here in section 3.4 to gain a broader understanding of the impact of CCS across a variety of models.

3.3 Integrated Assessment Models

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

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

3.3.1 Transformation of the energy sector

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 (Bassi et al., 2015).

In these studies decarbonising electricity generation is a core component of cost effective mitigation strategies. This is usually accompanied by electrification of end-use sectors, particularly heating of buildings and transport. In most of the integrated modelling scenarios which are part of the IPCC Fifth Assessment Report Database (AR5), decarbonisation happens first in electricity generation, followed by industry, buildings, and transport (IPCC, 2014c).

In this context, the importance of CCS is evident. This technology is applicable to power generation (and upstream and downstream industry) and could enable countries to continue to include fossil fuels in their energy mix (IPCC, 2005) and therefore can unlock assets that would otherwise be stranded (Clark and Herzog, 2014, J. Gale and Dixon, 2014). For example, the IEA (IEA, 2013) has proposed a roadmap to assist governments and industry in integrating CCS in their emissions reduction strategies. This roadmap would enable to store a total cumulative mass of approximately 120 $GtCO_2$ between 2015 and 2050.

3.3.2 Carbon removal technologies depicted in IAMs

Carbon removal technologies include carbon positive, near neutral and negative technologies (Gibbins and Chalmers, 2011). CCS is carbon positive when e.g. applied to processes that produce product containing fuel while is carbon negative when e.g. applied to plant producing carbon free products such as electricity, hydrogen or heat.CCS can be combined with Negative Emission Technologies (NET) in order to generate negative emissions. NETs include afforestation, agricultural soil carbon storage, biochar, bioenergy with carbon capture and storage (BECCS), direct air capture, ocean liming, enhanced weathering, and ocean fertilisation. The technical potential of NET has been estimated to be 120 $GtCO_2$ until 2050. This amount of CO_2 represents an extension of the 2050 carbon budget by 11-13% for a 50-80% probability to remain below 2 °C temperature increase (Caldecott et al., 2015). Estimations of NET potential until 2100 are affected by great uncertainties, especially regarding availability and accessibility of geological storage, and are therefore difficult to estimate.

BECCS technologies are part of NET and combine biomass with CCS, for processes in the bio-refining sector, biofuel sector, power and heat sector and in industrial processes for the cement, steel and paper sector. Future projections of BECCS potential estimate negative greenhouse gas emissions up to $10.4GtCO_2eq/yr$ by 2050 (Koornneef et al., 2012). These results come from Biomass Integrated Gasification Combined Cycle (BIGCC) and Circulating Fluidised Bed (CFB) combined with CCS, while other technologies result in lower negative emission potentials.

3.4 Review of a model comparison exercise: EMF27

This section provides an overview of results from the EMF27 scenarios, focusing on the impact of CCS on burnable/unburnable carbon. The section describes the project, the models and the scenarios and reviews the assumptions on CCS modelling, cost and storage. However the section does not propose a new modelling tool.

3.4.1 Description of the project and models involved

The Scenario Database of the IPCC Fifth Assessment Report (AR5) includes 31 models and 1184 scenarios (IPCC, 2014d). The scenarios were collated by means of an open call and they all meet the following requirements:

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

The majority of the scenarios were provided via model inter-comparison exercises, having the purpose of comparing the outcome of various models for the same scenarios. The scenarios have been classified within the AR5 Scenario Database according to their climate target, radiative forcing levels, scale of deployment of carbon dioxide removal, availability of mitigation technologies and policy configurations (IPCC, 2014d). In order to overcome issues related with the representation of radiative forcing in the single models, the emissions of all the scenarios included in the database were run through the single climate model MAGICC 6.3 in order to correlate CO_2-equivalent concentration, radiative forcing and climate outcome between scenarios.

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

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

Specifically, the Energy Modelling Forum (EMF) 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 (Kriegler et al., 2014b). Some of the models included in EMF27 have also been analysed in AMPERE2 (Riahi et al., 2014) and AMPERE 3 (Kriegler et al., 2014a). The main properties of the EMF27 models have been summarised in Table 5 and include equilibrium concept, solution dynamic, time horizon, land use sector representation and coverage of greenhouse gases.

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

Table 5. General properties of the models included in the EMF27 project (modified from Kriegler et al. (2014b))

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

3.4.2 Scenarios investigated in EMF27

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

The climate mitigation scenarios include a baseline scenario, where future policies dedicated to climate change mitigation are not pursued, and two climate mitigation scenarios. The mitigation scenarios “450 ppm” and “550 ppm” aim to reach atmospheric GHG concentration at levels of respectively 450ppm CO_2eq and 550 ppm CO_2eq by 2100 (Kriegler et al., 2014a).

The technology scenarios include a series of options from the availability of a full portfolio of technologies to specific technologies limitation to reliance on conventional fossil fuel technologies only. In this report three technology scenarios have been selected in order to analyse the role of CCS (Riahi et al., 2014):

- The full technology scenario (“Fulltech”)
- The conventional solutions scenario (“Conv”)
- The scenario without CCS (“noCCS”).

These scenarios have been reported in numerous publications (Krey et al., 2014, Kriegler et al., 2014b, Riahi et al., 2014) however the amount of information is limited and repeated throughout the different articles. According to Riahi et al. (2014), 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.

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

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

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

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

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

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

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

These numbers highlight the importance of CCS in a climate change mitigation scenarios and also confirm what was previously reported by Kriegler et al. (2014b) and Krey et al. (2014), which both reported that most of the models were not able to run the noCCS scenario under the climate mitigation scenario 450ppm. 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 (van Vliet et al., 2014). The availability or otherwise of CCS has the strongest impact on carbon prices (Krey and Riahi, 2009) and on the variation of mitigation costs (Kriegler et al., 2014b, Riahi et al., 2014).

3.4.3 Review of CCS modelling in EM27

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

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

However, in Koelbl et al. (2014a) 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.

3.4.4 Storage availability assumptions for CCS

Table 6 summarises some of the CCS modelling assumptions (Koelbl et al., 2014a). Most of them refer to the storage of CO_2. The assumptions on the availability of CCS include nowadays (4 models), 2020 (7 models) and 2030 (1 model). Half of the models assume unlimited storage capacity while most of them do not include a limit to the maximum storage rate. Therefore this means that most of the models are not including limitation to both storage rate and capacity. The number of storage types varies from 1 to 11, where only one model includes all the types of storage sites (on and offshore EOR, depleted gas, undepleted gas, depleted oil, as well as ECBM onshore, and two types of aquifers).

Table 6. CCS properties of some of the model included in the EMF27 project (modified from Koelbl et al. (2014a))

Model name	Availability	Is there a maximum storage rate	Number of storage types	Storage capacity in $GtCO_2$
BET	2020	No	No differentiation	3538
FARM	2020	No	No differentiation	Unlimited
GCAM	2020	No	2	7178
GRAPE	2020	No	4	~20000
IMACLIM	Always	No	No differentiation	Unlimited
IMAGE	2005	No	11	5856
MERGE	2020	No	No differentiation	Unlimited
MESSAGE	2020–2030	No	No differentiation	Unlimited
POLES	2015	No	2	Unlimited
REMIND	2020	Yes	No differentiation	3959
TIAM-WORLD	2030	No	8	11600
WITCH	Always	No	No differentiation	Unlimited

3.4.5 Cost assumptions for CCS

Among the sixty-four references listed in the AR5 database webpage, eleven explicitly refer to cost or economic evaluations of CCS technology performed by means of integrated assessment models. Most of these papers include emission prices and global aggregate mitigation costs rather than capture or storage prices. Only one reference (Akimoto et al., 2012) reports the marginal abatement cost of CCS, reported in Figure 1.

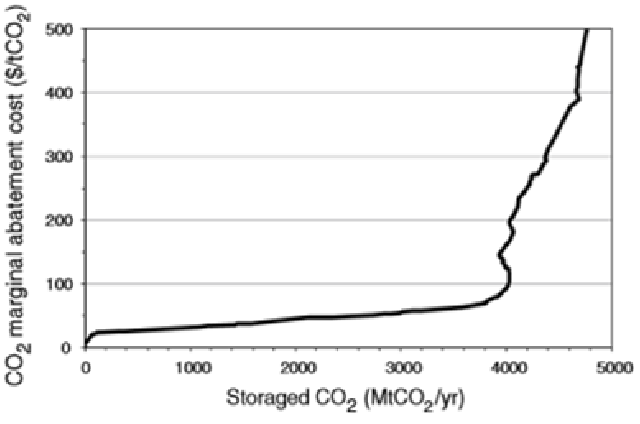


Figure 1. Interrelationship between cost-effective CCS measures and CO_2 MAC of 2030 on a global scale (Akimoto et al., 2012)

Annex III of the IPCC report "Climate Change 2014: Mitigation of Climate Change" (IPCC, 2014a) reports the following costs for CCS combined with power generation:

- Overnight capital expenditure: 2000-4000 USD2010/kW
- Construction time: 4-5 years

- Fixed annual operation and maintenance cost: 13-58 USD2010/kw
- Variable operation and maintenance cost: 8.3-15 USD2010/kw.

Furthermore, Investment costs and efficiencies for power generation combined with CCS have been estimated by Koelbl et al. (2014b) and the results have been reported in Table 7 and Table 8 for capture and transportation of CO_2, respectively.

Table 7. Ranges of investment costs, efficiency and efficiency loss (p.p. percentage points of capture efficiency loss) for power plants and capture unit (modified from Koelbl et al. (2014b)). Investment costs are expressed in USD2005 per kWe

		2020				2050			
		Investment costs		Efficiency		Investment costs		Efficiency	
		w/o CCS	Capture	w/o CCS (%)	Capture (p.p.)	w/o CCS	Capture	w/o CCS (%)	Capture (p.p.)
IGCC Coal	Min	749	219	38	4	527	88	40	3
	Max	2839	1212	52	11	2705	1109	58	9
IGCC Biomass	Min	1161	548	32	5	817	273	35	3
	Max	3251	902	50	11	3098	825	54	7
CCGT	Min	436	266	48	6	354	128	50	5
	Max	949	1013	64	11	865	867	67	9

Table 8. Ranges of CO_2 transport costs per distance category (Koelbl et al., 2014b)

Distance in km	<50	50–200	200–500	500–2000	2000–∞
Min USD2005/t CO_2	0.05	0.11	0.68	1.6	6
Max USD2005/t CO_2	3.2	18	49	200	216
Min USD2005/t CO_2/km	0.002	0.001	0.002	0.001	0.002
Max USD2005/t CO_2/km	0.13	0.144	0.139	0.16	0.072

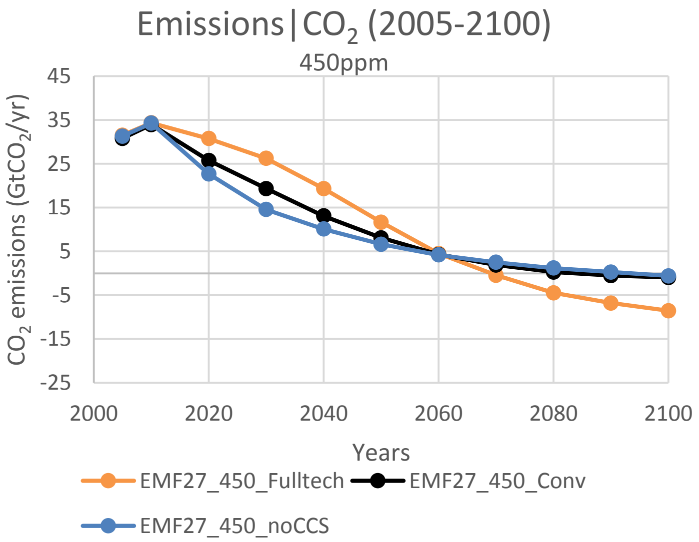
It is recognised the data presented in Table 7 are representative of only a small subsection of potential CCS technologies, and exclude coal with either post-combustion or oxy-combustion capture technologies. Similarly, the near term, i.e., 2020, investment costs and efficiency penalties for the technologies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

3.5 Overview of unburnable carbon and CCS in EMF27 results

3.5.1 Emissions and capture of carbon dioxide

Figure 2 reports the emissions of the three selected technology scenarios (Fulltech, Conv, noCCS) for a 450ppm (left) and 550ppm (right) 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.



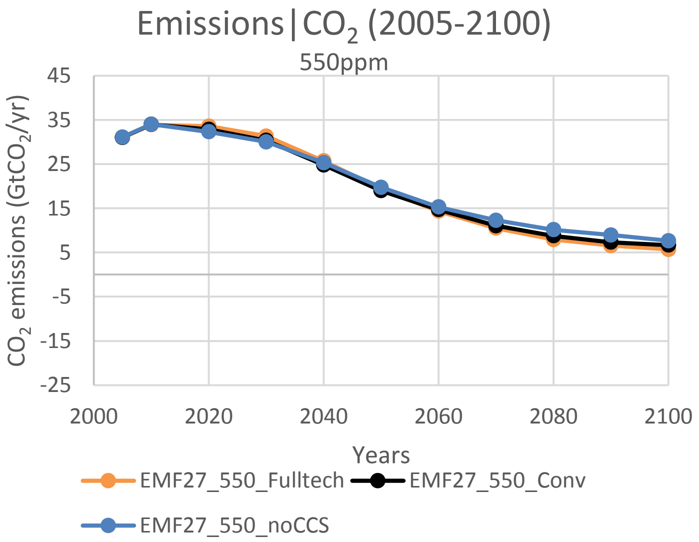


Figure 2. Average global emissions of CO2 (GtCO2/yr) for 450 ppm and 550 ppm scenarios across EMF27 models

Figure 3 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.

There are some counter-intuitive results in Figure 3. Firstly, the total level of capture and storage achieved in the 450ppm (i.e. more climate-constrained) scenario is lower than that of the 550pm scenario. Secondly, on comparison of the Conv and Fulltech scenarios in the 450ppm case, it is apparent that Conv utilises CCS less than Fulltech, which is unexpected because Conv has more constrained access to the alternatives to CCS for decarbonisation. This feature is not present in the 550ppm scenario. The data provided from EMF27 studies is not sufficient to pinpoint the cause of these results, but two possibilities are put forward:

- In the 450ppm scenario the bioenergy resource is constrained. This may limit the potential for BECCS approaches delivering negative emissions.
- In the 450ppm scenario the capture efficiency may lead to sufficient emissions being released to make fossil fuelled CCS an unattractive option.

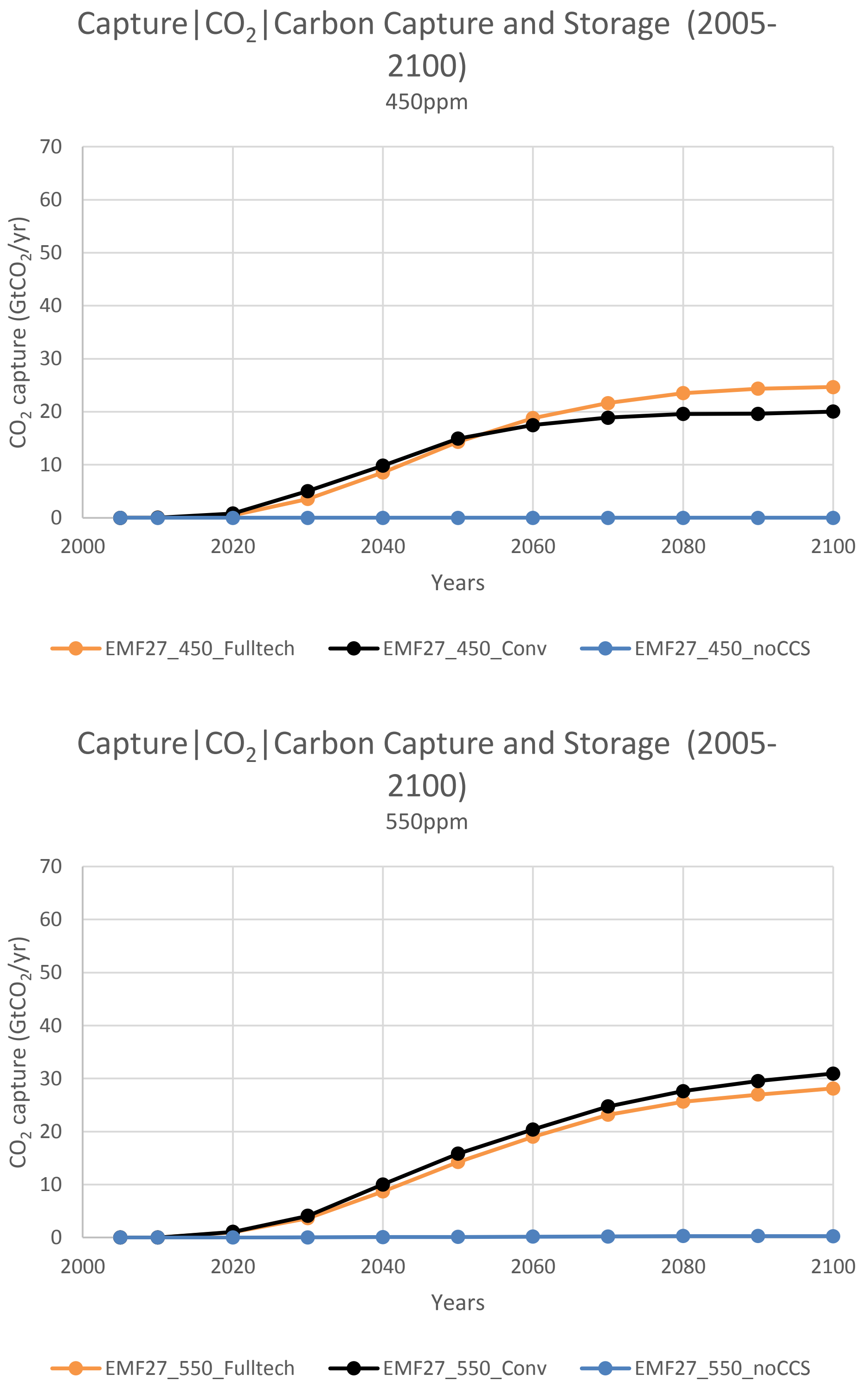


Figure 3. Average capture of CO2 (GtCO2/yr) for 450 ppm and 550 ppm scenarios across EMF27 models

3.5.2 Fossil fuel consumption with and without CCS

Figure 4 reports the fossil fuel usage for the three technology scenarios for all fossil fuels for the 450ppm scenario. It also splits out share of each fossil fuel at snapshot years of 2050 and at 2100. The error bars on the top chart represent the minimum and maximum values from all of the models providing a solution at each time period. There is a large variation of model results, 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 Figure 4, it is clear that the utilisation of fossil fuel drops in all scenarios, indicating the challenges faced by these energy forms over coming decades and competition from renewable sources of energy under climate change mitigation scenarios. This is in contrast with what has been reported by IEA (2014b) and also by BHP Billiton (2015), who still forecast a growing fossil fuel demand in the future . However, the range of outcomes (i.e. the error bars) 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 fossil fuel use drops rapidly to very low levels late in the century. From this 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.

