IIASA International Institute for Applied Systems Analysis www.iiasa.ac.at

Assessing the challenges of global long-term mitigation scenarios

Gambhir, A., Napp, T., Hawkes, A., McCollum, D., Fricko, O., Havlik, P., Riahi, K., Drouet, L., Bosetti, V., Bernie, D. and Lowe, J.

IIASA Policy Report
November 2015

Assessing the challenges of global long-term mitigation scenarios

November 2015

Authors: Ajay Gambhir[1], Tamaryn Napp[1], Adam Hawkes[1], David McCollum[2], Oliver Fricko[2], Petr Havlik[2], Keywan Riahi[2], Laurent Drouet[3], Valentina Bosetti[3], Dan Bernie[4] and Jason Lowe[4]

[1]Grantham Institute, Imperial College London, UK

[2]International Institute for Applied Systems Analysis, Laxenburg, Austria

[3]Centro Euro-Mediterraneo sui Cambiamenti Climatici

[4]Met Office Hadley Centre, UK

Version 1.0

Reference: AVOID 2 WPC2a

This work was supported by AVOID 2 programme (DECC) under contract reference no. 1104872

Funded by

Executive summary

The implications of global mitigation to achieve different long-term temperature goals (LTTGs) can be investigated in integrated assessment models (IAMs), which provide a large number of outputs including technology deployment levels, economic costs, carbon prices, annual rates of decarbonisation, degree of global net negative emissions required, as well as utilisation levels for fossil fuel plants. All of these factors can be considered in detail when judging the real-world feasibility of the mitigation scenarios produced by these models.

This study presents a model inter-comparison of three widely used IAMs (TIAM, MESSAGE and WITCH) to analyse multiple mitigation scenarios exploring a range of LTTGs and a range of constraints, including delayed mitigation action, limited end-use electrification and delayed deployment of carbon capture technologies. The scenario outputs across the three models are examined and discussed and a matrix of the different factors concerning scenario feasibility is presented.

The scenarios add to the existing literature (as summarised in the IPCC's fifth assessment report Working Group III on mitigation of climate change) in four principal ways:

- They use harmonised socio-economic pathways across the three models, specifically the second of the new Shared Socio Economic Pathways (SSP2), whose storyline is broadly a continuation of recent trends in economic growth throughout the 21st century, and which therefore provides a reasonably challenging CO_2 emissions reference scenario against which mitigation must occur;
- They explore a large range of long-term temperature goals, from 2^{O}C, through 2.5^{O}C, 3^{O}C and 4^{O}C levels of median temperature change by 2100, in order to analyse the energy mix, technology, cost and other implications of mitigation to these levels when compared to a reference scenario in which no specific mitigation occurs;
- For each temperature goal, the models systematically examine the additional costs and implications of immediate global mitigation action, action starting in 2020 and action starting in 2030, in order to examine the importance of delayed action across many dimensions;
- They add two technology constraint scenarios unexplored in the IPCC fifth assessment report, but which are likely to be critical determinants of the cost and feasibility of achieving significant mitigation: the first a relatively weak level of electrification of end-use sectors (transport, buildings and industrial manufacturing); and the second a delay in the deployment of carbon capture and storage in both the power and industrial sectors, such that it is not deployed before 2050.

The analysis suggests that achieving a 2^{O}C-consistent mitigation pathway is achievable in the sense that the models used provide analytical solutions to the problem of meeting future global energy service demand without exceeding a 21st century CO_2 budget (from fossil fuel and industrial sources) which is broadly consistent with a median temperature change of 2^{O}C by 2100. However, a number of factors contribute to the achievement of this level of mitigation across the models used: unprecedentedly rapid rates of annual CO_2 reductions and energy efficiency improvements in the coming decades; the potential idling of hundreds of GW of unabated coal plants before the end of their useful economic lifetime; rapidly rising carbon prices; costs which range from, at the low end, 1.3-2.3% of 21st century GDP, and at the high end 8.0-9.6% of 21st century GDP (depending on the model and mitigation timing and technology constraints); and the requirement for global net negative CO_2 emissions

towards the end of the 21st century. The task to meet the 2^{O}C target is clearly a challenging one across many dimensions, each of which is worthy of detailed consideration.

In particular, the 2^{O}C scenarios present challenges with respect to:

- ensuring that mitigation action at a global level in line with the target begins as soon as possible, given the significant costs of delays, particularly to 2030;
- achieving sustained energy efficiency improvements over the course of the century and very rapid near-term improvements, which though technically feasible, would be unlikely to occur without very effective policies;
- ensuring commercial-scale deployment of CCS is feasible as soon as technically and economically possible, such that hundreds of GW of CCS power stations can be deployed in the coming decades;
- developing supply chains for other low-carbon technologies such as wind, biomass, solar and nuclear to ensure that hundreds of GW globally can be deployed each decade in the near future;
- operationalising BECCS technology and/or other negative emissions technologies so that global CO_2 emissions can become first neutral and then net-negative in the latter half of the century;
- increasing the penetration of electricity-using heating, transport and industrial process technologies throughout the end-use sectors;
- the political economy issues that would be associated with the early idling of coal-fired power stations without CCS fitted.

To a large extent these points reinforce those made in the IPCC's fifth assessment report. In addition, the new analysis suggests that – as well as the importance of CCS in terms of scenario feasibility and cost effectiveness – its deployment in the first half of the century is important to keep costs down, compared to scenarios in which it is not deployed until 2050. Furthermore, the higher the degree of electrification in the end-use sectors (transport, buildings, industry), the lower the overall mitigation costs.

In addition, this new analysis shows some modelled scenarios with very large average annual emissions reduction rates – larger even than those in the fifth assessment report. For example, one model (WITCH) reduces emissions at 14% per annum in the decade 2030-2040 (and 10% per annum over the period 2030-2050) in a 2^{O}C scenario with global mitigation action delayed until 2030. This level of emissions reductions is even higher than for the WITCH model (9% over the period 2030-2050) in a similar scenario in the "Ampere" model inter-comparison study that contributed to the fifth assessment report, reflecting that a slightly lower 21st century cumulative CO_2 budget (1,340GtCO_2) is being used in this report, relative to that used in the Ampere study (1,400 GtCO_2).

1 Introduction

The IPCC's 5th assessment report Working Group III [1] is based on hundreds of scenarios which assess the environmental, economic and energy technology consequences of reducing greenhouse gas (GHG) emissions in line with future long term climate goals.

These scenarios have been produced using integrated assessment models (IAMs), which represent how future demand for energy, land use and other GHG-producing goods and services are linked to projections of population and economic growth, what technologies and energy sources are used to meet this future demand, and what GHG emissions result.

The large number of scenarios included in the IPCC's 5th assessment allows analysis of a number of sensitivities and assumptions, most notably around the:

- timing of global coordinated mitigation action;
- availability of key technologies such as nuclear and carbon capture and storage;
- degree to which energy efficiency will improve over time;
- level of deployment of renewables such as biomass, wind and solar.

A more detailed examination of the main implications of these scenarios is undertaken in the AVOID 2 WPC1 report [2], which highlighted that the 2^{O}C mitigation goal is still in reach at reasonable cost, although a substantial transformation of the global energy system is required throughout the 21st century, which means that any delays to action, any lack of ambition in energy efficiency improvements, and any absence of major technologies could result in significant additional costs and even jeopardise the achievability of this goal.

This report describes the outputs from a new, post-IPCC fifth assessment, set of scenarios designed to further explore the many dimensions of emissions reduction at a global level, with a particular focus on critically assessing the degree of feasibility and challenge associated with the most stringent mitigation scenarios. In constructing the scenarios, a number of novel aspects have been undertaken compared to the hundreds of scenarios explored in the IPCC's 5th assessment report:

- Constraints using newly-derived CO_2 budgets from Met Office Hadley Centre;
- Model inter-comparison using one of the new shared socio-economic pathways (SSP2);
- Production of a database of scenarios which allows key metrics (fossil share of primary energy, electricity share of final energy, mitigation costs, CO_2 sequestered) to be shown in a stepwise manner when moving between different temperature targets, different levels of delay (to 2020, to 2030) and different technology constraints. This goes further than what the IPCC 5th assessment database allows (as that focuses primarily on 2 and 2.5^{O}C scenarios);
- Some new technology constraint scenarios (CCS only available for deployment from 2050, as opposed to no CCS which has been widely explored in the IPCC's 5th assessment, and constrained electrification of end-use sectors, which has not yet been explored).

The full description of these scenarios, and methods used to explore them, is given in Section 2. Section 3 discusses the scenario results, with analysis of several different aspects of the most stringent mitigation scenarios in order to indicate the range of implications associated with this degree of mitigation. Section 4 constructs a matrix by which to assess the relative degree of challenge associated with each mitigation scenario, combining the different insights introduced in Section 3. Section 5 derives the key policy-relevant messages from this assessment, in order to highlight the major challenges to ensure that the 2^{O}C target remains in reach.

2 Methods

Table 1 describes the full scenario set used in this study.

Table 1: Mitigation scenarios explored in this study

Temperature change / ^{O}C by 2100 (relative to pre-industrial)	**Cumulative (2000-2100) CO_2 emissions from fossil fuel combustion and industry ($GtCO_2$)**	**Scenario variants**
2	1,340	• Immediate action from model base year* • Action from 2020, following moderate action • Action from 2020, following moderate action, with the introduction of CCS delayed until 2050 • Action from 2020, following moderate action, with limited potential for electricity in end-use sectors • Action from 2030, following moderate action
2.5	2,260	• Immediate action from model base year • Action from 2020, following moderate action • Action from 2030, following moderate action
3	3,560	• Immediate action from model base year • Action from 2020, following moderate action • Action from 2030, following moderate action
4	5,280	• Immediate action from model base year • Action from 2020, following moderate action • Action from 2030, following moderate action

Notes: *Model base years are shown in table 2.

In the scenarios described in table 1, "moderate" action refers to a level of emissions reductions (to 2020 or 2030, respectively) in line with the less stringent end of countries' Cancun pledges (where these have been quantified) and reference or unmitigated emissions where these have not been quantified, with full details given in Annex A. The 2020 and 2030 global CO_2 figures, at 39 $GtCO_2$ and 41 $GtCO_2$, are 18% and 24% higher than 2010 CO_2 emissions levels from fossil fuels and industrial processes (at 33 $GtCO_2$). This compares to the total GHG emissions levels estimated by UNEP's 2014 Emissions Gap report [3] in the least stringent version of the Cancun pledges, at 12% and 20% higher than 2010 GHG emissions. However, as shown in Annex A, the 2020 and 2030 fossil and industry CO_2 estimates for the weak interpretation of the Cancun pledges in this study compare fairly closely to those in the Ampere study [4] in which two of the three models in this inter-comparison (WITCH and MESSAGE) participated.

Where the potential for end-use electrification has been limited, this has been done so as to allow only moderate increases in the share of electricity in the end-use (i.e. transport, buildings and industry) sectors over and above current shares. This reflects barriers to the increasing penetration of electricity end-use technologies such as heat pumps, electric vehicles, as well as electric process heating in the industrial manufacturing sectors. Full details of how these electrification caps have been derived are given in Annex B.

Three different IAMs have been inter-compared in order to explore variations in key input assumptions around future technology costs, fossil fuel supply and costs, as well as energy efficiency improvement potential:

- The Imperial College London Grantham Institute's TIMES integrated assessment model (TIAM-Grantham) [5], [6];
- The International Institute for Applied Systems Analysis (IIASA)'s MESSAGE model (MESSAGE-GLOBIOM) [7], [8], [9];
- The Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC)'s WITCH model [10].

Annex C provides a brief description of each model, and table 2 its key features. In order to limit the degree of differentiation, socio-economic assumptions have been equalised across models. For this study, one of the pathways in the shared socio-economic pathways (SSPs) database of scenarios has been used [11]. The SSPs have been developed to provide a standardised set of assumptions for the integrated assessment model and impacts, adaptation and vulnerability (IAV) communities. The storylines underlying each SSP range from relatively conservative assumptions on population growth, economic growth and other factors driving the degree of challenge for mitigation and adaptation, to drivers which make either or both of these objectives highly challenging. For this study, SSP2 has been selected (specifically the OECD variant which provides a median level of GDP growth throughout the century), as it is considered the most closely associated with recent socio-economic growth patterns [12]. This helps to assess the feasibility of meeting the stringent targets even in the face of future energy demand growth based on current trends in socio-economic growth.

Table 2: Integrated assessment models in this study and their key features

Model	**New nuclear**	**CCS**	**BECCS**	**Solar (PV and CSP)**	**Wind (on and offshore)**	**Time step (years)**	**Base year**	**Solution approach**
TIAM-Grantham [5], [6]	Yes	Yes	Yes	Yes	Yes	10	2012	Inter-temporal optimisation
MESSAGE-GLOBIOM [7], [8], [9]	Yes	Yes	Yes	Yes	Yes	10	2010	Inter-temporal optimisation and recursive dynamic
WITCH [10]	Yes	Yes	Yes	Yes	Yes	5	2010	Inter-temporal optimisation

Notes: Key input assumptions around technology costs are shown in figure 6; CCS = carbon capture and storage; BECCS = bioenergy with carbon capture and storage (a key "negative emissions" technology)

The IAM scenarios have been limited to an assessment of the impacts of reducing CO_2 emissions from energy systems (resulting from the combustion of fossil fuels) and industrial process (principally from the chemistry of the cement production process). Since future temperature change will depend not just on CO_2 emissions from these sources, but also from a) CO_2 emissions from land use and b) non-CO_2 emissions from a variety of sources such as agriculture, waste and industrial manufacturing, these sources must also be assessed in any future climate scenario. This has been done by deriving estimated emissions from other GHG sources in scenarios consistent with different LTTGs using data from the Representative Concentration Pathways as well as IIASA's Greenhouse Gas Air Pollution Interactions and Synergies (GAINS) model, as described in detail in Annex D.

3 Results

3.1 Can the models achieve the different scenarios?

All of the models can meet the most stringent temperature goal, which is a 2^{O}C rise in global average surface temperature by 2100 (relative to pre-industrial levels), provided that mitigation action begins in 2020 or earlier and that substantial changes to the energy system occur throughout the century. Resultant emissions in the scenarios with mitigation action starting in 2020, as well as the unmitigated reference scenarios, are shown in figure 1.

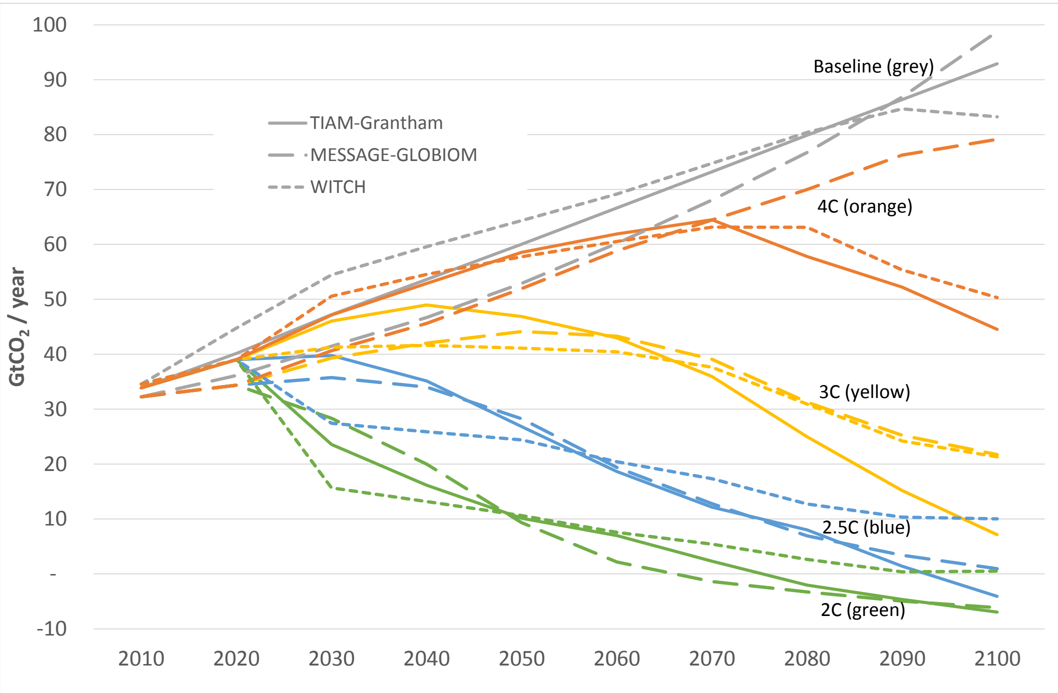

Figure 1: Global fossil fuel and industry CO_2 emissions for each model, for reference and mitigation scenarios, with global mitigation action delayed until 2020

Notes: Emissions levels are capped at 39 $GtCO_2$ in scenarios with global mitigation action delayed until 2020. Model emissions may be lower than this cap before 2020 (for example if model assumes cost-effective uptake of energy efficiency options)

If global coordinated mitigation action is delayed until 2030, two models (WITCH, MESSAGE-GLOBIOM) can still technically meet the 21st century CO_2 budget. The TIAM-Grantham model can only solve by relying in the last decade of the century on a theoretical "backstop" technology which mitigates CO_2 at a cost of \$10,000/tCO_2. Its results have been included here for illustrative purposes only, since the level of backstop technology is an arbitrary choice and does not indicate scenario impossibility in an absolute sense. In addition to the model solution considerations, two models (WITCH and TIAM-Grantham) show very large CO_2 price shocks, as shown in figure 2. In the WITCH model, the CO_2 price increases from zero to \$1,400/tCO_2 between 2030 and 2040, whilst in the TIAM-Grantham model, the CO_2 price increases by more than \$1,000/tCO_2 per decade from 2060 onwards. Such decadal rises in CO_2 prices (with \$1000/tCO_2 equivalent to an increase of \$270/bbl in the price of crude oil) have been suggested to be a useful indication of scenario infeasibility, as they would represent substantial shocks to the global energy-economic system [13]. In the MESSAGE-GLOBIOM model, the CO_2 price increases more gradually, but this is largely as a result of much lower CO_2 emissions growth in the period 2010-2030. These indicators suggest that delaying mitigation action to 2030 takes the models to the margin of technical feasibility.