With regard to the lower charts in Figure 4, gas and coal are the fuels where gains are made 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.

Similarly to Figure 4, Figure 5 reports the projections of fossil fuel usage for the three technology scenarios for the 550ppm scenario. As expected, the presence of CCS in these scenarios unlocks more fossil fuel reserves than the 450ppm scenario, though at the expense of the climate, manifested as a higher probability of exceeding 2^{0}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 by 2050 and by 2100 across EMF27 models has been reported in Table 9. Values from individual models are presented in Figure 6 and Figure 7, showing the range of outcomes observed. Furthermore, the range of outcomes for each fossil fuel individually are presented in the Annex.

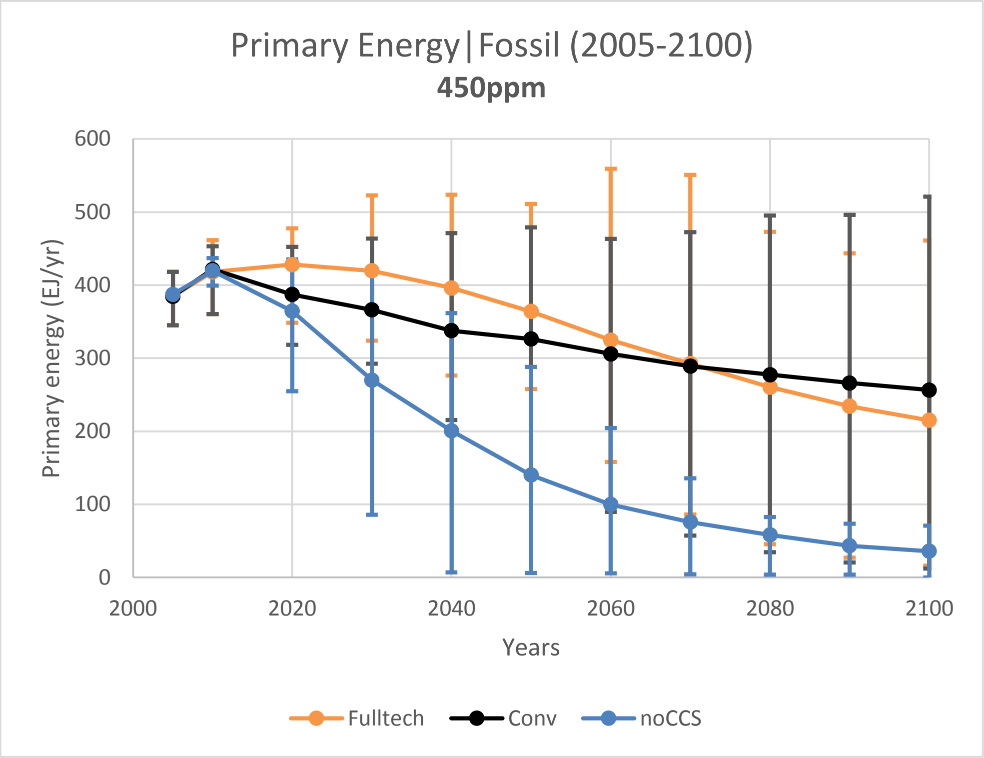
Table 9. Average primary energy usage in 2050 and 2100 across EMF27 models (EJ)

Climate mitigation scenario	**450 ppm**			**550 ppm**		
Technology scenario	Conv	Fulltech	noCCS	Conv	Fulltech	noCCS
Primary Energy (fossil, EJ) - 2050	326	364	140	474	457	299
Primary Energy (fossil, EJ) - 2100	256	215	36	478	437	143

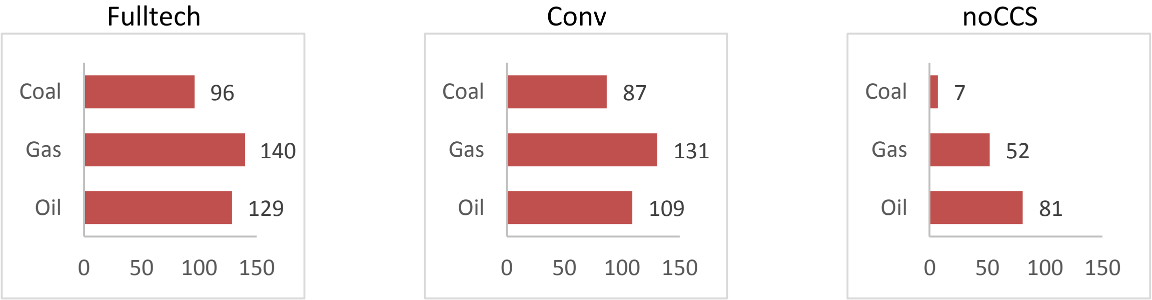
In summary, Table 10 shows the average cumulative consumption of fossil fuels over two timeframes (2005-2050 and 2005-2100) observed across the models. Clearly CCS has a very significant impact on consumption post 2050, enabling 65% of reserves to be used instead of 33% on the scenario without CCS.

Table 10. Cumulative fossil fuel consumption in the timeframes 2005-2050 and 2005-2100. Results reported in GtCO2, EJ and % of reserves. GtCO2 includes both emitted and abated CO2. Reserves 'low' estimate from McCollum et al. (2014). "woCCS" scenario corresponds to the noCCS scenario while "wCCS" scenario corresponds to the Fulltech scenario.

	$GtCO_2$		**EJ**		**% of reserves**	
	woCCS	wCCS	woCCS	wCCS	woCCS	wCCS
2005-2050	953	1,347	13,166	18,356	26%	37%
2005-2100	1,208	2,380	16,823	32,376	33%	65%



2050



2100

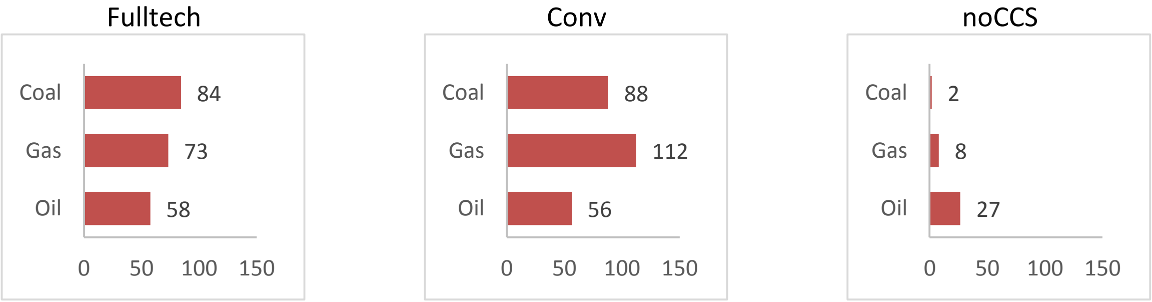
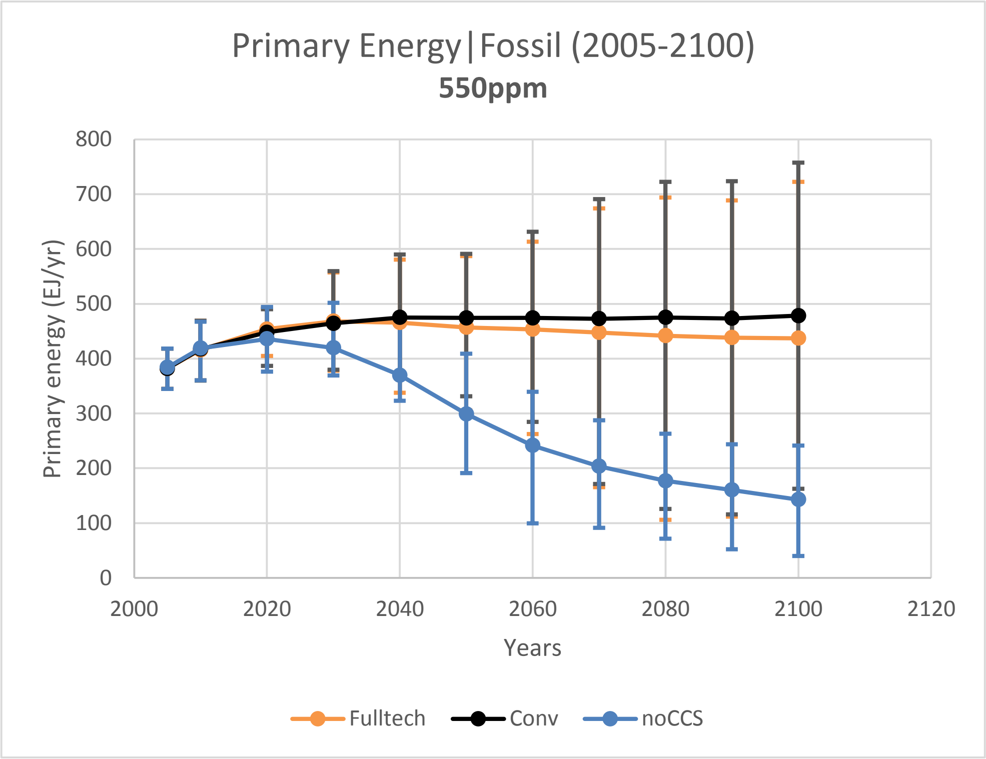
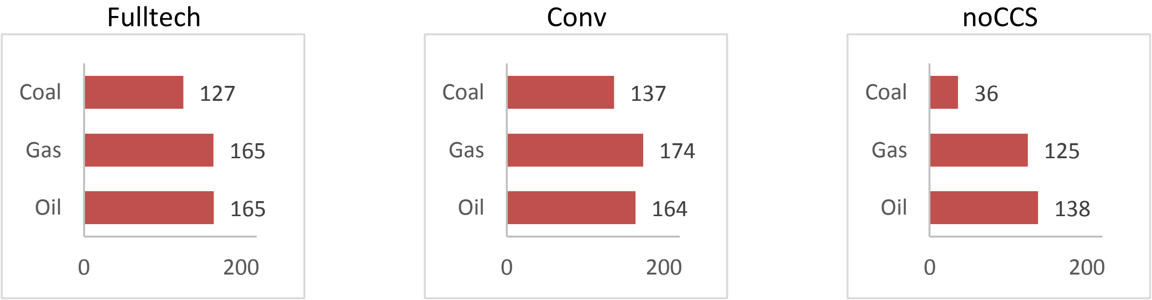


Figure 4. Total primary energy from fossil fuel use (EJ/yr, top) and fuel-type shares of single fossil fuel usage in 2050 and 2100 (EJ/yr, bottom) for the three technology scenarios (data for 2005: oil 164-167 EJ/yr, gas 98-99 EJ/yr, coal 121-122 EJ/yr). Values are averages across the EMF27 models.



2050



2100

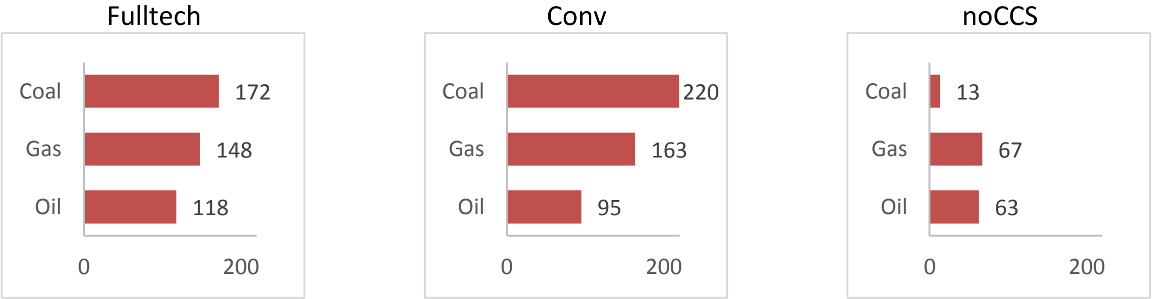
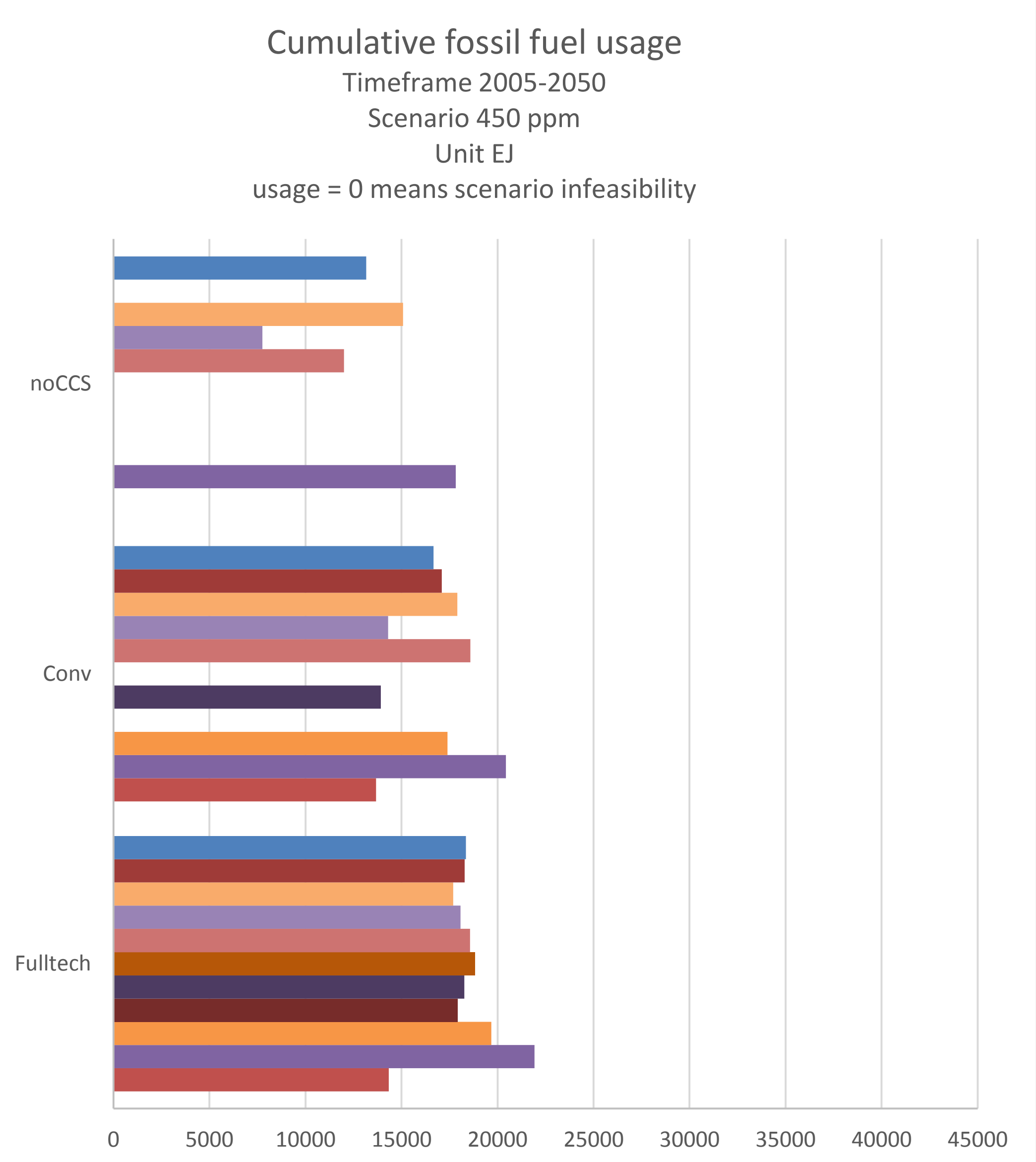
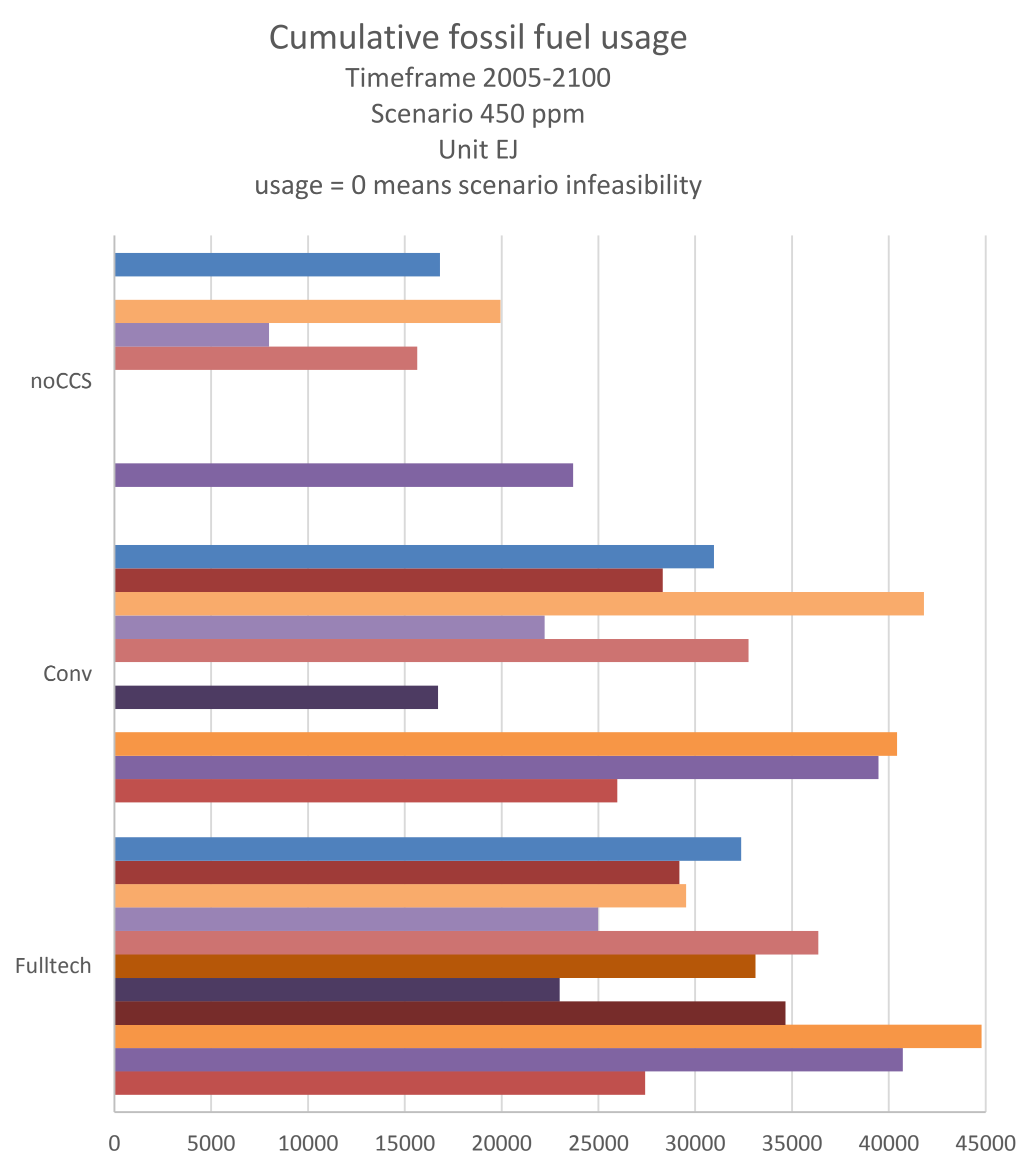


Figure 5. Total primary energy from fossil fuel use (EJ/yr, top) and distribution of single fossil fuel usage in 2050 and 2100 (EJ/yr, bottom) for the three technology scenarios (data for 2005: oil 164-167 EJ/yr, gas 98-99 EJ/yr, coal 121-122 EJ/yr). Values are averages across the EMF27 models.



	Fulltech	Conv	noCCS
🟦 Average	18355	16664	13166
🟥 WITCH	18282	17098	0
🟧 TIAM-WORLD	17695	17909	15083
🟪 REMIND 1.5	18073	14295	7753
🟥 POLES	18561	18588	12002
🟧 MESSAGE V.4	18832	0	0
🟪 MERGE	18267	13919	0
🟥 IMAGE 2.4	17901	0	0
🟧 IMACLIM V1.1	19671	17391	0
🟪 GCAM 3.0	21926	20434	17825
🟥 BET 1.5	14342	13674	0

Figure 6. Emissions from fossil fuel usage according to the EMF27 models (scenario 450 ppm timeframe 2005-2050)



	Fulltech	Conv	noCCS
■ Average	32369	30962	16821
■ WITCH	29177	28329	0
■ TIAM-WORLD	29523	41808	19949
■ REMIND 1.5	24977	22223	7986
■ POLES	36352	32750	15648
■ MESSAGE V.4	33096	0	0
■ MERGE	22992	16720	0
■ IMAGE 2.4	34659	0	0
■ IMACLIM V1.1	44794	40420	0
■ GCAM 3.0	40718	39468	23702
■ BET 1.5	27406	25983	0

Figure 7. Emissions from fossil fuel usage according to the EMF27 models (scenario 450 ppm timeframe 2005-2100)

3.6 Discussion

While the results presented above clearly point to the importance of CCS in underpinning the role of fossil fuels in future low carbon energy systems, they still leave a significant question unanswered: why CCS is not adopted in greater quantities. Figure 1 suggests that the marginal cost of CCS across the entire possible range of fossil fuel reserves (i.e. up to ~4000GtCO$_2$) is less than US$100/tCO$_2$. However, as shown in Figure 8, the marginal cost of abatement produced in the 450ppm 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 the figure for the 450 ppm and the 550 ppm scenario is well above the cost of carbon assumed by the IEA (2014a) for the 450 Scenario ($140/tCO$_2$ in most OECD countries in 2040). However it is worth noting that the costs here reported is not an assumption of the EMF models but rather an output of the models.

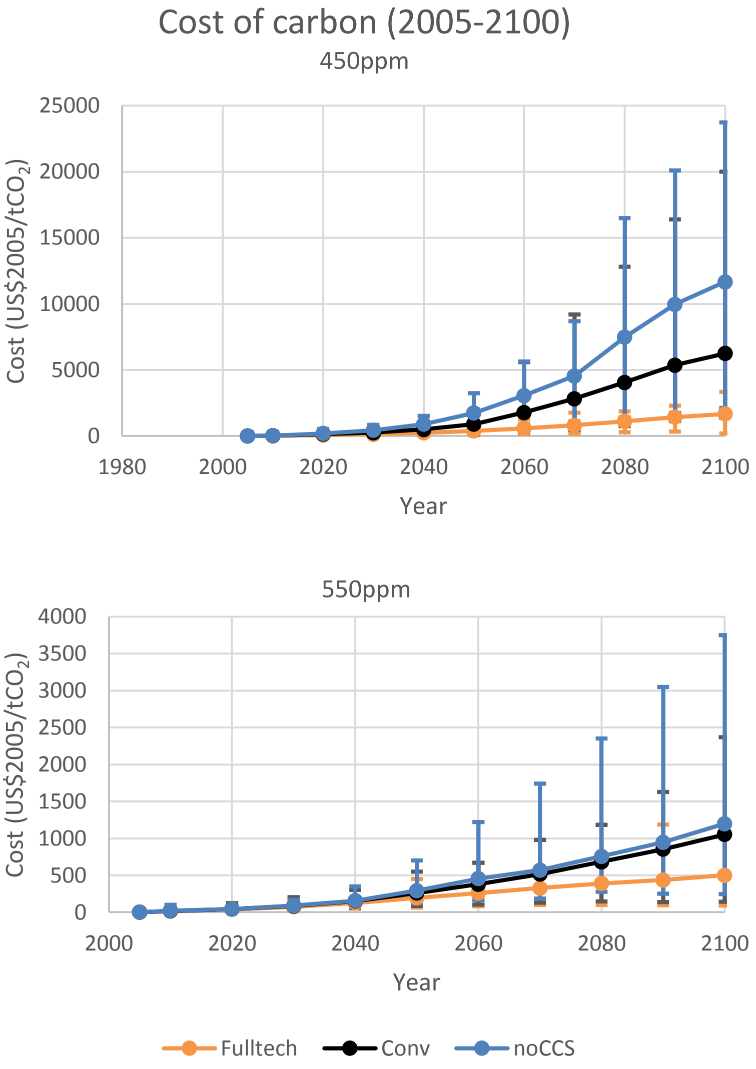


Figure 8. Cost of carbon (CO2) for 450 ppm and 550 ppm scenarios

One possible explanation for this phenomenon is that the rate of uptake of CCS-equipped facilities in limited in the models. From Table 6 we can conclude that CCS uptake is not limited by storage capacity or growth thereof. Therefore, another option is a limit on the rate that CCS-enabled facilities can be built (e.g. maximum capacity or activity growth rates, maximum new capacity installation by region, etc), or how quickly infrastructure related to CCS can be built. However, the detailed review produced on CCS assumptions in the relevant models (Koelbl et al., 2014a) did not cite any limits on uptake of these technologies, and further personal communications with the relevant modellers confirmed that any such limits were likely to be non-binding, particularly in later model years.

This report hypothesises that the constraint on CCS is therefore not cost related or supply chain related (i.e. build rate limited), particularly in later years. The key remaining possibility is that the residual emissions from CCS make it an unfavourable option in climate change mitigation scenarios; even these low levels of emissions are sufficiently high to conflict with extremely constrained global carbon budgets. This hypothesis is supported by previous works produced by UKERC (Anandarajah et al., 2008) and IEAGHG (IEAGHG, 2014a), who both reported a capture rate of 90% for coal based power generation with CCS. IEAGHG (2014a) 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 oxycombustion 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. The lack of data regarding state of the art capture rates of CCS plants makes the evaluation? Challenging.

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

4 CO_2 geo-storage; state of the evidence

In section 3 the impact of CCS on fossil fuel consumption has been investigated. Table 6 sets out the assumptions in various IAMs in EMF27 on the availability of geo-storage capacity. Following from this, this section reviews state of knowledge on the technical barriers to CCS deployment, focusing on the storage of CO_2 in subsurface geologic units. The intention of this investigation is to test the assumption that geo-storage capacity are indeed unlimited in practice, or if the IAM modelling community should reconsider the representation of this resource in the models.

The technical barriers to carbon capture and transport components of the CCS chain were evaluated in IEAGHG (2012a). There it was found that with sufficient financial incentive there would be few inherent roadblocks to the development of a CCS industry. For example, the rate of deployment implied by the IEA CCS Technology Roadmap of 2011 was lower, and in some cases far lower, than, e.g., the production of coal and gas fired power systems over recent decades, indicating that maximum construction rates are not being violated. However, some specific barriers were identified, including availability of specialized turbines for pre-combustion technologies was significant for capture. Also, competition for pipeline construction and petroleum engineering expertise between the CCS and general oil and gas industry were highlighted as key concerns for transport and storage.

For the subsurface storage component, however, there are few industrial analogues that can be made for CO_2 injection at the scales implied by technological pathways and integrated assessment models used by the IEA and IPCC. The focus of this review is thus the state of knowledge on global CO_2 storage capacity and its regional distribution with an emphasis on the capacity accessible in the near term. In the following we provide an in depth analysis of the methods for calculating the CO_2 storage resource. A summary is provided of current estimates of the globally distributed storage resource. This section ends with a discussion of the state of knowledge of the potential for local limitations in the near term deployment of CO_2 storage from storage capacity constraints.

4.1 Global storage potential

4.1.1 Overview of calculating the storage resource

Techniques applied for storage resource estimation vary depending on the scale, application, and information available for making the assessment. The size scales from largest to smallest can be classified, with some overlap, as: global, national, sedimentary basin, specific storage site or field, Table 11 (Bachu, 2015, Bachu et al., 2007, Blondes et al., 2013, Bradshaw et al., 2007, CSFL, 2007). A recent review of the historical development and current status of such calculations is provided by Bachu (2015). Current efforts assessing nationwide or regional CO_2 storage resources use evaluation methods that fall into two general categories – static and dynamic.

Table 11. Size scale and data needs for capacity estimation methodologies. See Bachu (2015), Bachu et al. (2007), Bradshaw et al. (2007).

Scale	Method Type	Data requirements	Example references
Global	Static	Approximations based on available national data	*Hendriks and Graus (2004); Benson et al. (2012); Dooley (2013); Cook and Zakkour (2015)*
National	Static	General geology	*USGS (2013); USDOE and NETL (2012); EU GeoCapacity (2009); Halland et al. (2011)*
Sedimentary basins	Static, dynamic	Geology, compartmentalization, boundary conditions	*USGS (2013); Zhou et al. (2008); Szulczewski et al. (2012); USDOE and NETL (2012);*
Fields	Dynamic, reservoir simulation	Full reservoir characterisation: Seismic, well logs, cores, well tests	Garnham and Tucker (2012); Lindeberg et al. (2009)

4.1.2 Capacity for saline aquifer storage – Volumetric, no pressure constraints

Static techniques use a product of the total pore volume available in a given storage site, region, etc. with an efficiency that can take into account a number of variables – estimated sweep of the reservoir, connectivity, etc. A general formulation of the approach calculates the mass of CO_2 that may be stored, M_{CO_2}, as the product of averages of the CO_2 density ρ, aereal extent of the considered storage location, A, height of the reservoir, H, porosity ϕ, and finally, the efficiency factor, E,

$$M_{CO2} = E\rho AH\phi. \qquad \text{Eq. 1}$$

The efficiency factor noticeably becomes the key uncertainty in this type of calculation, and has been used to incorporate a range of processes affecting the overall CO_2 sweep within the reservoir. Fluid dynamics based models estimating efficiency have been developed to incorporate the effects of capillary trapping and bouyancy on CO_2 sweep and migration (Blondes et al., 2013, Macminn et al., 2010, Okwen et al., 2010). Numerical simulation has also been used in IEAGHG (2009) to derive representative efficiency values for characteristic lithologies. Efficiency generally ranges from 1 – 10% of the pore volume in the formation.

These so-called volumetric techniques form the basis for most national storage resource assessments (EU GeoCapacity, 2009, USGS, 2013). There has not been a coordinated global resource assessment, but estimates have been periodically published based on an analysis of national and regional assessments (Benson et al., 2005, Benson et al., 2012, Cook and Zakkour, 2015, Dooley, 2013, IEAGHG, 2011), and these compilations can thus also be thought of as volumetric estimates of global storage capacity.

4.1.3 Imposing pressure constraints on the volumetric approach

More recently, static estimates that also incorporate the impacts of pressure build-up have been developed (Allinson et al., 2014, Gorecki et al., 2015, Thibeau and Mucha, 2011, Zhou et al., 2008). In this approach, the reservoir system is assumed to be closed – no fluid communication across lateral and vertical boundaries – and the pressure response calculated using the compressibility of fluid, β_w, and rock, β_p, material. Following from Zhou et al. (2008), the volume of CO_2 that can be accommodated before exceeding a limiting pressure, ΔP, is given by a simple mass balance,

$$M_{CO_2} = \rho \left(\beta_p + \beta_w \right) \Delta P \, V_f \, , \qquad \text{Eq. 2}$$

or in terms of a storage efficiency,

$$E = (\beta_p + \beta_w) \Delta P . \qquad \text{Eq. 3}$$

Ranges of values for the brine and consolidated rock compressibility, and allowable pressure increase before caprock fracturing becomes likely are provided in Table 12, adapted from Thibeau and Mucha (2011). The assumption that a system acts a closed volume for the duration of the injection will limit storage efficiency at 1 km depth to less than 1% of the pore volume of the system due to pressure effects alone. This is in marked contrast to the range of volumetric based efficiency values with lower bounds at 1% of the pore volume.

Table 12. Range of pressure limited storage efficiency under the assumption of storage in a closed volume, Equation 3. Adapted from Thibeau and Mucha (2011).

Terms for calculating pressure limited efficiency, Equation 2	Range of values for consolidated rocks
Water compressibility, β_w [Pa^{-1}]	$3 - 5 \times 10^{-10}$
Rock compressibility, β_p [Pa^{-1}]	$10^{-10} - 10^{-9}$
Allowable pressure increase, ΔP [Pa] per kilometer depth	$2\text{-}8 \times 10^{6}$
Pressure limited storage efficiency, *E* [% pore volume] per kilometer depth	0.1 – 1.2

4.1.4 Calculating capacity for saline aquifer storage – Dynamic models

Dynamic methods encompass those techniques which model the time-transient movement of CO_2 injected into a storage site. They provide time-varying resource estimates, accounting for the limitations that pressure build-up and dissipation in the reservoir will place on allowable injection rates. They are also accepted to provide the most realistic estimates of a true storage capacity, while demanding more information about the storage site than is generally required by the volumetric evaluations.

Unlike the static techniques there is no standard procedure for producing a dynamic estimate. Simple approaches amenable for use in nationwide capacity estimates include the semi-open model of Zhou et al. (2008) and the models applied in Szulczewski et al. (2012). More commonly, commercial reservoir simulation (3D numerical simulation on a geologic model) is used to evaluate storage capacity at the basin and field scale (Gorecki et al., 2015, Huang et al., 2014, IEAGHG, 2014b, Jin et al., 2012, Winkler et al., 2010).

4.1.5 Analysis of estimates produced by the different techniques

A number of studies compared the results of capacity estimation using these different methodologies at a range of scales from specific fields to an entire region (Allinson et al., 2014, Bader et al., 2014, Goodman et al., 2013, Gorecki et al., 2015, IEAGHG, 2014b, Thibeau and Mucha, 2011, Winkler et al., 2010). The estimates made using the different methodologies are plot against the average of the estimates in Figure 9. As anticipated, static estimates incorporating pressure constraints are systematically lower than volumetric estimates ignoring limitations imposed by pressure build-up. IEAGHG (2009) estimates that static pressure limited estimates based on Equation 3 are at least an order of magnitude lower than volumetric capacity estimates, and this is fairly typical of the data in Figure 9.