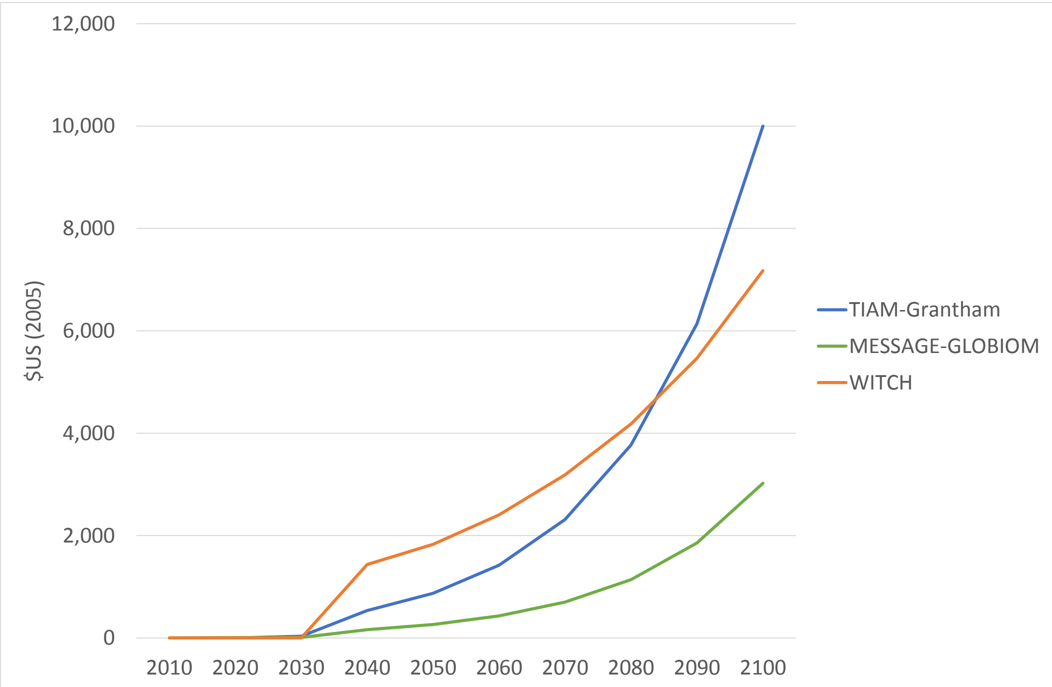

Figure 2: Global carbon price in 2^{O}C scenario with global mitigation action delayed until 2030

3.2 What drives emissions reductions in the coming decades?

The IPCC's fifth assessment report summary for policy makers [14] presents a decomposition of historic emissions changes, separating decadal changes in global CO_2 emissions (from fossil fuel combustion) into four factors: GDP per capita; population; energy intensity of GDP; and CO_2 intensity of energy. This analysis is shown in figure 3, combined with a similar decomposition of one of the mitigation scenarios in this study – the 2^{O}C scenario with global mitigation action delayed until 2020. The analysis shows that the major drivers of emissions growth in past decades – GDP per capita and population growth – will in the current decade begin to be increasingly offset by changes in energy intensity per unit GDP (as energy efficiency of the global economy improves). Once global mitigation action takes hold in 2020, the three models project very rapid reductions in carbon intensity per unit of primary energy demand, as well as continued improvements in energy intensity of energy. The figure also highlights the fairly large spread in projections between the models, with MESSAGE-GLOBIOM projecting only moderate CO_2 emissions growth in the current decade to 2020 as a result of more rapid energy intensity reductions than the other two models.

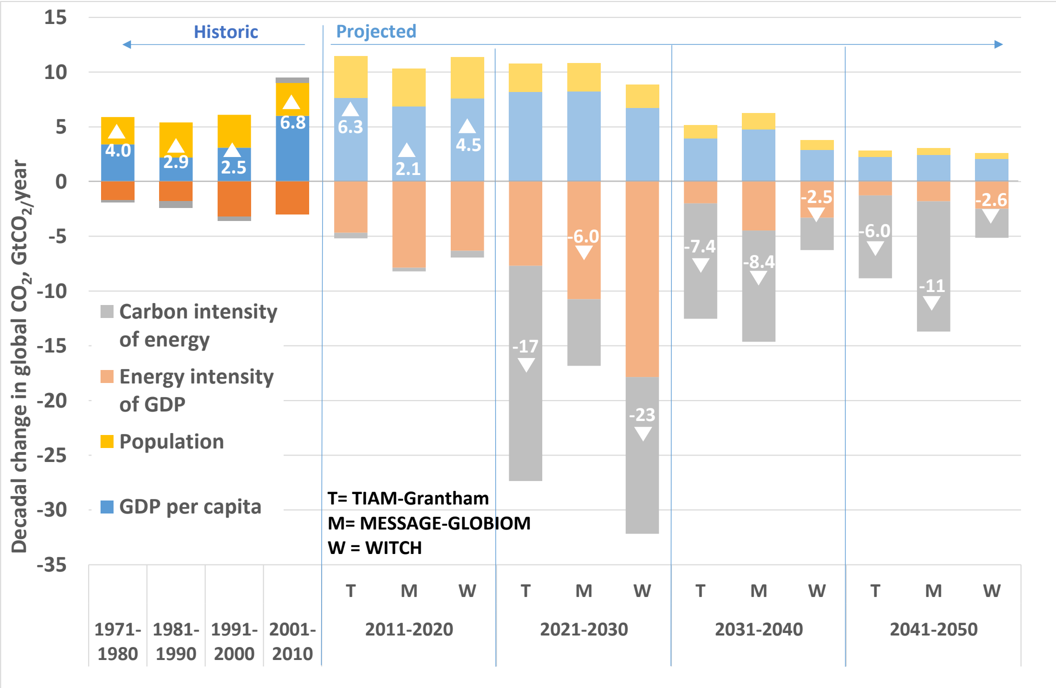

Figure 3: Decomposition of decadal changes in annual global CO_2 emissions into four factors, for historic data and projected for 2^{O}C scenario with global mitigation action delayed until 2020

Notes: Historic data is for fossil fuel combustion CO_2 only, whereas projected data includes cement manufacture process emissions (making these CO_2 emissions about 5% higher than for just fossil fuel combustion). Projected results for the three IAMs inter-compared in this study are shown.

Figure 4 shows the variation across models for emissions in four major emitting regions (USA, China, India and Western Europe) for both the reference scenario as well as the 2^{O}C scenario with global mitigation action delayed until 2020. Of note is the very large spread in reference emissions across the models, particularly for the fast-emerging regions (China and India), reflecting different assumptions on potential rates of improvement of energy intensity and carbon intensity of energy, as well as industrial structure. Clearly these are areas of significant uncertainty and the model spread is instructive of how such uncertainties, even in the presence of harmonised economic and population growth across the three models, can manifest themselves in very different future emissions projections. The mitigation scenario emissions are somewhat more aligned for all three models, although there are differences as to when certain regions reach near-zero or even negative emissions levels. Given the nature of the scenario design – to mitigate globally in those regions offering the cheapest marginal abatement costs for any given time period – the degree of effort in any region will be the result of assumptions on low-carbon technology costs and measures in that region relative to other regions, as well as the reference emissions technology in that region. In any case, the regional analysis is striking in that it sets out how each major region must almost completely decarbonise by the end of the century.

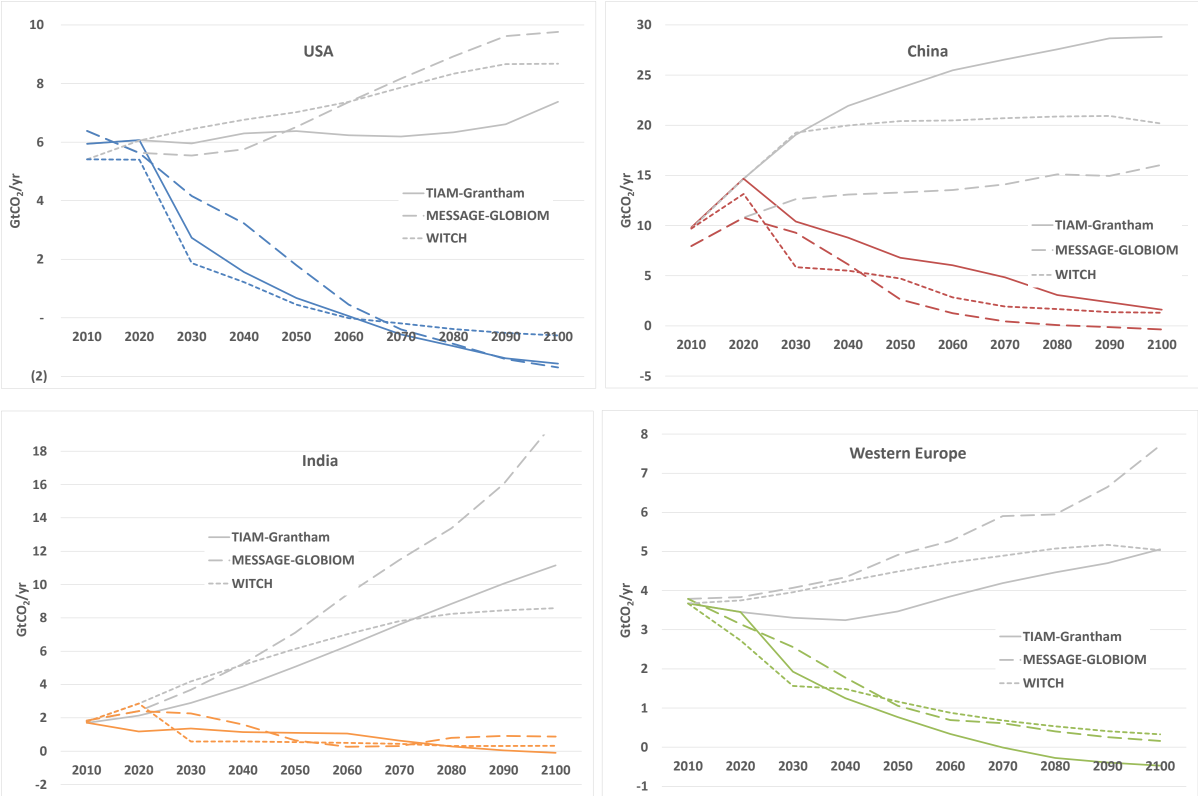

Figure 4: Global CO_2 emissions in reference and 2^OC scenario with global mitigation action delayed until 2020, for four major world regions

Notes: The IIASA MESSAGE-GLOBIOM model aggregates USA with Canada, Guam and Puerto Rico; China with other centrally planned Asian economies (Cambodia, North Korea, Laos, Mongolia, Vietnam); and India with other South Asian economies (Pakistan, Sri Lanka, Bangladesh, Bhutan, Maldives, Afghanistan). Although the main country shown constitutes the vast majority of the aggregated regions in terms of emissions, GDP and population, results for these countries should be treated as only indicative.