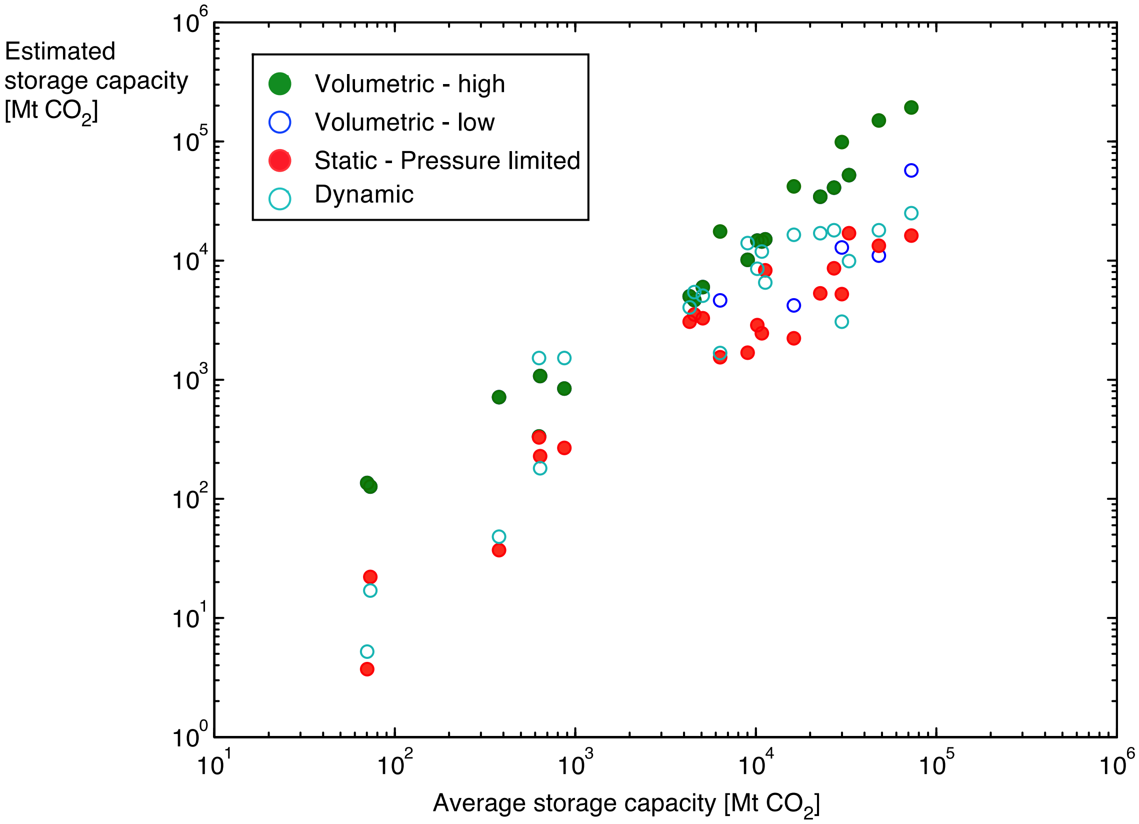


Figure 9. Comparison of CO_2 storage capacity estimated from fields and regional basins of varying size using three different techniques. Where there is no point for the low volumetric estimate, the study only reported a single value. Data from Winkler et al. (2010), Goodman et al. (2013), Bader et al. (2014), Gorecki et al. (2015), Thibeau and Mucha (2011)

Figure 10 shows a cross correlation plot – the capacity estimate of a field using one technique is plot against the estimate of the same field using a second technique - of the results from the different methods. There are only weak positive correlations among all of the comparisons. This is reflected in both the general upward slope of the data in Figure 9 (note the log-log scale), and the significant scatter – an order of magnitude and greater spread at any given averaged value of storage.

This suggests that useful capacity estimates can not readily be derived from volumetric estimates, i.e. volumetric estimates cannot be appropriately corrected for pressurization effects. Thibeau and Mucha (2011) suggest the use of the closed system approximation, Equation 3, for initial ranking purposes. On the one hand, this may lower expectations about the presence of a suitably large field as occurred in the case of the France Nord Project (Bader et al., 2014). The lack of correlation, however, with dynamic estimates of storage capacity suggests that such a comparison between fields within an order of magnitude of each other in size is unlikely to provide an accurate ranking.

The scatter in this data reflects the complex nature of the response of highly heterogeneous and variable geological systems to the injection of CO_2. One might expect the comparison of static pressure-limited and volumetric estimates to have a stronger correlation given the nature of Equation 3. Even in this case natural variability in rock compressibility, reservoir pressures, and depths weakens the relationship.

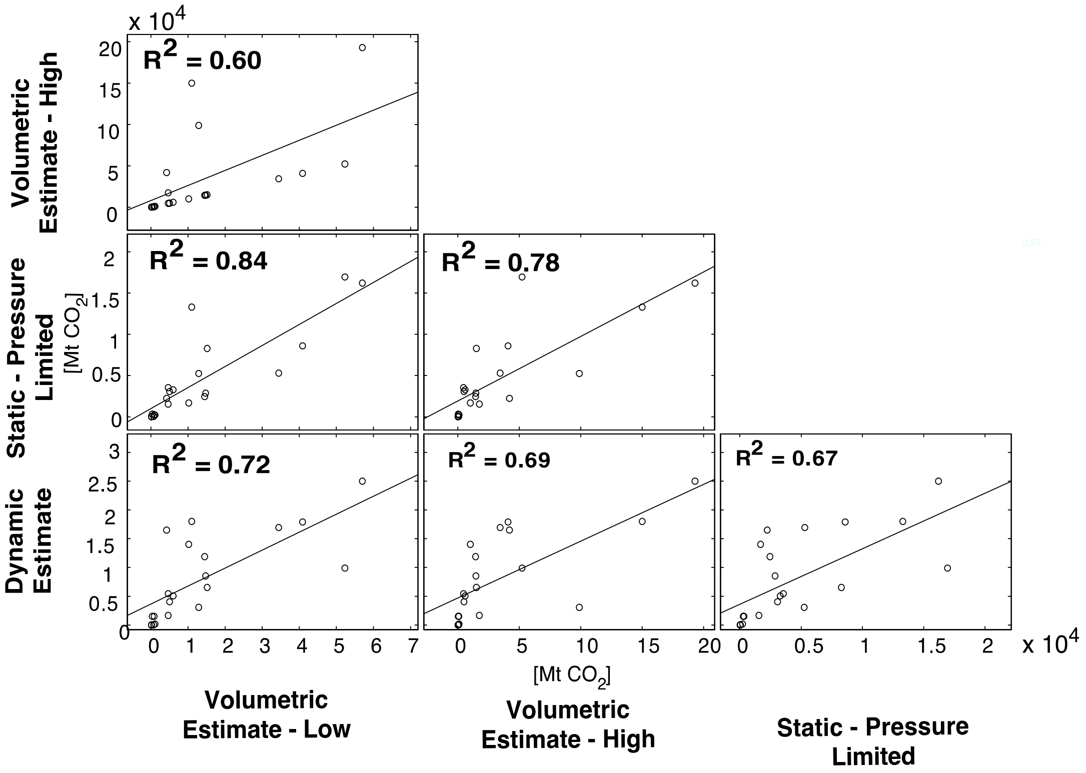


Figure 10. Cross correlation plot for capacity estimation using three methodologies. This uses the same data as Figure 9.

This varying response has been partly reflected already in the experiences of the few existing industrial scale projects – there is little to no observable pressure build-up after 10 years of injection at the Sleipner site (Verdon et al., 2013) whereas pressurization let to fracturing the cap rock at In Salah (White et al., 2014). Similarly, local analyses of pressurization issues have resulted variously in increased confidence of the local or regional capacity for injection (Szulczewski et al., 2012, Winkler et al., 2010), or the cancellation of further development plans (Bader et al., 2014).

Volumetric approaches are often justified on the basis of being representative of an open system, either naturally or through the use of engineered pressure management, i.e., brine production (USDOE and NETL, 2012, USGS, 2013). It thus is interesting to note that volumetric approaches are comparable to dynamic estimates of capacity in open systems meeting these assumptions only after many decades, or more frequently, centuries of injection (Gorecki et al., 2015, IEAGHG, 2014b). In this light, the suggestion that the volumetric approach is warranted because many reservoirs are large or brine production may be economically viable appears to be significantly weakened.

The increasing body of work on pressurization (Allinson et al., 2014, Bader et al., 2014, Birkholzer and Zhou, 2009, Birkholzer et al., 2015, Birkholzer et al., 2009, Gorecki et al., 2015, IEAGHG, 2014b, Thibeau and Mucha, 2011, Zhou et al., 2008) has recently been reviewed by Birkholzer et al. (2015). It is clear that these issues have first order impacts on storage capacity at any scale, and thus should be incorporated into capacity estimation. Recent national efforts characterizing the storage resource have thus begun to incorporate both dynamic modelling and pressure limited static calculations in their capacity estimates (Gammer et al., 2011, Halland et al., 2011) and it has been identified as a clear management issue for commercial CCS by Friedmann (2009).

The relatively simple dynamic models of Szulczewski et al. (2012) have not been benchmarked against detailed reservoir simulation, but the trends of dynamic pressure limited capacity derived from the simulations (Allinson et al., 2014, Bader et al., 2014, Gorecki et al., 2015, IEAGHG, 2014b, Thibeau and Mucha, 2011, USDOE and NETL, 2012, Winkler et al., 2010) follow the trends of the simpler models. In general it appears that dynamic simulation, whether using reservoir simulation or a simpler model, even at the regional scale, should be applied for a realistic assessment of the storage resource availability on the decadal timescale.

4.1.6 Pressure management and brine production

Engineering strategies for pressure management, and particularly the production of brine from the reservoir, are effective at mitigating the impact of local and regional pressurization (Birkholzer et al., 2012, Court et al., 2011, Flett et al., 2008, Flett et al., 2009, IEAGHG, 2012b, Le Guenan and Rohmer, 2011, Lindeberg et al., 2009, Liu et al., 2013, Yang, 2008). Brine production has been included in the development plan for the Gorgon storage project (Flett et al., 2008, Flett et al., 2009) and is also assumed to be necessary for realizing the full capacity potential for storage in the Utsira formation (Lindeberg et al., 2009).

A pressure management strategy using brine production wells will have a significant impact on the overall cost of CO_2 storage. Significant costs will include further reservoir characterization needed to choose the placement of wells, the construction of the wells, and the management of the produced water. Many studies have found that effective pressure relief requires approximately the same volume of brine produced as CO_2 injected (IEAGHG, 2012b, Lindeberg et al., 2009). Birkholzer et al. (2012) have shown, however, that optimal well placement can allow for significantly reduced volumes of brine to be used in effective pressure management.

The most common strategy for managing produced waters would likely be re-injection of the brine into shallower aquifers, or to provide pressure support for nearby hydrocarbon production (Flett et al., 2008, Flett et al., 2009, IEAGHG, 2012b). In cases where the storage site is offshore, and brine salinity is compatible with seawater, discharge to the ocean would also likely be used (Lindeberg et al., 2009, Yang, 2008). These are the two most widely used management practices for produced waters associated with oil production (Clark and Veil, 2009). Desalination could also be used (Bourcier et al., 2011), although the inherently high salinity of the brine and associated costs limit the potential of this option.

The technology for pressure management and handling produced water is mature and information for producing cost estimates for use in techno-economic models of CCS, or integrated assessment models that use CCS should be readily available. The extent to which pressure management will be required to reach near term storage injection targets, however, will not be clear until more national and regional scale assessments of storage capacity using dynamic modelling are performed, e.g. Szulczewski et al. (2012). More pressure management options, i.e. brine production, and their associated costs should also be incorporated into integrated assessment models allowing for the use of energy production associated with CCS. This is discussed in further detail below.

4.1.7 Calculating capacity for oil and gas fields

The calculation of capacity for oil and gas fields is considered relatively simple due to both the existence of detailed characterization of the fields as well as the demonstration of a volumetric trapping capacity with hydrocarbon (Bachu et al., 2007). As such, first order capacity estimates in such systems are a volumetric balance, assuming that hydrocarbon that can be recovered can be replaced by CO_2. A typical example from USDOE and NETL (2012) is given by

$$M_{CO2} = AH\phi(1 - S_w)\beta\rho E,$$

where S_w is the water saturation in the pore space and β is the formation factor for the oil, a conversion to account for density differences between oil at reservoir conditions compared with the surface. The efficiency factor, E, can be defined as needed, but often corresponds to the recovery factor of hydrocarbon, either observed or estimated.

A major contributor to the significant difference in estimates of storage capacity in hydrocarbon fields as compared with saline aquifers is that the spatial domain of the field, given by AH, is limited to the distribution of producible hydrocarbon, rather than the pore space in the greater volume of the geologic unit in which the hydrocarbons are found. This often results in more than an order of magnitude greater storage capacity estimated to be available in saline aquifers than hydrocarbon fields.

4.2 Geographical distribution of volumetric estimates of CO_2 storage

4.2.1 Global storage capacity and its distribution

Studies covering international regions using a consistent assessment methodology, have thus far employed volumetric estimates of capacity, and have only been performed for North American and OECD Europe (EU GeoCapacity, 2009, Halland et al., 2011, NORDICCS, 2015, Poulsen et al., 2014, USDOE and NETL, 2012, USGS, 2013). These estimates can be considered *Effective* storage capacity estimates under the resource pyramid of Bachu et al. (2007). They use probabalistic static techniques in which some attributes of the reservoir system associated with the storage efficiency parameter are assigned a probability distribution, based on expert opinion, and in some cases, the theoretical analyses of IEAGHG (2009).

There has not yet been a centrally coordinated effort to produce an estimate of the global distribution of CO_2 storage resource, but compilations of the literature have been frequently made. Three of the most recent are summarized in Table 13. The underlying literature constitutes a comprehensive bibliography of national and regional storage assessments.

Table 13. Summary of recent estimates of the global CO_2 Storage Resource ($GtCO_2$)

Region/ Reference	Dooley (2013)	Cook and Zakkour (2015) - Low	Cook and Zakkour (2015) - High	Benson et al. (2012) - Low	Benson et al. (2012)– High	Hendriks and Graus (2004) as updated by Koelbl et al. (2014a)
Global	5,510	11,954	30,109	10,450	33,153	10,817
N. and C. America	2,314	1,949	20,821	1856	20,473	8,321
S. America	473	2,003		2,000	2,000	163
Asia	419	2,651	2,801	1,447	3,226	490
Oceania	230	40	202	59	59	31
N. Africa and Middle East	171	10	10	449	449	362
W. Europe	114	136	455	117	381	142
E. Europe/W. Asia	178			177	177	737
Subsaharan Africa	13	152	152	48	48	569

The global resource availability estimate ranges from 5,000 to 30,000 Gt CO_2. The regional breakdown from these compilations is summarized in the bar graph of Figure 11, with a logarithmic vertical axis.

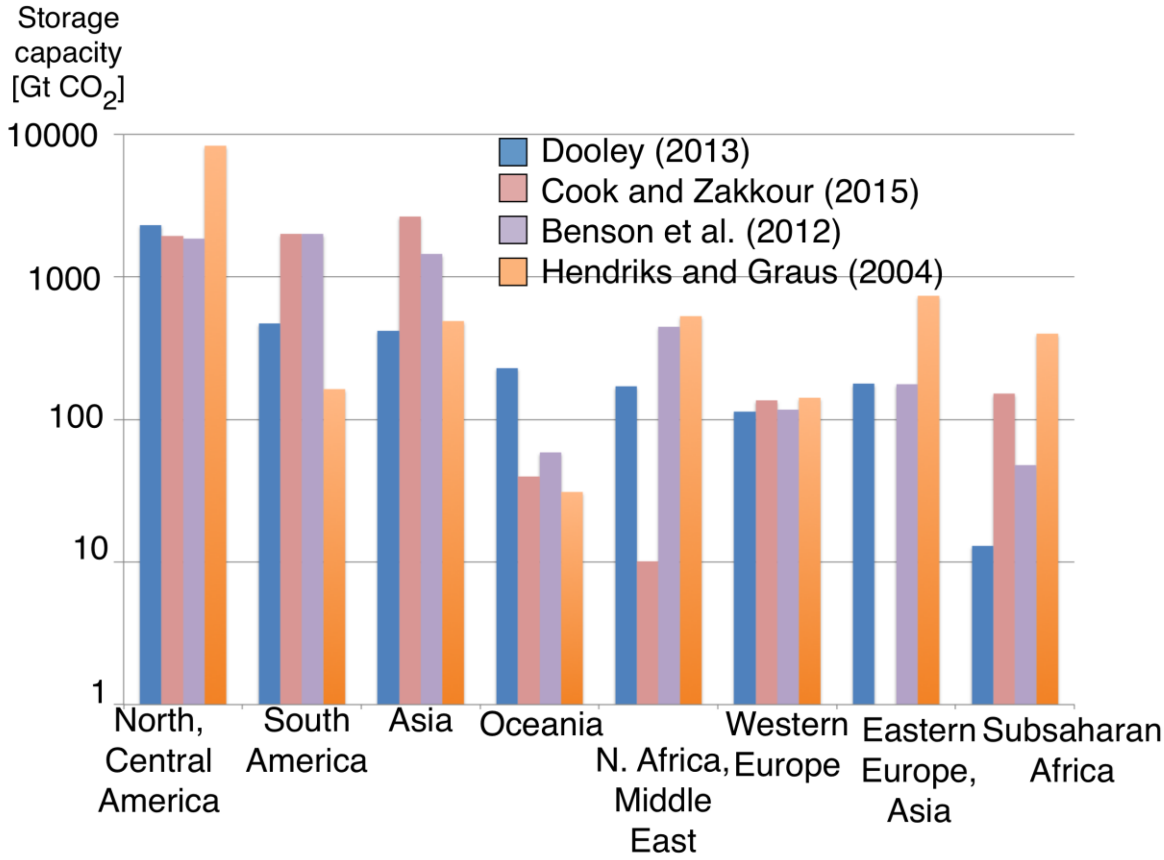


Figure 11. Recent estimates of the globally distributed CO_2 storage resource. The low values are shown in the plot where both low and high estimates are given.

4.2.2 Distribution of storage capacity in oil and gas reservoirs

Oil and gas reservoirs are important for early deployment of CCS for a number of reasons – they are proven traps for buoyant fluid, prior characterization of traps and availability of existing production infrastructure can lower costs to field development for CO_2 storage, and enhanced oil recovery can provide a revenue stream to increase the value of the project. Projects associated with hydrocarbon fields may also avoid the significant issues associated with pressurization, either because concurrent hydrocarbon and water production relieves pressure build-up (Verdon et al., 2013), or the mature field is significantly underpressurised from past production (Garnham and Tucker, 2012).