3.3 How fast does the energy system decarbonise?

Table 3 shows the average annual rate of global CO_2 emissions reductions in the decade following the start of global mitigation action, for each temperature goal. Energy system decarbonisation rates are very rapid in the most delayed 2^OC scenario, in which global coordinated mitigation action towards the 2^OC goal doesn't begin until 2030. The most drastic decarbonisation decade is that following the start of such mitigation action (2030-2040) which sees global CO_2 emissions fall by an average 7-14% per annum. Where action is delayed until 2020, the 2020-2030 decade sees average annual CO_2 emissions reductions of 2-8% per annum.

Table 3: Average annual rate of change of global CO_2 in decade following start of global mitigation

Scenario	TIAM-Grantham	MESSAGE-GLOBIOM	WITCH
2C immediate	-2.2%	-0.9%	-6.0%
2C delay to 2020	-5.2%	-1.9%	-8.7%
2C delay to 2030	-10.8%*	-6.6%	-14.2%
2.5C immediate	+1.0%	+0.4%	-1.5%
2.5C delay to 2020	-0.1%	+0.4%	-3.5%
2.5C delay to 2030	-2.0%	-0.8%	-5.7%
3C immediate	+2.0%	+1.0%	+1.0%
3C delay to 2020	+1.4%	+1.4%	+0.6%
3C delay to 2030	+1.1%	+0.9%	-0.2%
4C immediate	+1.1%	+1.1%	+2.3%
4C delay to 2020	+1.7%	+1.7%	+2.6%
4C delay to 2030	+1.4%	+1.4%	+2.7%

Notes: *TIAM-Grantham relies on a hypothetical "backstop" technology removing CO_2 at a cost of 2005US$ 10,000/tCO_2 in order to provide a solution for this scenario

For the higher temperature goals, rates of decarbonisation are much less rapid. For the 2.5^{O}C scenarios, two models (TIAM-Grantham and MESSAGE-GLOBIOM) show emissions continuing to rise in the immediate action scenarios and in the case of MESSAGE-GLOBIOM in the delay to 2020 scenario as well. The highest decarbonisation rate is for the WITCH model (-5.7% per year) when action is delayed until 2030. For the 3^{O}C and 4^{O}C goals, in almost all modelled scenarios, CO_2 emissions actually continue to grow in the decade following the start of global mitigation action.

As recently as 2010, decarbonisation rates in excess of 3% per annum were deemed to be "extreme", based on a review of models at that time [15]. More recent analysis includes scenarios with delayed action beginning in 2030, in which average decarbonisation rates over the period 2030-2050 are also very high (5.9-8.5%) [4]. This results from the models' ability to rapidly substitute carbon-intensive for low-carbon technologies – a rapidity which can only be slowed by imposing explicit constraints on the models. Hence, the increasingly rapid rates of decarbonisation observed in the most recent assessments are a facet of the requirement to decarbonise at that rate in order to meet a given CO_2, GHG or other emissions or climate target, given that emissions have continued to rise over time. Such rates have been compared to historic decarbonisation rates across countries, noting that countries such as France and Sweden achieved rates of 2-3% per annum following the early 1970s oil crisis, but that at both a national and global scale, sustained rates as high as recently modelled are "unprecedented" [4].

However rapid projected decarbonisation rates are in the decade(s) following the start of mitigation action towards the 2^{O}C target, a definitive assessment of feasibility cannot be stated based on this metric, given that the policy conditions to enable global mitigation action have not yet emerged. It may therefore be premature to judge what rates of decarbonisation are feasible. A detailed analysis of the energy system changes across the century does, however, shed light on where the greatest challenges lie.

3.4 How does the energy system change over the century?

For the 2^{O}C scenario with mitigation action delayed until 2020, all models depend on a wide range of technologies and measures to meet the 2^{O}C goal, although to different extents for different technologies. Figure 5 shows that the fossil fuel share of primary energy reduces to 48-62% by 2050 and to 22-32% by 2100, compared to a level of more than 80% since 1970 [16]. Although total primary energy demand will increase by 2100, total fossil fuel demand will shrink – this means that the size (in terms of revenues) of the fossil fuel industry will decline in real terms (i.e. not accounting for price inflation).

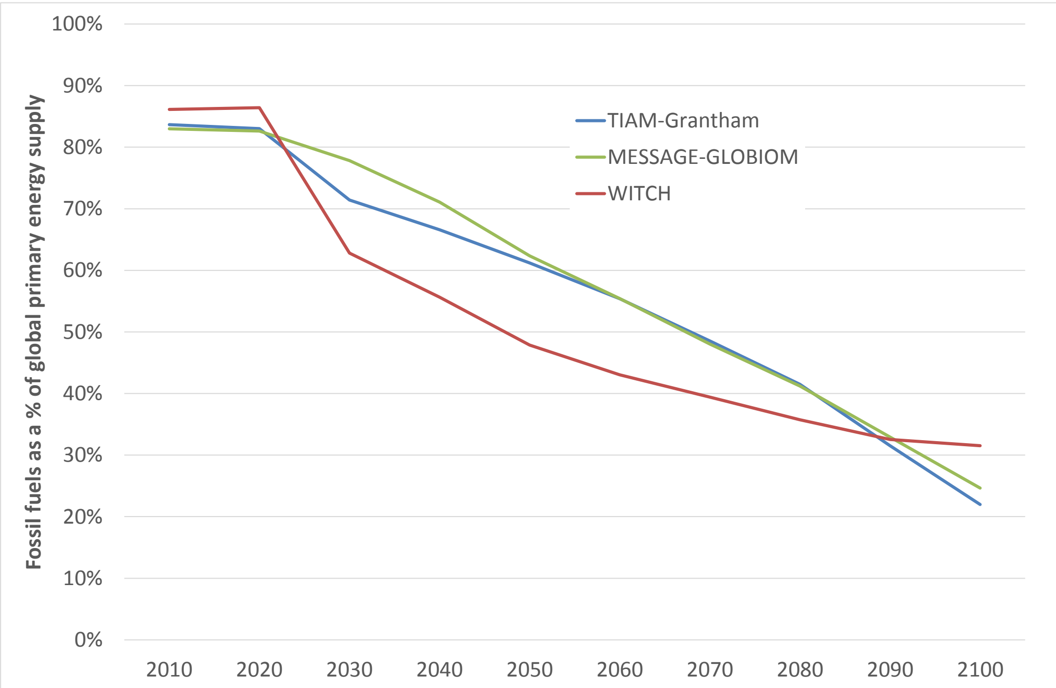

Figure 5: Fossil fuel share of global primary energy (2^{O}C scenario, global mitigation action delayed until 2020)

The change in the mix of primary energy across the three models is shown in figure 6. The models show a broad range of energy demand reduction in the mitigation scenarios, with a 2100 value of 1,150-1,450 EJ /year in the reference reducing to 550-1,250 EJ /year in the 2^{O}C scenario with delayed action to 2020. This represents a very wide range of energy efficiency improvement rates – in the most extreme case, the WITCH model sees primary energy intensity of global GDP reduce from 7.8MJ/$2005 in 2010 to 1.0MJ/$2005 GDP by 2100 –an average annual reduction of 2.3% per year. By contrast, TIAM-Grantham shows a reduction rate of 1.3% per year, and MESSAGE-GLOBIOM 1.7% per year. However, the annual average rates of reduction in the first decade following the start of global coordinated mitigation action are particularly high, ranging from 2.4% (TIAM-Grantham) to 6.8% (WITCH). These projected rates compare to historical primary energy reduction rates of

1.2% per year since 1970 [17]. Whilst these efficiency improvements are technically possible and reflected in other studies with a focus on maximising energy efficiency potential [17], it is unclear whether such a sector-wide, global improvement in energy efficiency is socially and politically realistic.

Even in the model with the highest energy intensity of GDP by 2100 (TIAM-Grantham), the 2^{O}C goal can be achieved. This happens through a very significant shift of the energy system from fossil fuel-based to a mix of low-carbon sources dominated by wind, solar and biomass, as shown in figure 6.

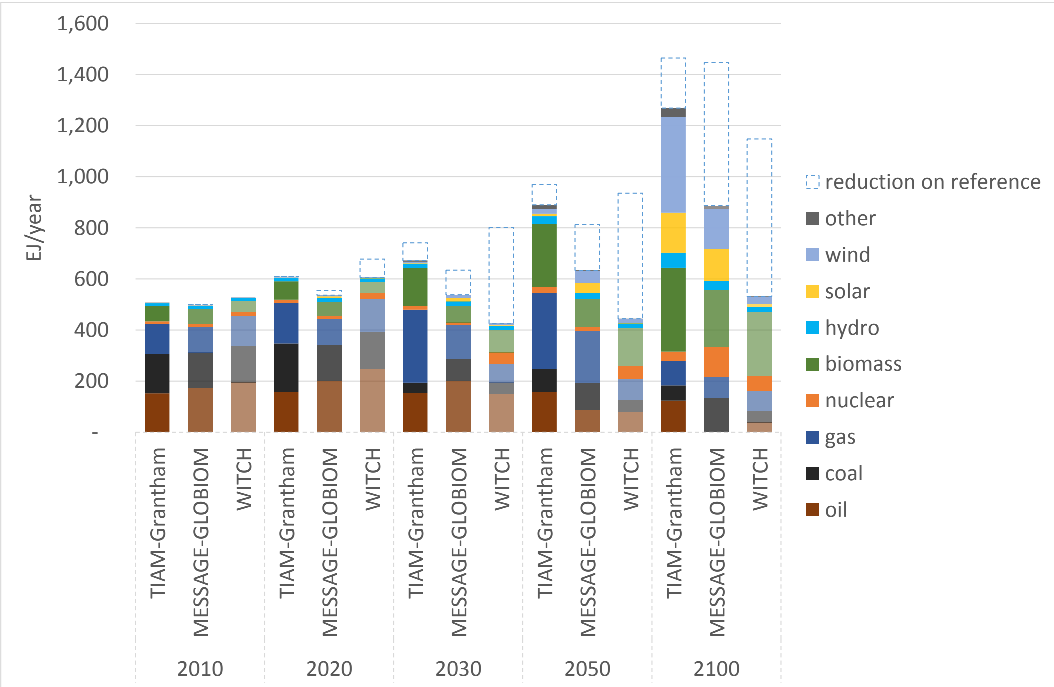

Figure 6: Global primary energy demand to 2100 (2^{O}C scenario, global mitigation action delayed until 2020)

In each model, the electricity sector sees a fundamental shift from a system dominated by fossil fuel (mostly coal), nuclear and hydro in 2010 to a broad mix of renewables, nuclear and coal and gas with CCS by 2100, as shown in figure 7. The increase in electricity generation in the TIAM-Grantham model is particularly striking, with a ten-fold increase in electricity generation between 2012 and 2100, reflecting that, in the latter half of the century, electricity increases as a share of final energy from 24% in 2050 (compared to about 18% today [18]) to 65% in 2100, dominated by buildings (88%) and industry (75%).