Table 14 and Figure 12 shows the regional distribution of storage capacity in oil and gas reservoirs from the compilations of Cook and Zakkour (2015), Benson et al. (2012), Hendriks and Graus (2004), *Koelbl et al. (2014a).* The subset capacity ranges 1-2 orders of magnitude less than the total storage capacity (Figure 11). In some regions, and particularly in the Middle East, capacity in oil and gas fields is estimated to be or significant or even a majority of the total capacity.

Table 14. Regional distribution of CO_2 storage capacity in hydrocarbon reservoirs

Region/ Reference	Cook and Zakkour (2015)	Benson et al. (2012)	Hendriks and Graus (2004), Koelbl et al. (2014a)
Global	382	997	1,015
N. and C. America	140	143	116.35
S. America	2.7	89	69.44
Asia	9.4	72.2	82.13
Oceania		19.6	18.07
N. Africa And Middle East	210.4	439.5	303.9
W. Europe	19.89	20.22	77.23
E. Europe/W. Asia		177	315.56
Subsaharan Africa		36.6	32.5

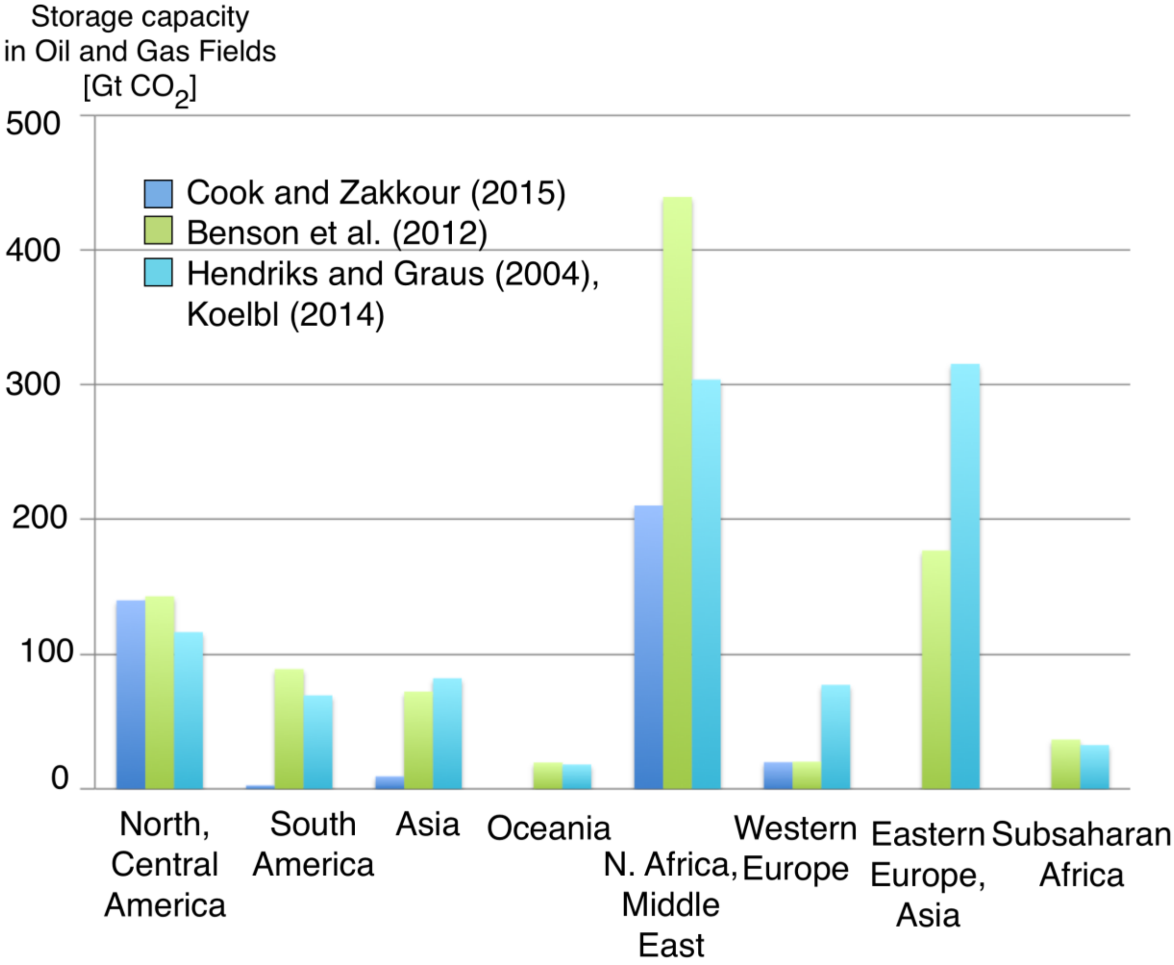


Figure 12. The estimated geographic distribution of storage capacity in oil and gas fields.

4.3 Limitations to CCS deployment due to the availability of the storage

The storage capacity implied by Table 13, combined with CO_2 emissions from the regions Cook and Zakkour (2015) implies that decades to centuries of storage resource is available. On the other hand, these estimates are as a rule volumetric and from the discussion in the preceding section it appears possible that, in the absence of pressure management, the amount of storage space available within 50 years of the start of commercial deployment are 1-2 orders of magnitude lower in some locations.

A more significant measure than total CO_2 emissions is the demand for CO_2 storage resource, generally only a fraction of a total emissions reduction portfolio. Dooley (2013) have placed global demand for CO_2 storage in a climate scenario maintaining CO_2 concentrations at 400-500ppm at an accumulated store of 1,340 Gt CO_2 by 2100. Thus there is little question that sufficient pore space is available to accommodate CO_2. The major uncertainty rather is the extent to which pressure management strategies would be required to use the demanded storage space, and the subsequent cost impact on total deployment.

Only a few studies were found evaluating the impact of a potential limit on storage capacity on the deployment of CCS in integrated assessment models (Bauer, 2005, Keppo and van der Zwaan, 2012, Koelbl et al., 2014a, Koelbl et al., 2014b).

In Koelbl et al. (2014a) the varying levels of deployment of CCS in twelve integrated assessment models were assessed against several assumptions, including the existence of global and regional capacity constraints, which ranged from 3,500 – 20,000 Gt, similar to the range in Table 13. The maximum cumulative storage demand was 3,000 Gt CO_2 by 2100. Because limiting capacity was not approached the varying levels of deployment in the models was not correlated to the total CO_2 storage supply. A sensitivity study of one model in Koelbl et al. (2014b), also showed that the deployment of CO_2 storage to 2050 was not sensitive to a regional storage capacity estimates ranging from 4,500 – 10,000 Gt CO_2. The primary reason was again because the capacity in most regions was not approached by 2050. On the other hand, a significant finding from Koelbl et al. (2014a) was that deployment of CCS by the end of the century was still increasing, while at the same time storage resource would be exhausted within decades.

Keppo and van der Zwaan (2012) analysed the impact of more severe constraints on CO_2 storage capacity to 2100 – comparing a scenario with baseline capacity similar to those provided in Table 13 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 Gt CO_2 (Compare Table 13 and Table 14). By 2100 CCS deployment is very limited due to the capacity constraints. It is interesting to note, however, that early deployment of CCS to 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.

From Table 14 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. (2014a) showed that from 2010 to 2050 between 100 and 500 Gt of storage demand would be consistent with a 2 degree Celsius 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, including oil and gas fields.

Integrated assessment models incorporate potential storage cost limitations through a set of rules that generally ignore the issues of pressurization and pressure management. The most flexible storage cost supply curves have been developed by Dooley and Friedman (2005) for North America, and Dahowski et al. (2009) for China. A commonly used regionally distributed supply cost curve for the rest of the globe was developed by Hendriks and Graus (2004). Notably, these datasets were developed prior to the work, e.g. Birkholzer and Zhou (2009), 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 pressurization of the storage resource may not (Allinson et al., 2014). Thus an additional constraint should be built into the models in which regional pressurization 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 (IEAGHG, 2012b), or by interviews with relevant oilfield operators.

5 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 are summarised below:

- This report hypothesises that the residual emissions associated with CCS are the main reason why the models reviewed in this study (i.e. EMF27 models) do not envisage a wider adoption of carbon capture and storage. This hypothesis must be checked to be validated or refuted with further research. If residual emissions are not preventing the models to reduce CO_2 emission via geological storage, then further options must be investigated.

- 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, especially if the hypothesis on residual emissions proves to be valid. Previous research (IEAGHG, 2014a) 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 to closer to 100%.

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

6 Conclusions

This report has considered whether carbon capture and storage (CCS) technology has the potential to enable access to more fossil fuel reserves in the future, where these reserves would otherwise be unburnable. It has reviewed the studies that have considered CCS in the context of unburnable carbon, analysed the status of CCS, and then studied its impact on fossil fuel consumption across a selection of the global climate change mitigation models used in the IPCC 5th assessment report. Finally, the report makes an in-depth study testing the extent of global CO_2 geo-storage capacity.

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 has 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 herein. Core 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 200EJ per year more fossil fuel is utilised per year in a 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 herein, 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 with respect to the EMF27 models, there are few limiting assumptions made on the availability of CCS. Almost all models reviewed had 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 in this regard is that the capital and operating costs of CCS technology are generally much lower than the marginal abatement costs[3] observed in the models. Therefore, if CCS is available (and not unfavourable for other reasons) further adoption should be observed in the models. The only plausible explanation that such adoption is not observed is that there is another

---

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

factor in the models preventing uptake. This report hypothesises that this further factor is the residual emissions from CCS installations, usually modelled as approximately 15% of emissions from the source in question. These residual emissions, though small, could be significant enough to prevent the technology being adopted further. Testing this hypothesis is outside the scope of this work.

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

References

ADB (2013). Prospects for Carbon Capture and Storage in Southeast Asia. *In:* Asian Development Bank, Mandaluyong City, Philippines, 2013 (ed.).

Akimoto, K., Sano, F., Homma, T., Wada, K., Nagashima, M. & Oda, J. (2012). Comparison of marginal abatement cost curves for 2020 and 2030: longer perspectives for effective global GHG emission reductions. *Sustainability Science,* 7**,** 157-168.

Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M. & Meinshausen, N. (2009). Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature,* 458**,** 1163-1166.

Allinson, W. G., Cinar, Y., Neal, P. R., Kaldi, J. & Paterson, L. (2014). CO_2 Storage Capacity – Combining Geology, Engineering and Economics. *SPE Economics & Management,* 6**,** 15-27.

Anandarajah, G., Strachan, N., Ekins, P., Ramachandran, K. & Hughes, N. (2008). Pathways to a Low Carbon Economy: Energy systems modelling - Working Paper. *In:* UKERC (ed.).

APEC (2005). CO_2 Storage Prospectivity of Selected Sedimentary Basins in the Region of China and South East Asi.

Bachu, S. (2015). Review of CO_2 Storage efficiency in deep saline aquifers. *International Journal of Greenhouse Gas Control,* In Press doi:10.1016/j.ijggc.2015.01.007.

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, N. P. & Mathiassen, O. M. (2007). CO_2 storage capacity estimation: Methodology and gaps. *International Journal of Greenhouse Gas Control,* 1**,** 430-443.

Bader, A. G., Thibeau, S., Vincke, O., Jannaud, D., Saysset, S., Joffre, G. H., Giger, F. M., David, M., Gimenez, M., Dieulin, A. & Copin, D. (2014). CO_2 Storage Capacity Evaluation in Deep Saline Aquifers for an Industrial Pilot Selection. Methodology and Results of the France Nord Project. *Energy Procedia,* 63**,** 2779-2778.

Bassi, S., Boyd, R., Buckle, S., Paul Fennell, Dowell, N. M., Makuch, Z. & Staffell, I. (2015). Bridging the gap: improving the economic and policy framework for carbon capture and storage in the European Union

Bauer, N. (2005). Carbon Capturing and Sequestration: An Option to Buy Time?, Doctoral Thesis. University Potsdam Faculty of Economics and Social Sciences.

Benson, S., Cook, P., Anderson, J., Bachu, S., Nimir, H. B., Basu, B., Bradshaw, J., Deguchi, G., Gale, J., von Goerne, G., Heidug, W., Holloway, S., Kamal, R., Keith, D., Lloyd, P., Rocha, P., Senior, B., Thomson, J., Torp, T., Wildenborg, T., Wilson, M., Zarlenga, F., Zhou, D., Celia, M., Gunter, B., Ennis King, J., Lindeberg, E., Lombardi, S., Oldenburg, C., Pruess, K., Rigg, A., Stevens, S., Wilson, E. & Whittaker, S. (2005). Underground geological storage. *IPCC Special Report on Carbon Dioxide Capture and Storage.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Benson, S. M., Bennaceur, K., Cook, P., Davison, J., de Coninck, H., Farhat, K., Ramirez, A., Simbeck, D., Surles, T., Verma, P. & Wright, I. (2012). Carbon Capture and Storage. Chapter 13 *Global Energy Assessment.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Bentham, M., Mallows, T., Lowndes, J. & Green, A. (2014). CO_2 Storage Evaluation Database (CO_2 Stored). The UK's online storage atlas. *Energy Procedia,* 63**,** 5103-5113.

BGR (2012). Reserves, Resources and Availability of Energy Resources.

BHP Billiton (2015). Climate Change: Portfolio Analysis. *In:* Billiton, BHP (ed.).

Birkholzer, J. J. & Zhou, Q. (2009). Basin-scale hydrogeologic impacts of CO_2 storage: Capacity and regulatory implications. *International Journal of Greenhouse Gas Control,* 3**,** 745-756.

Birkholzer, J. T., Cihan, A. & Zhou, Q. (2012). Impact-driven pressure management via targeted brine extraction – Conceptual studies of CO_2 storage in saline aquifers. *International Journal of Greenhouse Gas Control,* 7**,** 168-180.

Birkholzer, J. T., Oldenburg, C. M. & Zhou, Q. (2015). CO_2 migration and pressure evolution in deep saline aquifers. *International Journal of Greenhouse Gas Control,* 40**,** 203-220.

Birkholzer, J. T., Zhou, Q. & Tsang, C.-F. (2009). Large-scale impact of CO_2 storage in deep saline aquifers: A sensitivity study on pressure response in stratified systems. *International Journal of Greenhouse Gas Control,* 3**,** 181-194.

Blondes, M. S., Brennan, S. T., Merrill, M. D., Buursink, M. L., Warwick, P. D., Cahan, S. M., Cook, T. A., Corum, M. D., Craddock, W. H., DeVera, C. A., Drake, R. M., Drew, L. W., Freeman, P. A., Lohr, C. D., Oldea, R. A., Roberts-Ashby, T. L., Slucher, E. R. & Varela, B. (2013). National assessment of geologic carbon dioxide storage resources – Methodology implementation: U.S. Geological Survey Open-File Report 2013 – 1055, 26 p.

Bourcier, W. L., Wolery, T. J., Wolfe, T., Haussmann, C., Buscheck, T. A. & Aines, R. D. (2011). A preliminary cost and engineering estimate for desalinating produced formation water associated with carbon dioxide capture and storage. *International Journal of Greenhouse Gas Control,* 5**,** 1319-1328.

Bowen, A. & Ranger, N. (2009). Mitigating climate change through reductions in greenhouse gas emissions: the sceince and economics of future paths for global annual emissions.

BP (2012). BP Statistical Review of World Energy. London, UK.

BP (2015). BP Statistical Review of World Energy. *In:* BP (ed.).

Bradshaw, J. (2006). Geological Assessment and Storage Capacity: An International Perspective: Storage Retention Time of CO_2 in Sedimentary Basins: Examples from Petroleum Systems. UNFCC, SBSTA.

Bradshaw, J., Allinson, G., Bradshaw, B. E., Nguyen, V., Rigg, A. J., Spencer, L. & Wilson, P. (2004). Australia's CO_2 geological storage potential and matching of emission sources to potential sinks. *Energy,* 29**,** 1623-1631.

Bradshaw, J., Bachu, S., Boijoly, D., Burruss, R., Holloway, S., Christensen, N. P. & Mathiassen, O. M. (2007). CO_2 storage capacity estimation: Issues and development of standards. *International Journal of Greenhouse Gas Control,* 1**,** 62-68.

Caldecott, B., Lomax, G. & Workman, M. (2015). Stranded Carbon Assets and Negative Emissions Technologies. *In:* Environment, Stranded Assets Programme at the University of Oxford's Smith School of Enterprise and the (ed.) *Working Paper Series.* Online.

Carbon Counts, ERM & Environonics (2014). Assessment of Carbon Capture and Storage (CCS) potential in Egypt. *In:* Report for the World Bank, unpublished. (ed.).

Carbon Counts, ERM & Geosciences, W. (2015). Assessment of Carbon Capture and Storage (CCS) potential in Botswana. Report for the World Bank, unpublished.

Carbon Storage Taskforce (2009). National Carbon Mapping and Infrastructure Plan – Australia: Full Report. *In:* Department of Resources, Energy and Tourism (ed.). Canberra: Canberra, Australia.

Carbon Tracker Initiative (2011). Unburnable Carbon – Are the world's financial markets carrying a carbon bubble? *In:* Tracker, Carbon (ed.) *Carbon Tracker Initiative.*

Carbon Tracker Initiative (2013). Unburnable carbon 2013: Wasted capital and stranded assets. *In:* Initiative, Carbon Tracker (ed.).

Carbon Tracker Initiative (2015). The $2 trillion stranded assets danger zone: How fossil fuel firms risk destroying investor returns. *In:* Initiative, Carbon Tracker (ed.).

Channel, J., Cummi, E., Nguyen, P., Prior, E., Syme, A. R., Jansen, H. R., Rahbari, E., Kleinman, S. M. & Kruger, T. (2015). ENERGY DARWINISM II: Why a Low Carbon Future Doesn't Have to Cost the Earth. *In:* Solutions, Citi GPS: Global Perspectives & (ed.).

Cherepovitsyn, A. & Ilinsky, A. (2011). Comparison of the Geological Disposal of Carbon Dioxide and Radioactive Waste in European Russia. *In:* Toth, F.L. (ed.) *Geological Disposal of Carbon Dioxide and Radioactive Waste: A Comparative Assessment.* Springer Netherlands.

Clark, C. E. & Veil, J. A. (2009). Produced Water Volumes and Management Practices in the United States. Argonne National Laboratory ANL/EVS/R-09/1.

Clark, V. R. & Herzog, H. J. (2014). Can "stranded" Fossil Fuel Reserves Drive CCS Deployment? *Energy Procedia,* 63**,** 7261-7271.

Cook, G. & Zakkour, P. (2015). CCS deployment in the context of regional developments in meeting long-term climate change objectives. *In:* IEAGHG (ed.).

Court, B., Celia, M. A., Nordbotten, J. M. & Elliot, T. R. (2011). Active and integrated management of water resources throughout CO_2 capture and sequestration operations. *Energy Procedia,* 4**,** 4221-4229.

CSFL (2007). Phase II Final Report from the Task Force for Review and Identification of Standard for CO_2 Storage Capacity Estimation. Carbon Sequestration Leadership Forum: Washington DC. pp. 43.

Dahowski, R. T., Li, X., Davidson, C. L., Wei, N. & Dooley, J. J. (2009). Regional Opportunities for Carbon Dioxide Capture and Storage in China. *In:* PNNL-19091., Pacific Northwest National Laboratory. (ed.).

Dooley, J. J. (2013). 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**,** 5141-5150.

Dooley, J. J. & Friedman, S. J. (2005). 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. UCRL-SR-209663.

Environmental Audit Committee (2014). Green Finance. *In:* Commons, House of (ed.) *Report of Session 2013-14.* Online.

EU GeoCapacity (2009). GeoCapacity Final Report. Geological Survey of Denmark and Greenland.

ExxonMobil (2015). The Outlook for Energy: A View to 2040. *In:* ExxonMobil (ed.).

Fang, Z. & Li, X. (2011). Preliminary assessment of CO_2 geological storage potential in Chongqing, China. *Procedia Environmental Sciences,* 11**,** 1064-1071.

Flett, M., Beacher, G., Brantjes, J., Burt, A., Dauth, C., Koelmeyer, F., Lawrence, R., Leigh, S., McKenna, J., Gurton, R., Robinson IV, W. F. & Tankersley, T. (2008). Gorgon Project: Subsurface Evaluation of Carbon Dioxide Disposal Under Barrow Island. SPE 116372. SPE Asia Pacific Oil & Gas Conference and Exhbition, 20-22 October 2008 2008 Perth, Australia.

Flett, M., Brantjes, J., Gurton, R., McKenna, J., Tankersley, T. & Trupp, M. (2009). Subsurface development of CO_2 disposal for the Gorgon Project. *Energy Procedia,* 1**,** 3031-3038.

Friedmann, S. J. (2009). Emerging Technical Challenges of 5-Million-Ton/yr Injections. SPE 126942. SPE International Conference on CO_2 Capture, Storage, and Utilization, 2-4 November 2009 San Diego.

Gammer, D., Green, D., Holloway, S. & Smith, G. (2011). The Energy Technologies Institute's UK CO_2 Storage Appraisal Project (UKSAP). SPE 148426. SPE Offshore Europe Oil and Gas Conference and Exhibition, 6-8 September 2011 2011 Aberdeen, UK.

Garg, A. & Shukla, P. (2009). Coal and energy security for India: Role of carbon dioxide capture and storage. *Energy,* 34**,** 1032-1041.

Garnham, P. & Tucker, O. (2012). The Longannet to Goldeneye Project: Challenges in Developing and End-to-End CCS Scheme. Paper CMTC 151716. Carbon Management Technology Conference, 7-9 February, 2012 2012 Orlando, Florida.

Geosciences, C. f. (2010). ATLAS on geological storage of carbon dioxide in South Africa.

Gibbins, J. & Chalmers, H. (2011). Is all CCS equal? Classifying CCS applications by their potential climate benefit. *Energy Procedia,* 4**,** 5715-5720.

Global CCS Institute (2014). Summary report. *In:* Global CCS Institute (ed.) *The Global Status of CCS: 2014.*

Goodman, A., Bromhal, G., Strazisar, B., Rodosta, T., Guthrie, W. F., Allen, D. & Guthrie, G. (2013). Comparison of methods for geologic storage of carbon dioxide in saline formations. *International Journal of Greenhouse Gas Control,* 18**,** 329-342.

Gorecki, C. D., Ayash, S. C., Liu, G., Braunberger, J. R. & Dotzenrod, N. W. (2015). A comparison of volumetric and dynamic CO_2 storage resource efficiency in deep saline formations. *International Journal of Greenhouse Gas Control,* 42**,** 213-225.

Goto, K., Yogo, K. & Higashii, T. (2013). A review of efficiency penalty in a coal-fired power plant with post-combustion CO_2 capture. *Applied Energy,* 111**,** 710-720.

Halland, E. K., Gjeldvik, I. T., Johansen, W. T., Magnus, C., Meling, I. M., Pedersen, S., Riis, F., Solbakk, T. & Tappel, I. (2011). CO_2 Storage Atlas Norwegian North Sea. *In:* Directorate, Norwegian Petroleum (ed.).

Hammond, G. P., Akwe, S. S. O. & Williams, S. (2011). Techno-economic appraisal of fossil-fuelled power generation systems with carbon dioxide capture and storage. *Energy,* 36**,** 975-984.

Heemann, R., Ketzer, J. M. M., Hiromoto, G. & Scislewski, A. (2011). Assessment of the Geological Disposal of Carbon Dioxide and Radioactive Waste in Brazil, and Some Comparative Aspects of Their Disposal in Argentina. *In:* F.L. Toth, Editor (ed.) *Geological Disposal of Carbon Dioxide and Radioactive Waste: A Comparative Assessment.* Springer Netherlands.

Hendriks, C. & Graus, W. (2004). Global Carbon Dioxide Storage Potential and Costs. *In:* EEP-02001, Ecofys. (ed.).

Herrmann, L., Dunphy, E. & Copus, J. (2010). Oil and gas for beginners. *Deutsche Bank*.

Holler, S. & Viebahn, P. (2011). Assessment of CO_2 Storage Capacity in Geological Formations of Germany and Northern Europe. *Energy Procedia,* 4**,** 4897-4904.

Huang, X., Bandilla, K. W., Celia, M. A. & Bachu, S. (2014). Basin-scale modeling of CO_2 storage using models of varying complexity. . *International Journal of Greenhouse Gas Control,* 20**,** 73-86.

IEA (2008). CO_2 capture and storage: a key carbon abatement option.

IEA (2009a). CO_2 storage in depleted gas fields. *Technical Study.*

IEA (2009b). CO_2 storage in depleted oilfields: global application criteria for carbon dioxide enhanced oil recovery. *Technicla report.*

IEA (2012). World Energy Outlook 2012. *In:* IEA (ed.). Online.

IEA (2013). Technology Roadmap: Carbon Capture and Storage 2013. *In:* IEA (ed.) *Technology Roadmap.* Online.

IEA (2014a). World Energy Model Documentation - 2014 version.

IEA (2014b). World Energy Outlook 2014 - Executive Summary. *In:* IEA (ed.). Online.

IEA (2015a). Energy and Climate Change *World Energy Outlook Special Report.*

IEA (2015b). Energy Technology Perspectives: The 2°C Scenario (2DS).

IEAGHG (2008). A Regional Assessment of the Potential for CO_2 Storage in the Indian Subcontinent. 2008/2, May 2008.

IEAGHG (2009). Development of Storage Coefficients for Carbon Dioxide Storage in Deep Saline Formations, 2009/13, Nocember, 2009.

IEAGHG (2011). Global Storage Resources Gap Analysis for Policy Makers, 2011/10, September, 2011.

IEAGHG (2012a). Barriers to implementation of CCS: capacity constraints.

IEAGHG (2012b). Extraction of Formation Water from CO_2 Storage. 2012/12, November, 2012.

IEAGHG (2014a). CO_2 capture at coal based power and hydrogen plants. *In:* IEAGHG (ed.).

IEAGHG (2014b). CO_2 Storage Efficiency in Deep Saline Formations: A Comparison of Volumetric and Dynamic Storage Resource Estimation Methods. 2014/09, October, 2014.

IPCC (2005). IPCC Special Report: Carbon capture and storage.

IPCC (2007). 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 (2013a). *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, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2013b). *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, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2013c). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2013d). *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, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2014a). *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, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2014b). *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, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2014c). *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, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2014d). Integrated Assessment Modelling Consortium (IAMC) AR5 Scenario Database (Working Group III). *In:* 2014, International Institute for Applied Systems Analysis (ed.). Online.

J. Gale, J. & Dixon, T. (2014). CCS as a critical part of the carbon budget.

Janetos, A. C. (2009). Science challenges and future directions: Climate Change Integrated Assessment Research. *In:* US DOE (ed.).

Jimenez, O., Davila, M., Arevalo, V., Medina, E. & Castro, R. (2011). Geological Carbon Dioxide Storage in Mexico: A First Approximation. *Earth and Enviornmental Sciences*.

Jin, M., Pickup, G., Mackay, E., Todd, A., Sohrabi, M., Monaghan, A. & Naylor, M. (2012). Static and Dynamic Estimates of CO_2-storage Capacity in Two Saline Formations in the UK. SPE 131609. *SPE Journal,* 17**,** 1108-1118.

Keppo, I. & van der Zwaan, B. (2012). The Impact of Uncertainty in Climate Targets and CO_2 Storage Availability on Long-Term Emissions Abatement. *Environ. Model Assess,* 17**,** 177-191.

Ketzer, J. M. M., Machado, C. X., Rockett, G. C. & Iglesias, R. S. (2015). Brazilian Atlas of CO_2 Capture and Geological Storage. *In:* Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage. (ed.).

Koelbl, B. S., Broek, M. A. v. d., Faaij, A. P. C. & Vuuren, D. P. v. (2014a). Uncertainty in Carbon Capture and Storage (CCS) deployment projections: a cross-model comparison exercise. *Climatic Change,* 123**,** 461-476.

Koelbl, B. S., van den Broek, M. A., van Ruijven, B. J., Faaij, A. P. C. & van Vuuren, D. P. (2014b). Uncertainty in the deployment of Carbon Capture and Storage (CCS): A sensitivity analysis to techno-economic parameter uncertainty. *International Journal of Greenhouse Gas Control,* 27**,** 81-102.

Koide, H. & Kusunose, K. (2011). Geological Disposal of Carbon Dioxide and Radioactive Waste in the Geotectonically Active Country of Japan. *In:* F.L. Toth, Editor (ed.) *Geological Disposal of Carbon Dioxide and Radioactive Waste: A Comparative Assessment.* Springer Netherlands.

Koornneef, J., Breevoort, P. v., Hamelinck, C., Hendriks, C., Hoogwijk, M., Koop, K., Koper, M., Dixon, T. & Camps, A. (2012). Global potential for biomass and carbon dioxide capture, transport and storage up to 2050. *International Journal of Greenhouse Gas Control,* 11**,** 117-132.

Krey, V., Luderer, G., Clarke, L. & Kriegler, E. (2014). Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. *Climatic Change,* 123**,** 369-382.

Krey, V. & Riahi, K. (2009). 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 Economics,* 31, Supplement 2**,** S94-S106.

Kriegler, E., Riahi, K., Bauer, N., Schwanitz, V. J., Petermann, N., Bosetti, V., Marcucci, A., Otto, S., Paroussos, L., Rao, S., Arroyo Currás, T., Ashina, S., Bollen, J., Eom, J., Hamdi-Cherif, M., Longden, T., Kitous, A., Méjean, A., Sano, F., Schaeffer, M., Wada, K., Capros, P., P. van Vuuren, D. & Edenhofer, O. (2014a). Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change,* 90, Part A**,** 24-44.

Kriegler, E., Weyant, J., Blanford, G., Krey, V., Clarke, L., Edmonds, J., Fawcett, A., Luderer, G., Riahi, K., Richels, R., Rose, S., Tavoni, M. & van Vuuren, D. (2014b). 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**,** 353-367.

Le Guenan, T. & Rohmer, J. (2011). Corrective measures based on pressure control strategies for CO_2 geological storage in deep aquifers. *International Journal of Greenhouse Gas Control,* 5**,** 571-578.

Lewis, M. C., Voisin, S., Hazra, S., Mary, S. & Walker, R. (2014). Stranded assets, fossilised revenues. *In:* Cheuvreux, Kepler (ed.).

Lindeberg, E., Vuillaume, J.-F. & Ghaderi, A. (2009). Determination of the CO_2 storage capacity of the Utsira formation. *Energy Procedia,* 1**,** 2777-2784.

Liu, G., Gorecki, C. D., Saini, D., Bremer, J. M., Klapperich, R. J. & Braunerger, J. R. (2013). Four-site case study of water extraction from CO_2 storage reservoirs. *Energy Procedia,* 37**,** 4518-4525.

Luo, Z. (2008). Status of CCS in China. 2nd US-China Symposium on CO_2 Emission Control Science & Technology, 2008 Hangzhou, China.

M. Meinshausen, Meinshausen, N., Hare, W., Raper, S. C. B., Frieler, K., Knutti, R., Frame, D. J. & Allen, M. R. (2009). Greenhouse-gas emission targets for limiting global warming to 2^0C. *Nature,* 458**,** 1158-1162.

Macminn, C. W., Szulczewski, M. L. & Juanes, R. (2010). CO_2 migration in saline aquifers. Part 1. Capillary trapping under slope and groundwater flow. *Journal of Fluid Mechanics,* 662**,** 329-351.

Mayer, N. & Brinker, L. (2014). Deflating the "Carbon Bubble". *In:* Energy, IHS (ed.).

McCollum, D., Bauer, N., Calvin, K., Kitous, A. & Riahi, K. (2014). Fossil resource and energy security dynamics in conventional and carbon-constrained worlds. *Climatic Change,* 123**,** 413-426.

McGlade, C. & Ekins, P. (2014). Un-burnable oil: An examination of oil resource utilisation in a decarbonised energy system. *Energy Policy,* 64**,** 102-112.

McGlade, C. & Ekins, P. (2015). The geographical distribution of fossil fuels unused when limiting global warming to 2^0C. *Nature,* 517**,** 187-190.

McKelvey, V. E. (1972). 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. *American Scientist,* 60**,** 32-40.

Nakanishi, S., Mizuno, Y., Okumura, T., Miida, H., Shidahara, T. & Hiramatsu, S. (2009). Methodology of CO_2 aquifer storage capacity assessment in Japan and overview of the project. *Energy Procedia,* 1**,** 2639-2646.

NETL (2010). Carbon Sequestration Atlas of the United States and Canada, Third Edition. *In:* US Department of Energy, National Energy Technology Laboratory, Pittsburgh (ed.).

NORDICCS. (2015). Available: http://www.sintef.no/projectweb/nordiccs/objectives/

Ogawa, T., Nakanishi, S., Shidahara, T., Okumura, T. & Hayashi, E. (2011). Saline-aquifer CO_2 sequestration in Japan – methodology of storage capacity assessment. . *International Journal of Greenhouse Gas Control,* 5**,** 318-326

OGRC (Oil and Gas Reserves Committee) (2005). Comparison of Selected Reserves and Resource Classifications and Associated Definitions *In:* SPE (ed.).

Okwen, R. T., Stewart, M. T. & Cunningham, J. A. (2010). Analytical solution for estimating storage efficiency of geologic sequestration of CO_2. . *International Journal of Greenhouse Gas Control,* 4**,** 102-107.

Park, S., Kim, J. K. & Lee, Y. (2010). Assessment of Potential CO_2 Storage Capacities of Major Sedimentary Basins in Korea. Proceedings of the Association of Korean Geoscience Societies, 2010 Autumn Meeting, 2010.

PetroChina Company Limited (2007). CCS Activities and Developments in China. Beijing, China.

Poulsen, N., Holloway, S., Neele, F., Smith, N. A. & Kirk, K. (2014). CO_2StoP Final Report. European Commission Contract No ENER/C1/154-2011-S12.611598.

Rempe, H., Schmidt, S. & Schwarz-Schampera, U. (2007). Reserves, Resources and Availability of Energy Resources 2006. *In:* Resources, German Federal Institute for Geosciences and Natural (ed.).

Riahi, K., Kriegler, E., Johnson, N., Bertram, C., den Elzen, M., Eom, J., Schaeffer, M., Edmonds, J., Isaac, M., Krey, V., Longden, T., Luderer, G., Méjean, A., McCollum, D. L., Mima, S., Turton, H., van Vuuren, D. P., Wada, K., Bosetti, V., Capros, P., Criqui, P., Hamdi-Cherif, M., Kainuma, M. & Edenhofer, O. (2014). Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technological Forecasting and Social Change,* 90, Part A**,** 8-23.

Robins, N., Keen, A. & Knight, Z. (2014). Coal and carbon revisited *In:* Research, HSBC Global (ed.).

Schindler, J. & Zitell, W. (2008). *Crude Oil: The Supply Outlook,* Berlin, Germany.

Shell (2013). New Lens Scenarios. *In:* Shell (ed.).

Spedding, P., Mehta, K. & Robins, N. (2013). Oil & carbon revisited *In:* Research, HSBC Global (ed.).

Surridge, A. D., Cloete, M. & Lloyd, P. J. (2011). The Geological Storage of Carbon Dioxide and Disposal of Nuclear Waste in South Africa. *In:* F.L. Toth, Editor (ed.) *Geological Disposal of Carbon Dioxide and Radioactive Waste: A Comparative Assessment.* Springer Netherlands.

Szulczewski, M. L., MacMinn, C. W., Herzog, H. J. & Juanes, R. (2012). Lifetime of carbon capture and sorage as a climate-change mitigation technology. Proceedings of the National Academy of Sciences, 2012. 5185-5189.

Takahashi, T., Ohsumi, T., Nakayama, K., Koide, K. & Miida, H. (2009). Estimation of CO_2 Aquifer Storage Potential in Japan. *Energy Procedia,* 1**,** 2631-2638.