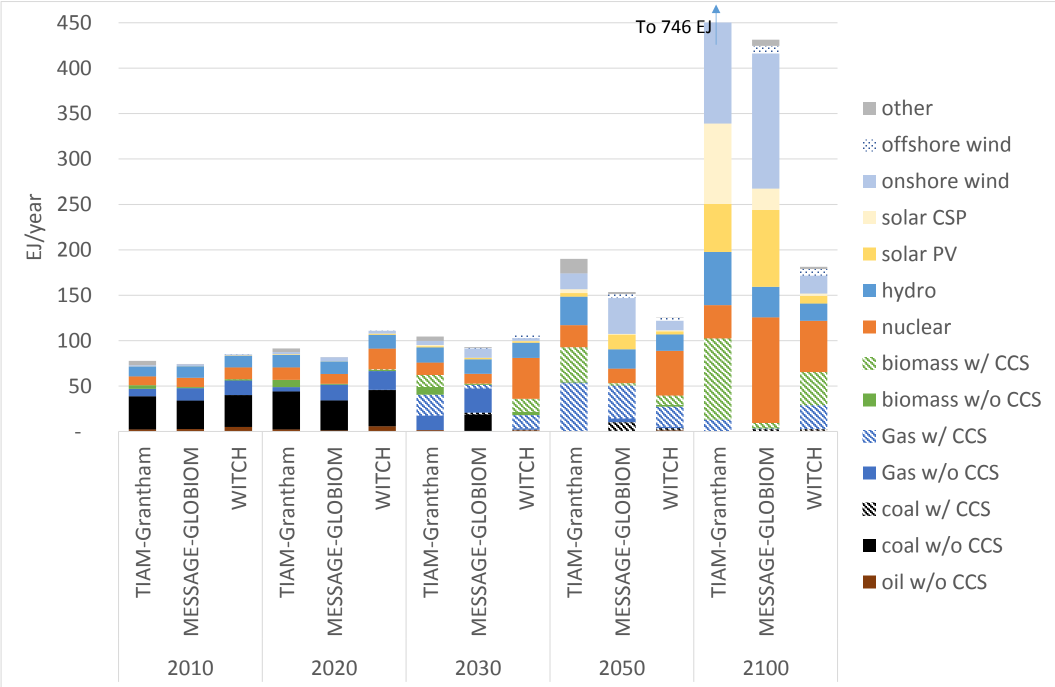

Figure 7: Electricity generation in 2^{O}C scenario with global mitigation action delayed until 2020

There is some variation between models in terms of the electricity generation technologies favoured. The period to 2050 sees a rapid penetration of CCS, which is already responsible for almost half of power generation globally by 2030 in the TIAM-Grantham model, and about 30% of generation in WITCH and MESSAGE-GLOBIOM. Nuclear takes a significant share of generation in WITCH and MESSAGE-GLOBIOM by 2100, whilst it is far less rapidly deployed in TIAM-Grantham, particularly compared to solar PV and CSP, as well as onshore wind. Although for all models nuclear is one of the more expensive technologies in capital cost terms (see figure 8), its relatively large-scale deployment in WITCH and MESSAGE-GLOBIOM reflects the technology's potential for supplying low-carbon, base-load power. In contrast, solar PV and wind are constrained in the models by the intermittency and variability of the resource.

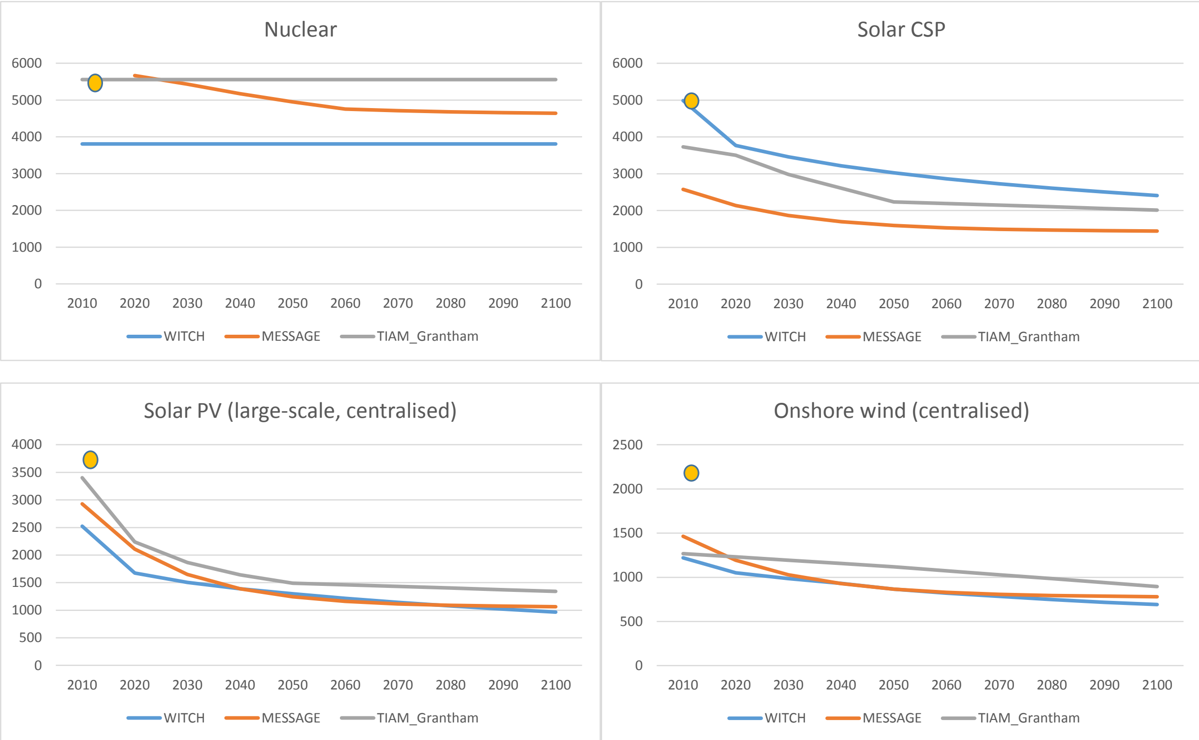

Figure 8: Capital costs of major low-carbon electricity generation technologies, $US(2005)/kW

Notes: These figures are for US costs as illustrative of global costs; Yellow dots show recent estimates of 2012 costs in the US [19], which in most cases are close to estimates shown. For onshore wind, other estimates exist with lower costs around $1,200/GW (full range $1,200-2,600/GW) [20] so the initial model values are considered to be reasonable although at the lower end of the range.

Table 4 shows the deployment rates of key low-carbon technologies in the decade following the start of global mitigation action in the 2^{O}C scenarios with action starting in 2020 and 2030. The table is limited to show only those technologies requiring a build rate of greater than 30 GW per year on average (i.e. 300GW or more per decade). Rates of 30 GW per year have been achieved in key technologies including solar PV, nuclear and (on and offshore) wind, which is why deployment rates below this level are not deemed particularly challenging.

Table 4 indicates that a major challenge will include achieving hundreds of GW of installed CCS and nuclear capacity, with large-scale deployment starting as early as 2020 in the 2^{O}C scenario with action starting in 2020. Whilst these technology choices are not prescriptive, but rather indicate what would be deployed in a least-cost scenario without specific deployment constraints, they nevertheless highlight the potential importance of CCS and nuclear in achieving rapid decarbonisation of an energy system deeply reliant on fossil fuel combustion. Table 3 also shows the power generation technologies deployed in a 2^{O}C scenario with delayed action to 2020, where CCS is not available until 2050 as well as where electrification rates are capped. The former scenario indicates the increased importance of nuclear and the importance of gas and biomass generation (without CCS) as well as solar (PV and CSP). The latter scenario, in which electricity demand is lower than the other scenarios, still sees significant requirements for CCS (with gas and biomass), wind and nuclear power. Hence, as relatively unproven technologies, there is an immense benefit to successfully demonstrating both CCS and biomass (with and without CCS) power generation.