Thibeau, S. & Mucha, V. (2011). Have We Overestimated Saline Aquifer CO_2 Storage Capacities? *Oil & Gas Science and Technology – Rev. IFP Energies nouvelles,* 66**,** 81-92.

UK SAP. (2011). *The Energy Technology Institute's Storage Appraisal Project (UKSAP)* [Online]. Available: http://www.eti.co.uk/project/uk-storage-appraisal-project/

USDOE and NETL (2012). The United States 2012 Carbon Utilization and Storage Atlas Fourth Edition.

USGS (2013). National assessment of geologic carbon dioxide storage resources – Results: U.S. Geological Survey Circular 1386, 41 p., .

V. Scott, Haszeldine, R. S., Tett, S. F. B. & Oschlies, A. (2015). Fossil fuels in a trillion tonne world. *Nature Climate Change,* 5**,** 419-423.

van Vliet, J., Hof, A., Mendoza Beltran, A., van den Berg, M., Deetman, S., den Elzen, M. J., Lucas, P. & van Vuuren, D. (2014). The impact of technology availability on the timing and costs of emission reductions for achieving long-term climate targets. *Climatic Change,* 123**,** 559-569.

Verdon, J. P., Kendall, J.-M., Stork, A. L., Chadwick, R. A., White, D. J. & Bissell, R. C. (2013). Comparison of geomechanical deformation induced by megaton-scale CO_2 storage at Sleipner, Weyburn and In Salah. Proceedings of the National Academy of Sciences, 2013. E2762-E2771.

Wang, L. (2010). Research and Application of CCS in China. 5th IEA GHG Risk Assessment Network Workshop, May, 17-19 2010.

Wang, S., Vincent, C. J., Stephenson, M. H. & Zeng, R. (2014). Assessment of storage capacity for CO_2 in saline aquifers near hydrocarbon fields, Northern Songliao Basin, China. *Greenhouse Gases: Science and Technology,* 4**,** 366-383.

White, J. A., Chiaramonte, L., Ezzedine, S., Foxall, W., Hao, Y., Ramirez, A. & McNab, W. (2014). Geomechanical behavior of the reservoir and caprock system at the In Salah CO_2 storage project. Proceedings of the National Academy of Sciences, 2014. 8747-8752.

Winkler, M., Abernethy, R., Nicolo, M., Huang, H., Wang, A., Zhang, S., Simone, A., Clark, C., Crouch, S., De Groot, H., El Mahdy, R., Smith, M., Malik, S., Bourne, S., Pierpont, R. & Hugonet, V. (2010). The Dynamic Aspect of Formation Storage Use for CO_2 Sequestration. SPE 139730. SPE International Conference on CO_2 Capture, Storage, and Utilization, 10-12 Nov. 2010 2010 New Orleans, Louisiana.

World Bank (2012). Hashemite Kingdom of Jordan: Carbon Capture and Storage (CCS) Capacity Building Technical Assistance. *In:* The World Bank, New York (ed.).

World Energy Council (2007). Survey of Energy Resources 2007 *In:* Clarke, A. W. & Trinnaman, J. A. (ed.).

Yang, Q. (2008). Dynamic Modelling of CO_2 Injection in a Closed Saline Aquifer in the Browse Basin, Western Australia. SPE 115236. SPE Asia Pacific Oil & Gas Conference and Exhibition, 20-22 October 2008 2008 Perth, Australia.

Zakharova, E. (2004). Some aspects of application of CO_2 capture and storage technologies for CO_2 emission reduction in the Russian electric power production sector. Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, 1., 2004.

Zhou, D., Li, P., Zhao, Z., Liao, J., Zhang, C., Zhang, Y., Xie, H., Li, F. & Peng, J. (2013). Feasibility Study of CCS-Readiness in Guangdong Province, China (GDCCSR) Final Report: Part 2. Assessment of CO_2 Storage Potential for Guangdong Province, China.

Zhou, D., Zhao, Z., Liao, J. & Sun, Z. (2011). A preliminary assessment on CO_2 storage capacity in the Pear River Mouth Basin offshore Guangdong, China. *International Journal of Greenhouse Gas Control,* 5**,** 308-17.

Zhou, Q., Birkholzer, J. T., Tsang, C.-F. & Rutquist, J. (2008). A method for quick assessment of CO_2 storage capacity in closed and semi-closed saline formations. *International Journal of Greenhouse Gas Control,* 2**,** 626-639.

Annex 1. Data sources for global CO_2 storage capacity estimates

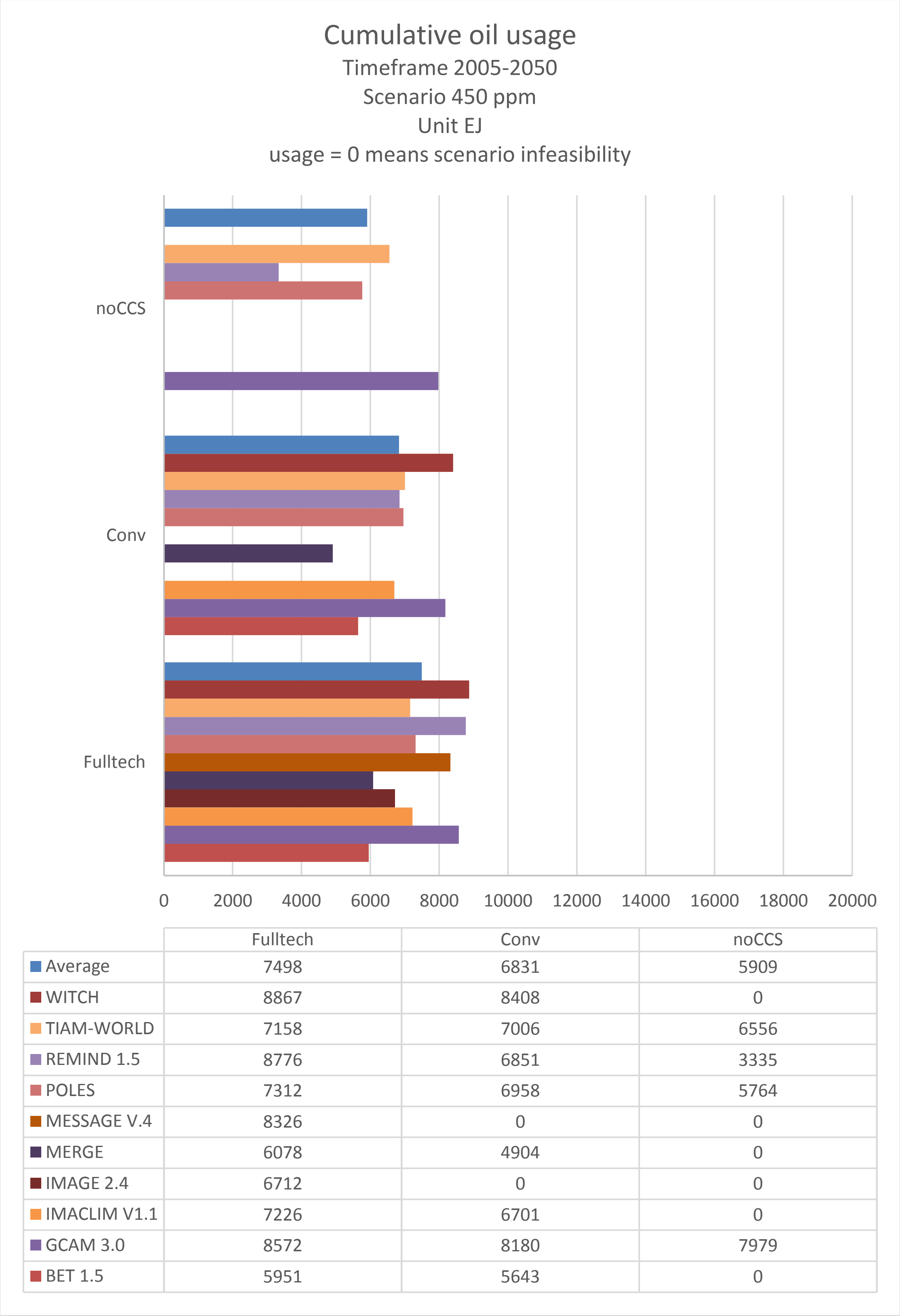
Table A1: Summaries of global estimates of CO_2 storage capacity based on recent compilations of Dooley (2013), Cook and Zakkour (2015), Benson et al. (2012) and Hendriks and Graus (2004) as updated by Koelbl et al. (2014a). The compilations combine regional estimates made using volumetric approaches. The left column shows the heading used in each compilation, e.g. country or region. Each compilation used a different set of headings and thus all of the headings are grouped by geographic regions, shaded in grey. The values in the grey shaded rows show the subtotal for each region, for each compilation. Where a field is left blank for a particular compilation, that compilation did not use that particular region name or did not include an estimate from that region.

Region	**Dooley (2013)- *practical storage capacity***		**Cook and Zakkour (2015)**			**Benson et al. (2012) Carbon Capture and Storage. Chapter 13 - Global Energy Assessment**			**Hendriks and Graus (2004), Koelbl et al. (2014a)**
Region	References	Capacity [Gt CO_2]	References	Capacity – low, [Gt CO_2]	Capacity – High [Gt CO_2]	References	Capacity – High [Gt CO_2]	Capacity – High [Gt CO_2]	Capacity – High [Gt CO_2]
Global Calculated		3912		6941.2	24441.1		6153	26813	10815.4
NORTH AND CENTRAL AMERICA		**2314**		**1949**	**20821**		**1856**	**20473**	**8321**
N. America						NETL (2010)	1856	20473	
USA	NETL (2010)	2280	USGS (2013) USDOE and NETL (2012)	1800	20400				4058
Canada	NETL (2010)	34	USDOE and NETL (2012)	48	320				4193
Mexico	Jimenez et al. (2011)		USDOE and NETL (2012)	101	101				49
Rest C. America									21
SOUTH AMERICA		**473**		**2002.7**			**2000**	**2000**	**163.4**
S. America	From below	473							99.4
Venezuela	IEA (2009a), IEA (2009b)		Bradshaw (2006), IEA (2008)	2.7	2.7				
Brazil	Heemann et al. (2011)		Ketzer et al. (2015)	2000	2000	Ketzer et al. (2015)	2000	2000	64
Argentina	Heemann et al. (2011)		-						
ASIA		**419**		**2651.2**	**2801.2**		**1447**	**3226**	**490**

China	Dahowski et al. (2009), Zhou et al. (2011)	311	Dahowski et al. (2009), Zhou et al. (2013), Fang and Li (2011), Wang et al. (2014)	2300	2300	PetroChina Company Limited (2007); Wang (2010); Luo (2008); APEC (2005); Dahowski et al. (2009)	1445	3080	120
Japan	Ogawa et al. (2011), Koide and Kusunose (2011)	13	Ogawa et al. (2011)	146	146	Nakanishi et al. (2009); Takahashi et al. (2009); Hendriks and Graus (2004)	2	146	13
SE Asia	From below	31							44
Philippines	IEA (2009a), IEA (2009b)		ADB (2013)	23.3	23.3				
Vietnam	IEA (2009a), IEA (2009b)		ADB (2013)	11.8	11.8				
Thailand	IEA (2009a), IEA (2009b)		ADB (2013)	8.9	8.9				
Indonesia	IEA (2009a), IEA (2009b)		ADB (2013)	11.2	11.2				63
Korea	Park et al. (2010)								4
Malaysia	IEA (2009a), IEA (2009b)								
India	IEAGHG (2008), Garg and Shukla (2009)	64	IEAGHG (2008)	150	300				180
Other Asia									66
OCEANIA		**230**		**40**	**202**		**59**	**59**	**31**
Australia	Carbon Storage Taskforce (2009), Bradshaw et al. (2004)	230	Carbon Storage Taskforce (2009)	40	202	Carbon Storage Taskforce (2009); Bradshaw et al. (2004)	59	59	
Oceania									31
N. AFRICA AND THE MIDDLE EAST		**171**		**10.1**	**10.1**		**449**	**449**	**531**
Middle East	IEA (2009a), IEA (2009b)	171	Hendriks and Graus (2004)			Hendriks and Graus (2004)	449	449	362
N. Africa									169
Israel									
Jordan			World Bank (2012)	9.7	9.7				
Egypt	IEA (2009a), IEA (2009b)		Carbon Counts et al. (2014)	0.4	0.4				
W. EUROPE		**114**		**136.4**	**455**		**117**	**381**	**142**

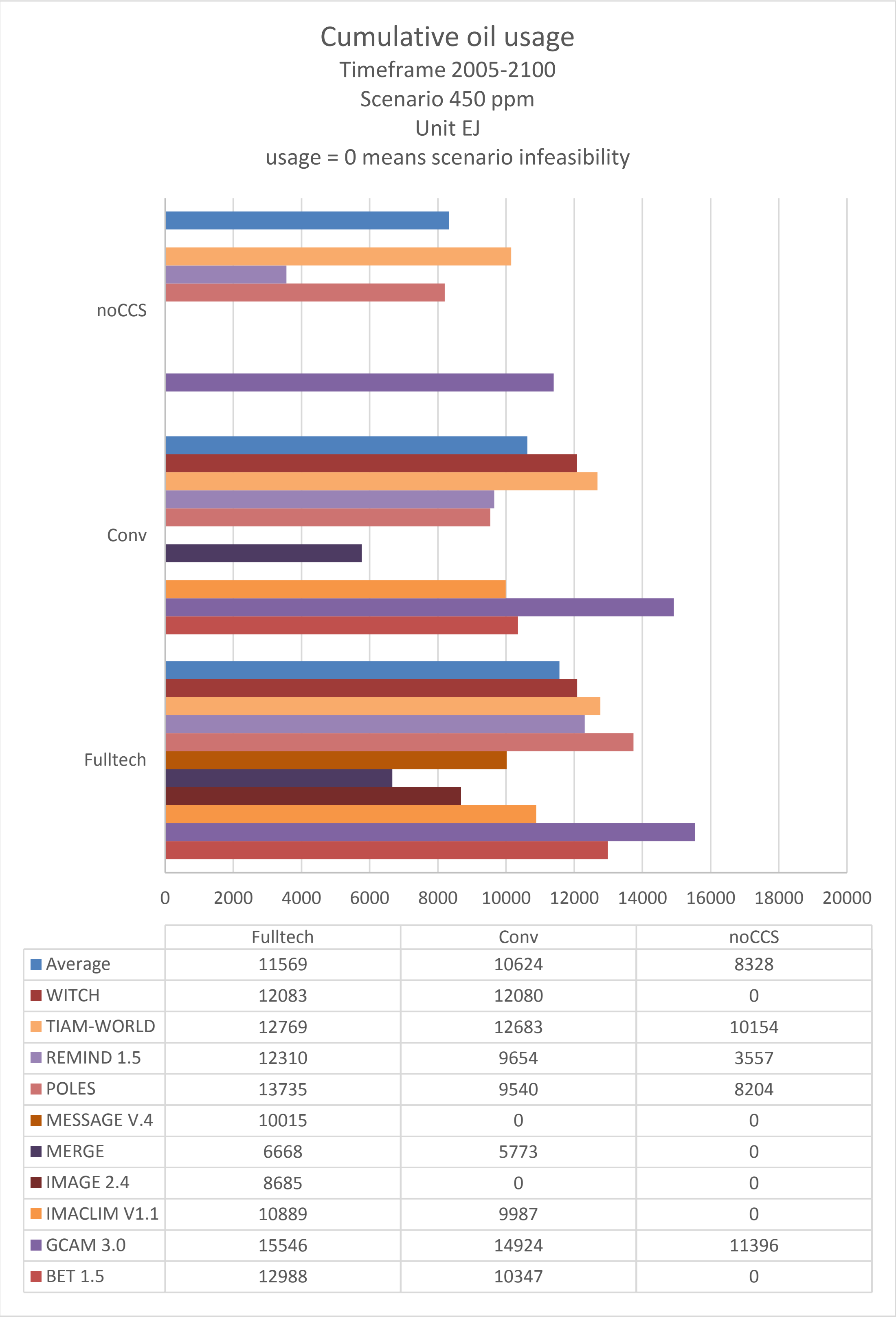
UK			UK SAP (2011), Bentham et al. (2014)	14.4	78				
Germany			Holler and Viebahn (2011)	5	Jan-00				
OECD Europe	EU GeoCapacity (2009) (www.geology.cz/geocapacity)	114	EU GeoCapacity (2009)	117	360	EU GeoCapacity (2009)	117	381	142
Ireland									
Norway	Halland et al. (2011)		Halland et al. (2011)	21	45				
E. EUROPE/W. ASIA		**178**					**177**	**177**	**737**
Russia	Cherepovitsyn and Ilinsky (2011)	178				Zakharova (2004)	177	177	503
C. Europe									36
Turkey									12
Ukraine									85
Stan Asia									101
SUBSAHARAN AFRICA		**13**		**151.8**	**151.8**		**48**	**48**	**400**
Botswana	IEA (2009a), IEA (2009b)		Carbon Counts et al. (2015)	1.8	1.8				
S. Africa	IEA (2009a), IEA (2009b), Surridge et al. (2011)	13	Geosciences (2010)	150	150	Hendriks and Graus (2004)	48	48	156
W. Africa									186
E. Africa									58

Annex 2. EMF27 primary energy by fuel (all models)



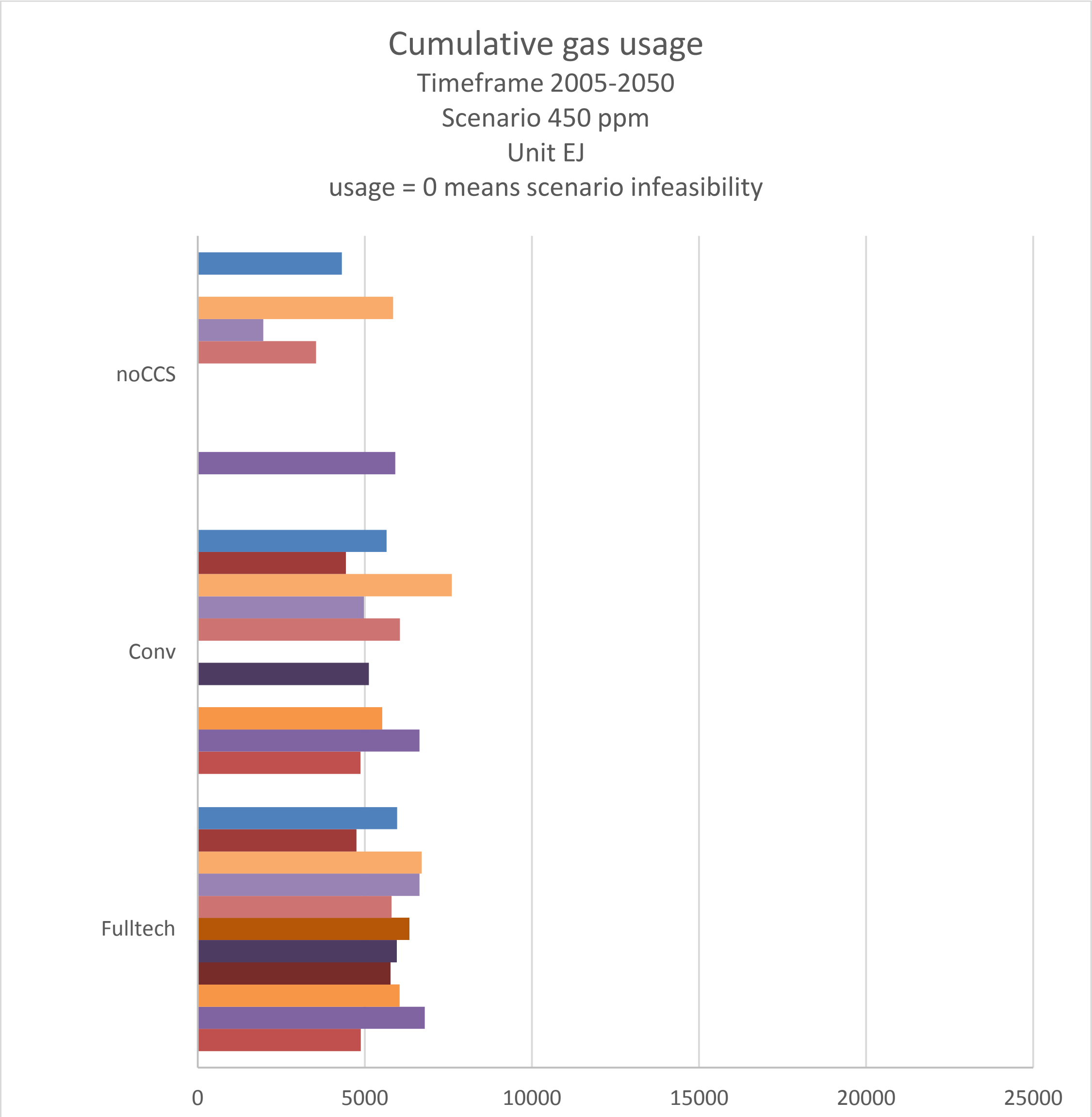
	Fulltech	Conv	noCCS
■ Average	7498	6831	5909
■ WITCH	8867	8408	0
■ TIAM-WORLD	7158	7006	6556
■ REMIND 1.5	8776	6851	3335
■ POLES	7312	6958	5764
■ MESSAGE V.4	8326	0	0
■ MERGE	6078	4904	0
■ IMAGE 2.4	6712	0	0
■ IMACLIM V1.1	7226	6701	0
■ GCAM 3.0	8572	8180	7979
■ BET 1.5	5951	5643	0

Figure 13. Emissions from oil usage according to the EMF27 models (scenario 450 ppm timeframe 2005-2050)



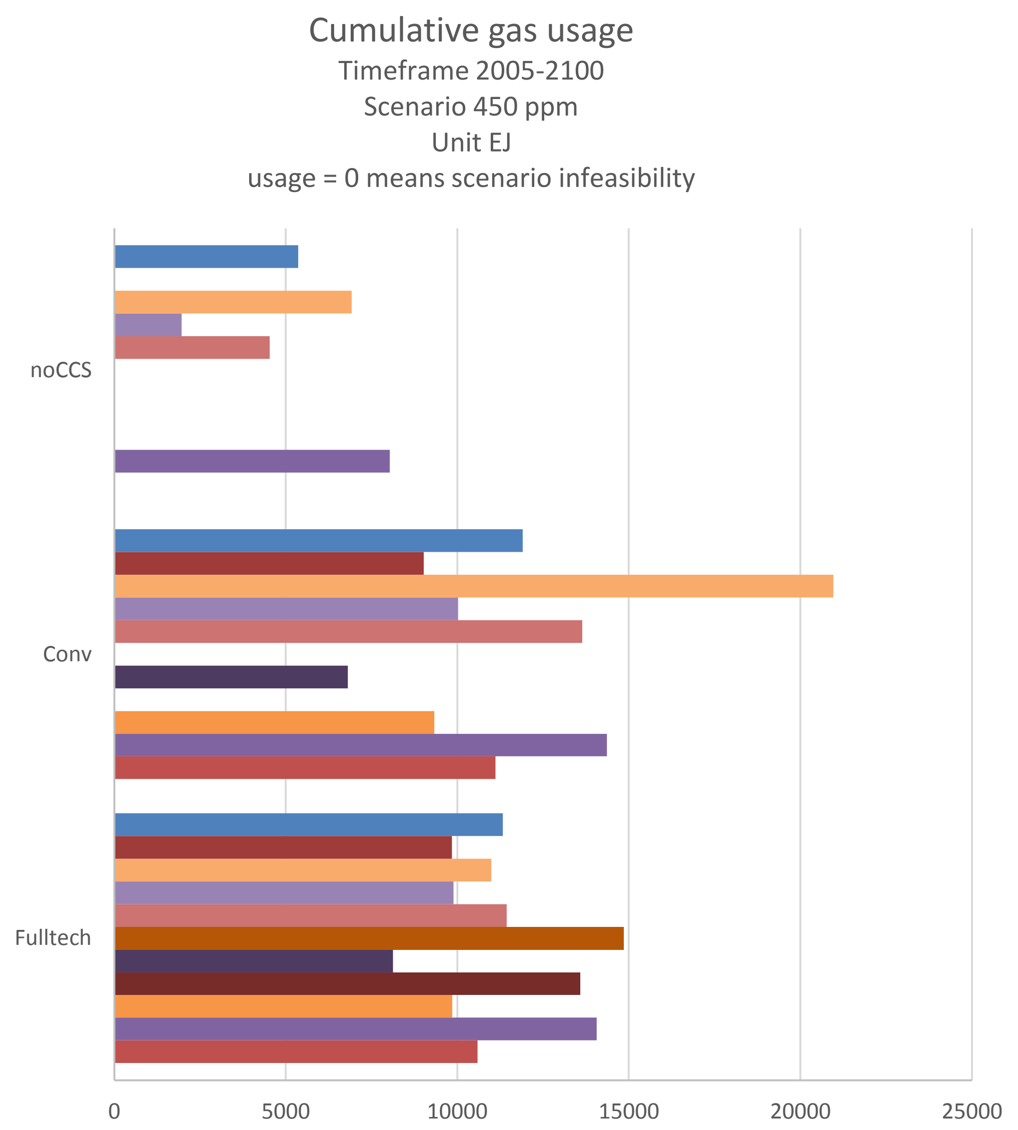
	Fulltech	Conv	noCCS
■ Average	11569	10624	8328
■ WITCH	12083	12080	0
■ TIAM-WORLD	12769	12683	10154
■ REMIND 1.5	12310	9654	3557
■ POLES	13735	9540	8204
■ MESSAGE V.4	10015	0	0
■ MERGE	6668	5773	0
■ IMAGE 2.4	8685	0	0
■ IMACLIM V1.1	10889	9987	0
■ GCAM 3.0	15546	14924	11396
■ BET 1.5	12988	10347	0

Figure 14. Emissions from oil usage according to the EMF27 models (scenario 450 ppm timeframe 2005-2100)



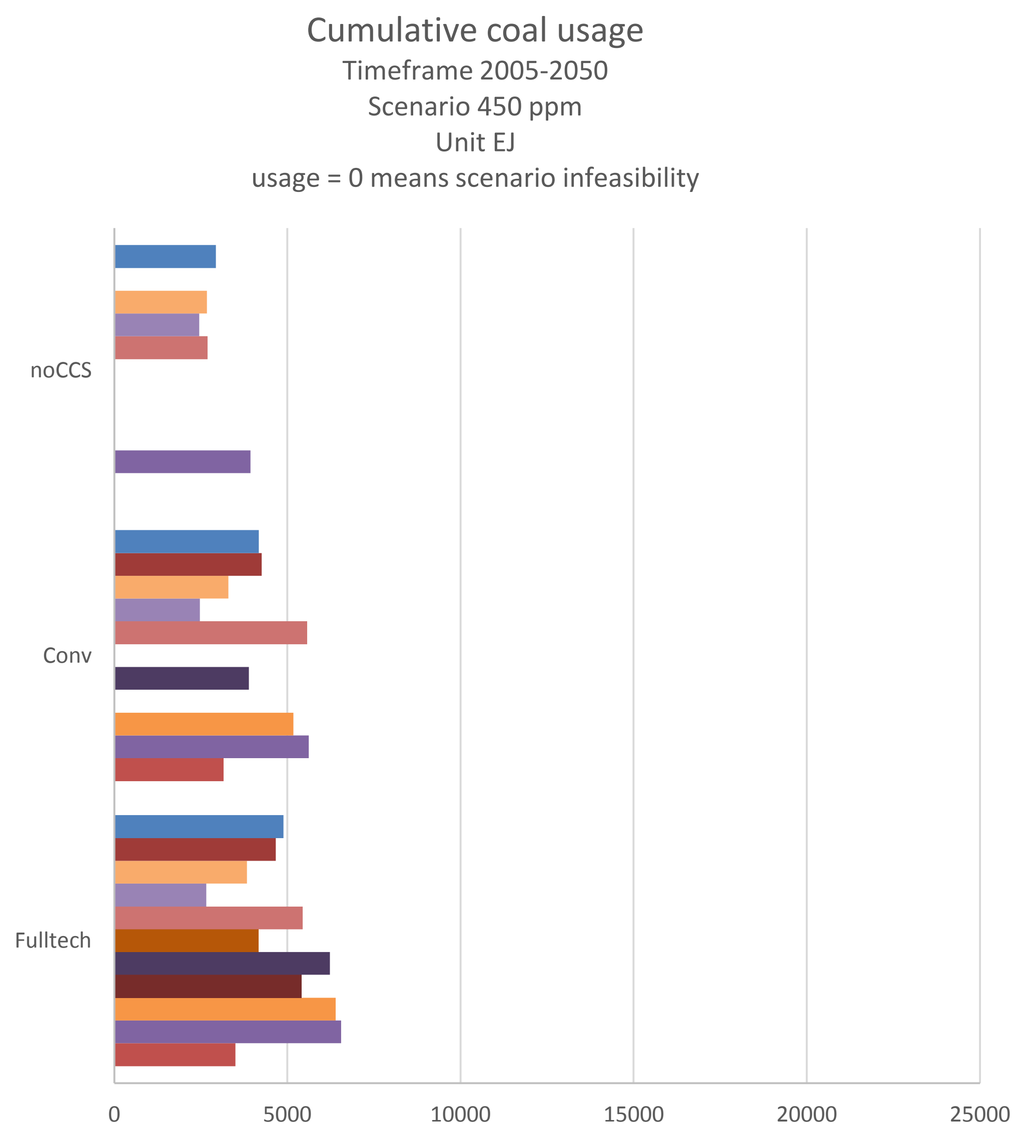
	Fulltech	Conv	noCCS
🟦 Average	5970	5653	4318
🟥 WITCH	4750	4433	0
🟧 TIAM-WORLD	6700	7602	5851
🟪 REMIND 1.5	6642	4971	1961
🟥 POLES	5803	6057	3546
🟫 MESSAGE V.4	6340	0	0
🟪 MERGE	5961	5128	0
🟫 IMAGE 2.4	5771	0	0
🟧 IMACLIM V1.1	6046	5523	0
🟪 GCAM 3.0	6798	6637	5914
🟥 BET 1.5	4886	4873	0

Figure 15. Emissions from gas usage according to the EMF27 models (scenario 450 ppm timeframe 2005-2050)



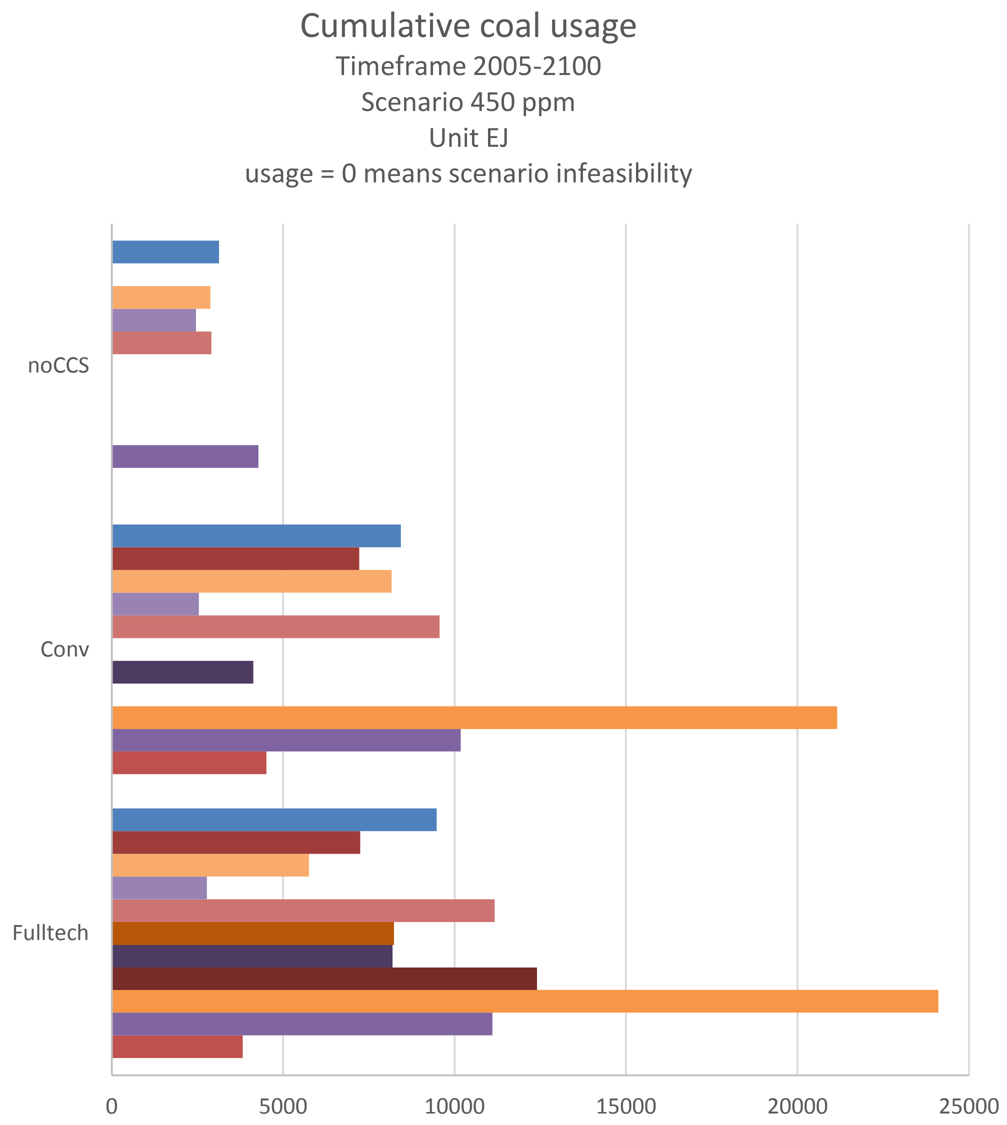
	Fulltech	Conv	noCCS
■ Average	11325	11910	5362
■ WITCH	9843	9024	0
■ TIAM-WORLD	10995	20962	6918
■ REMIND 1.5	9889	10024	1966
■ POLES	11445	13643	4535
■ MESSAGE V.4	14852	0	0
■ MERGE	8130	6814	0
■ IMAGE 2.4	13575	0	0
■ IMACLIM V1.1	9857	9332	0
■ GCAM 3.0	14068	14365	8028
■ BET 1.5	10595	11118	0

Figure 16. Emissions from gas usage according to the EMF27 models (scenario 450 ppm timeframe 2005-2100)



	Fulltech	Conv	noCCS
■ Average	4888	4180	2939
■ WITCH	4665	4257	0
■ TIAM-WORLD	3837	3300	2676
■ REMIND 1.5	2655	2473	2457
■ POLES	5446	5574	2692
■ MESSAGE V.4	4167	0	0
■ MERGE	6228	3887	0
■ IMAGE 2.4	5417	0	0
■ IMACLIM V1.1	6399	5175	0
■ GCAM 3.0	6556	5617	3931
■ BET 1.5	3505	3159	0

Figure 17. Emissions from coal usage according to the EMF27 models (scenario 450 ppm timeframe 2005-2050)



	Fulltech	Conv	noCCS
■ Average	9482	8436	3133
■ WITCH	7251	7225	0
■ TIAM-WORLD	5758	8162	2876
■ REMIND 1.5	2778	2544	2463
■ POLES	11172	9566	2909
■ MESSAGE V.4	8228	0	0
■ MERGE	8194	4134	0
■ IMAGE 2.4	12399	0	0
■ IMACLIM V1.1	24112	21158	0
■ GCAM 3.0	11105	10179	4283
■ BET 1.5	3823	4517	0

Figure 18. Emissions from coal usage according to the EMF27 models (scenario 450 ppm timeframe 2005-2100)