Table 4: Maximum absolute ramp-up rates of low-carbon technologies in 2^{O}C scenarios

Scenario	**Technology**	**Growth rate**
2^{O}C with delay to 2020	Gas with CCS	800 GW in 2020-2030 (TIAM-Grantham)
	Biomass with CCS	520 GW in 2020-2030 (WITCH)
	Nuclear	830 GW in 2020-2030 (WITCH)
	Onshore wind	480 GW in 2020-2030 (MESSAGE-GLOBIOM)
2^{O}C with delay to 2030	Gas with CCS	1,600 GW in 2030-2040 (TIAM-Grantham)
	Biomass with CCS	1,000 GW in 2030-2040 (TIAM-Grantham)
	Nuclear	640 GW in 2030-2040 (WITCH)
	Onshore wind	750 GW in 2030-2040 (MESSAGE-GLOBIOM)
	Solar PV	1,300 GW in 2030-2040 (TIAM-Grantham)
	Solar CSP	950 GW in 2030-2040 (TIAM-Grantham)
2^{O}C with delay to 2020 and CCS delayed until 2050	Gas without CCS	780 GW in 2020-2030 (TIAM-Grantham)
	Biomass without CCS	480 GW in 2020-2030 (TIAM-Grantham)
	Nuclear	1,050 GW in 2020-2030 (WITCH)
	Offshore wind	320 GW in 2020-2030 (WITCH)
	Solar PV	380 GW in 2020-2030 (MESSAGE-GLOBIOM)
	Solar CSP	550 GW in 2020-2030 (TIAM-Grantham)
2^{O}C with delay to 2020 and weak electrification	Gas with CCS	900 GW in 2020-2030 (TIAM-Grantham)
	Biomass with CCS	540 GW in 2020-2030 (WITCH)
	Nuclear	780 GW in 2020-2030 (WITCH)
	Onshore wind	440 GW in 2020-2030 (MESSAGE-GLOBIOM)

Notes: Only power generation technologies deployed at a rate greater than 30 GW per year on average (i.e. 300 GW per decade) have been shown; no exogenous constraints have been imposed on technology deployment rates in these scenarios.

Such rapid deployment rates of specific technologies are common to studies of this kind, with recent model inter-comparisons focused specifically on this issue showing median deployment rates of wind of between 600-1,500 GW per decade, solar 1,700 GW per decade and nuclear just below 500 GW per decade during the period 2030-2050 in 2^{O}C-consistent (in this case 450 ppm) scenarios with delayed action to 2030 [21], [22].

On the demand side, the energy mix across end-use sectors changes significantly over time, as shown in figure 6. Although economic growth is harmonised across models, they can obtain different compositions of growth by sector (i.e. by industrial, commercial and agricultural services). This, as well as differing energy efficiency improvement rates, explains why MESSAGE-GLOBIOM and TIAM-Grantham have different energy demand growth rates in the industrial and transport sectors. WITCH does not have a sectoral split for final energy demand although does separate out the light duty vehicles sector, as represented in the transport panel of figure 9. The figure shows that in all three models, total final energy demand shifts to electricity over the century, most markedly in the TIAM-Grantham model, in which electricity increases from 17% of total final energy in 2012 to 66% in 2100. This includes the virtual complete electrification of the buildings sector (about 90% of final energy by 2100, a proportion also reflected in the MESSAGE-GLOBIOM model) and industry sector (about 75% of final energy by 2100). In the transport sector, all models show a significant shift from oil over the course of the century, with TIAM-Grantham favouring hydrogen (fuel cell) vehicles and MESSAGE-GLOBIOM showing a more balanced split between gas, electricity, hydrogen and biofuels, by 2100.

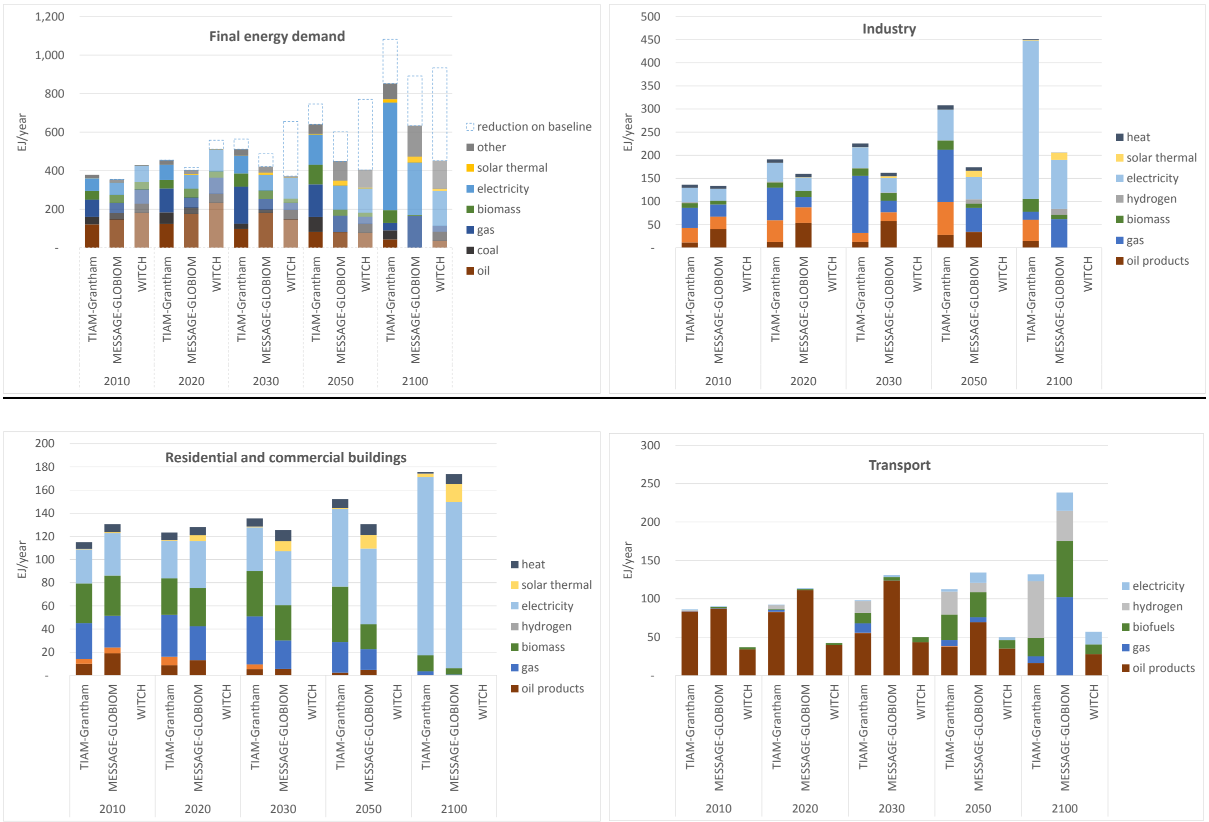

Figure 9: Total and sectoral global final energy demand, $2^{O}C$ scenario with global action delayed to 2020

Notes: WITCH model only shows end-use final energy demand for the light duty vehicles sector.

3.5 How much does mitigation cost?

The measures of mitigation cost (as shown in figure 10 and table 5) reported by each of the three models is different. TIAM-Grantham reports the annual change in global welfare compared to the reference, as defined by the sum of changes in consumer and producer surplus, which is essentially the change in energy system cost once changes in energy service supply and demand (that result from changes in energy prices) have been accounted for. MESSAGE-GLOBIOM links the changes in energy prices from its energy-technology module to an aggregated macro-economic growth model, in order to investigate the changes in production and consumption of all goods and services (i.e. not just energy, as in TIAM-Grantham) that result from the mitigation scenario. WITCH reports a “policy cost”, which results from a more detailed macro-economic model.

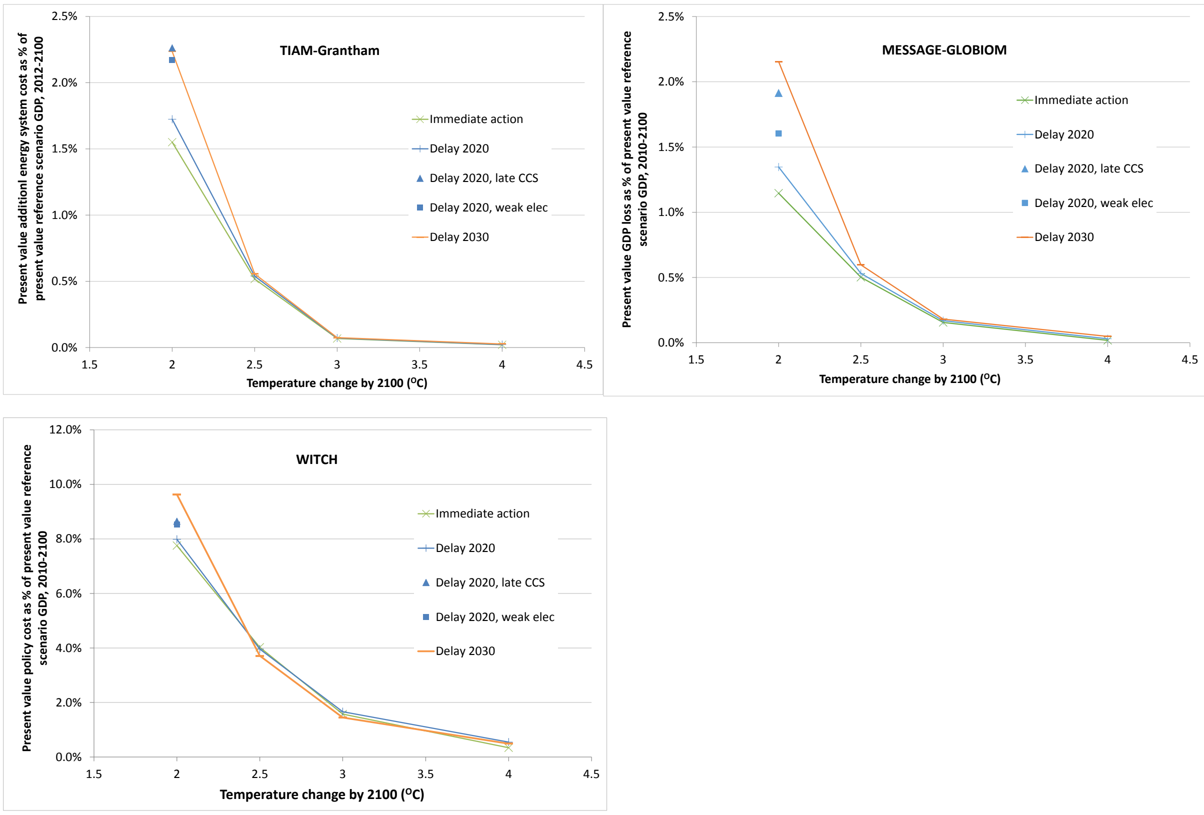

Figure 10: Mitigation cost to 2100, for each temperature goal, vs reference scenario

Notes: Present value costs and GDP are arrived at using a discount rate of 5% per year. The TIAM-Grantham 2ºC, delayed action to 2030 scenario hits a feasibility constraint in 2100, suggesting that strictly speaking this scenario is not feasible without a theoretical “backstop” technology costing \$10,000/tCO_2. As such the scenario has been included for comparability purposes only.

There is no simple relationship between how the mitigation cost is calculated and the magnitude of the cost i.e. the degree to which a mitigation cost including a more complete set of macro-economic feedbacks leads to a larger or smaller cost compared to a cost based purely on the energy system technology costs [23]. As can be seen from figure 8, the relative mitigation costs between scenarios are broadly similar across the three models, with an increasingly sharp rise in cost between the 3ºC and 2.5ºC, and the 2.5ºC and 2ºC scenarios, and with delayed global mitigation action and technology limitations leading to increased mitigation costs for the 2ºC scenarios in particular. The magnitude of mitigation costs is similar in TIAM-Grantham and MESSAGE-GLOBIOM, but in general much higher in WITCH.

The TIAM-Grantham and MESSAGE-GLOBIOM models' mitigation costs for the 2^{O}C scenario with immediate action and delayed action to 2020 (in a range of about 1.3-1.7% of present value GDP to 2100) are similar to those found in previous AVOID studies which used variants of these models to assess regional mitigation costs for China and India [24], [25], [26]. The higher costs for the WITCH model reflect its macro-economic structure, which includes a production function with energy supply technologies "nested" together and with limited substitutability, which may be too rigid to reflect longer-term possibilities for low-carbon technologies to replace high-carbon technologies in the energy supply sectors. In addition, there are limited mitigation options in the transport sector within the model. Combined, these tend to result in much higher mitigation costs.

Across all three models, the global cost range for achieving the 2^{O}C scenarios spans 1.1-10% of present value GDP to 2100 (equivalent to $34-288 trillion). This order of magnitude difference has been reported in previous modelling exercises, notably Clarke et al (2009) whose Energy Modelling Forum 22 (EMF 22) study showed present value mitigation costs for a 450ppm scenario ranging from $12-120 trillion over the century [27].

Table 5: Mitigation cost to 2100, for each temperature goal, vs reference scenario

Scenario	TIAM-Grantham	MESSAGE-GLOBIOM	WITCH
2C immediate	1.55%	1.15%	7.76%
2C delay to 2020	1.72%	1.35%	7.99%
2C delay to 2030	2.24%	2.15%	9.63%
2.5C immediate	0.52%	0.50%	4.02%
2.5C delay to 2020	0.54%	0.53%	3.96%
2.5C delay to 2030	0.56%	0.60%	3.71%
3C immediate	0.07%	0.16%	1.58%
3C delay to 2020	0.07%	0.17%	1.66%
3C delay to 2030	0.08%	0.18%	1.45%
4C immediate	0.02%	0.02%	0.34%
4C delay to 2020	0.02%	0.03%	0.55%
4C delay to 2030	0.03%	0.05%	0.49%

Notes: Units for each % cost as explained in Figure 10

3.6 What does rapid mitigation imply for coal-fired power stations?

Even where global mitigation action begins in 2020, there are likely to be significant stranded coal plants as a result of rapid decarbonisation to meet the long term temperature goal of 2^{O}C, with average capacity factors falling to between 0 and 0.5 by 2030 (compared to 0.65 currently), as shown in figure 11. In two models (WITCH and TIAM-Grantham) the capacity factors fall to approximately zero, implying the early scrapping of 1,400 GW of coal capacity by 2030. This is equivalent to scrapping 80% of existing economically viable coal capacity.

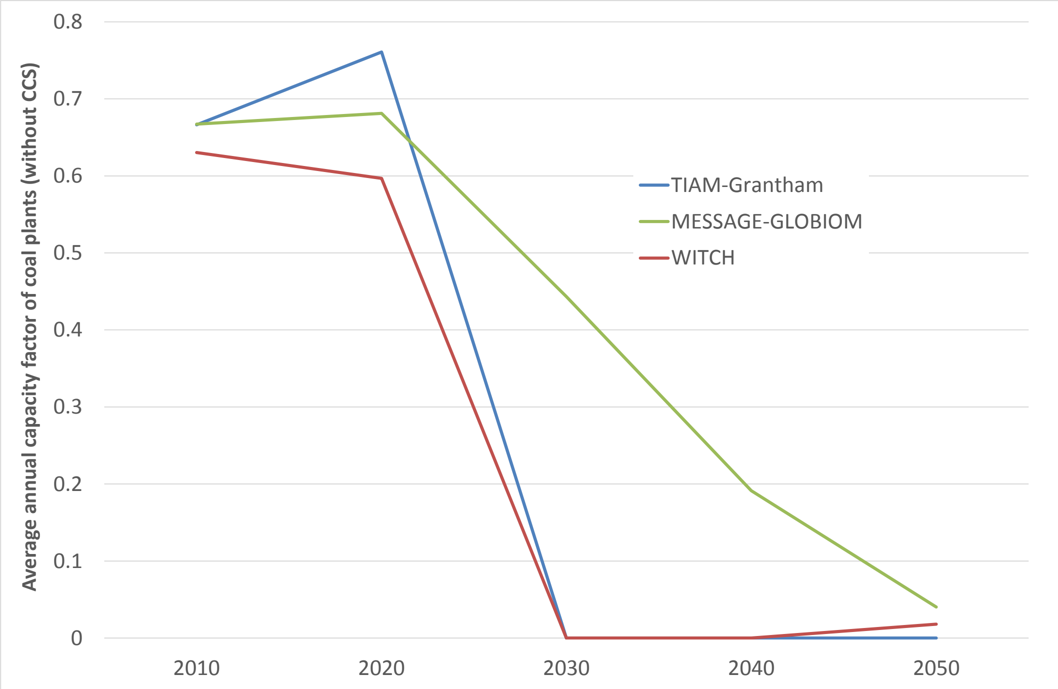

Figure 11: Average capacity factor of coal plant in 2^{O}C scenario with global action delayed to 2020

Notes: Capacity factor is the proportion of total capacity generating over the course of each year. Hence a capacity factor of 0.6 in a given year would imply that over the course of the year, on average each GW of installed coal plant capacity generates at 60% of its theoretical maximum output.

Idling of coal plant has been explored in a previous study using a variant of the MESSAGE model with a broadly 2^{O}C-consistent goal, finding that an average of 350 GW of coal plant would be stranded on average over the period 2030-2050 if global mitigation action were delayed to 2030 [28]. In this study, for the 2^{O}C scenario with delayed action until 2030, the MESSAGE-GLOBIOM model has just over 900 GW of coal by 2040, with an average capacity factor about half the level in 2030 – equivalent to about 450 GW of idle coal plants and therefore of a similar magnitude to the previous study's estimate.

3.7 How important is CO_2 capture in achieving the most stringent mitigation scenarios?

To achieve the 2^{O}C goal, all models show a significant role for CO_2 capture technologies, as illustrated in figure 12. This peaks by 2080 in two models (TIAM-Grantham and MESSAGE-GLOBIOM) where 30-35 $GtCO_2$/year (approximately the current CO_2 emissions level) is being captured. In theory there is a sufficiently large global geological storage potential to accommodate this cumulative level of sequestration, which in the TIAM-Grantham model (which has the highest cumulative level of sequestration) reaches 1,900 $GtCO_2$ by 2100, compared to estimates of storage of at least 2,000 $GtCO_2$ globally, with potentially much more [29], [30]. This does, however, highlight the importance of CCS, which must be sufficiently developed to be deployed at scale as soon as possible. With delayed CCS, mitigation costs increase very significantly, with half a percentage point of GDP lost over the century (as shown in figure 10). This compares to an almost doubling of mitigation cost if there is no CCS at all [4].

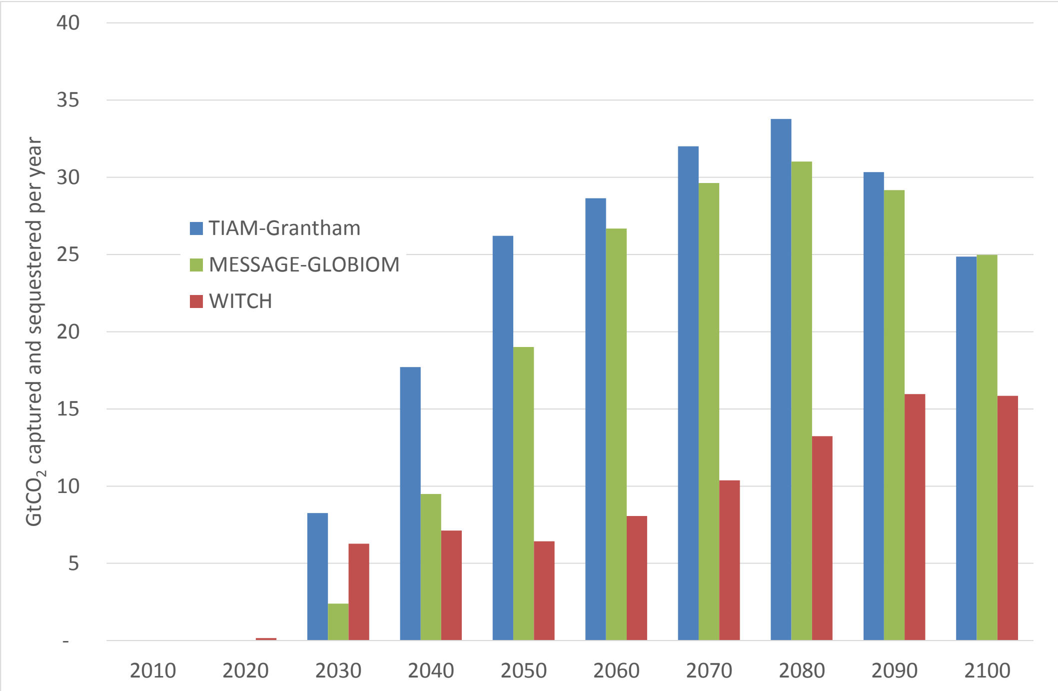

Figure 12: Global CO_2 captured from the fossil and industry sectors (2^OC, action delayed to 2020)

Figure 13 highlights the degree to which global CO_2 emissions become negative as a result of delays to global coordinated mitigation action. In the scenario with delayed action to 2020, two of the models (TIAM-Grantham and MESSAGE-GLOBIOM) show net negative emissions by 2080. In the scenario with delayed action to 2030, all three models show net negative emissions by 2080.

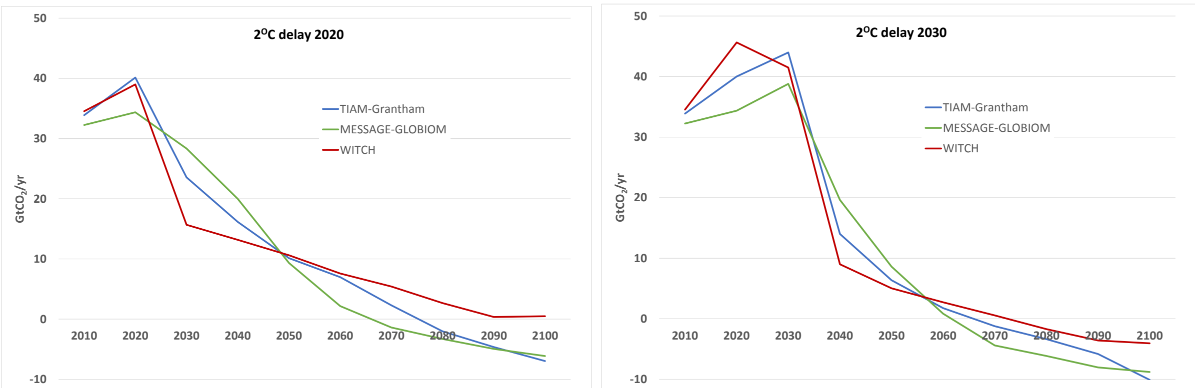

Figure 13: Global CO_2 emissions in 2^OC scenarios with global mitigation action delayed until 2020 and 2030

Notes: The TIAM-Grantham 2^OC, delayed action to 2030 scenario hits a feasibility constraint in 2100, suggesting that strictly speaking this scenario is not feasible without a theoretical "backstop" technology costing \$10,000/tCO_2. As such the scenario has been included for comparability purposes only.

To a large extent this reflects the RCP2.6 scenario originally presented in the literature, with net negative emissions by around 2070, even where mitigation action begins immediately [31]. This conclusion is also reflected in other assessments such as the UNEP Emissions Gap report, whose scenarios have net zero emissions achieved between 2060 and 2080 [3].

A significant driver of net negative emissions is bio-energy with carbon capture and storage (BECCS) technology, in which net sequestration of atmospheric CO_2 occurs, through the use of biomass to generate electricity or produce biofuels, with capture of CO_2 in these processes. Figure 14 shows the growing importance of BECCS over the century in each model, in the 2^{O}C scenario with global mitigation action delayed until 2020.

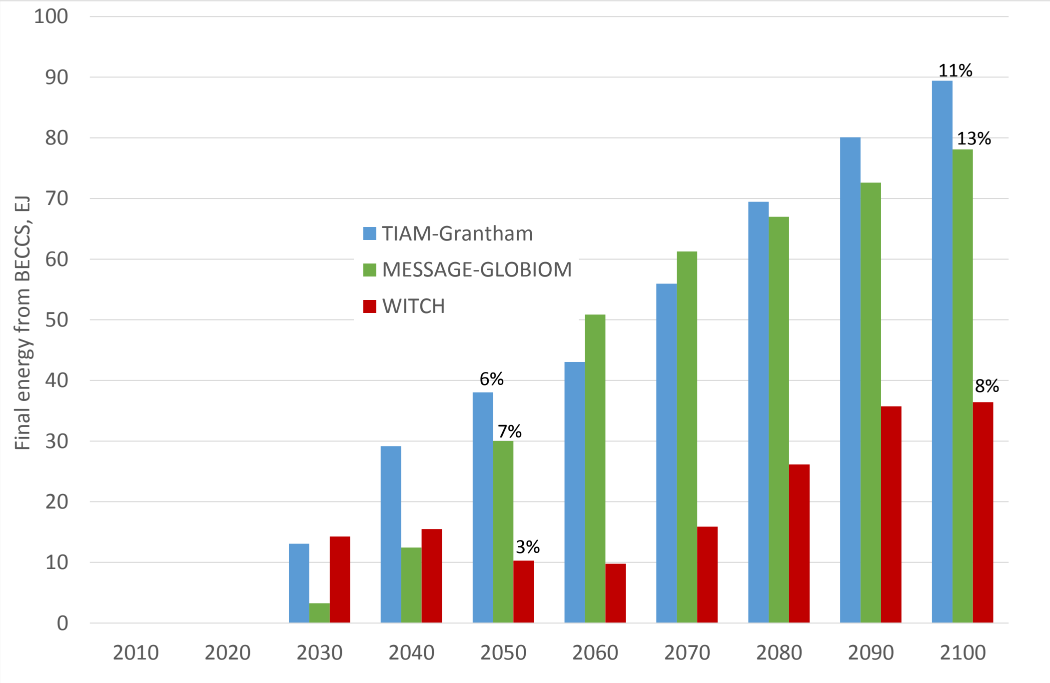

Figure 14: Final energy supplied by bio-energy with CCS (BECCS), 2^{O}C scenario with global mitigation action delayed until 2020

Notes: % figures for 2050 and 2100 years show % of total final energy supplied by BECCS.

4 What are the main challenges to mitigation?

The results presented and discussed in Section 3 highlight a number of challenges to achieving the mitigation scenarios, in particular those with the most stringent temperature goal (i.e. 2^{O}C) and with the most delayed action or constrained technologies. Table 6 outlines the different dimensions of feasibility explored. None of these dimensions is definitive in determining the degree of feasibility of any given scenario. Nevertheless, taken together, they provide an important set of indicators of how challenging each mitigation scenario is likely to be.

Table 7 sets out a (subjective) judgement on the degree of challenge associated with achieving each of the 2^{O}C scenarios explored in this model inter-comparison exercise. The 2^{O}C scenario with immediate action (in which action started from the models' base years of 2010 or 2012) is excluded from this analysis, since it has been included purely as a hypothetical scenario, which is in fact no longer attainable. The table suggests that the 2^{O}C scenario with action delayed to 2030 is the most challenging when considering the full range of criteria. It is a clear indication for the need to commence global mitigation action towards a 2^{O}C-consistent CO_2 budget as early as possible in the decade 2020-2030.

Table 6: Indicators for degree of challenge in achieving mitigation scenarios

Indicator	Relevance	Example of challenge
Does the model "solve"	Models contain a wide range of technologies and significant energy efficiency improvement capability. Lack of solution implies more ambitious technology deployment and efficiency improvements must be achieved in reality [1].	All models provide an analytical solution for all scenarios explored, although for 2°C scenario with global action delayed to 2030, TIAM-Grantham reaches its $10,000/t$CO_2$ limit by 2100, indicating this is at its own model-defined feasibility limit (See Section 3.1).
CO_2 price and rate of increase	Very high CO_2 prices would imply energy services are very expensive. Very rapid decadal rises in CO_2 price imply rapid adjustments to energy prices. Both of these could be socially unacceptable and / or result in economic instability [13].	For the 2°C scenario with global action delayed to 2030, two models (TIAM-Grantham and WITCH) see decadal CO_2 price increases of greater than $1,000/t$CO_2$ (See Section 3.1).
Rate of decarbonis-ation	Historical global rates of decarbonisation have been limited, and at a country level up to 3% per year during periods of policy to achieve a rapid shift away from oil [4].	WITCH and TIAM-Grantham both show average annual CO_2 reduction rates in excess of 10% per year over the decade 2030-2040, in 2°C scenario with global action delayed to 2030 (See Section 3.3).
Mitigation cost	High mitigation cost implies more expensive energy, which is likely to lead to resistance from households and businesses.	WITCH mitigation cost for 2°C scenario with global action delayed to 2030 costs almost 10% of 21st century GDP. This may be unacceptably high (see Section 3.5)
Idling of high-carbon assets	Early retirement (as evidenced by sustained zero capacity factors of coal plants within their lifetime) means potentially significant economic losses for coal-fired electricity generators. This will lead to resistance from utilities to idle these plants [28].	In the 2°C scenario with delayed action to 2030, TIAM-Grantham has 780 GW of zero capacity factor coal plants in 2040, of which 315 GW has 20 or more years of remaining life. In the 2°C scenario with delayed action to 2020, TIAM-Grantham has 1,400 GW of idle coal plant by 2030, of which almost 1,200 GW has 7 years of remaining life (See Section 3.6)
Technology deployment rates	Significant decadal increases in particular technologies must be questioned on the grounds of real-world ability to develop and scale up supply chains and access skills and labour, and financial and material resources [21], [22].	In the 2°C scenario with delayed action to 2020, the most striking deployment rates over the period 2020-2030 are for nuclear (830 GW in WITCH), gas with CCS (800 GW in TIAM-Grantham), biomass with CCS (520 GW in WITCH), and onshore wind (480 GW in MESSAGE-GLOBIOM) (See Section 3.4).
Rate of energy intensity improvements	Very rapid energy efficiency improvements across the economy would require a widespread shift to a range of technologies prone to behavioural barriers [32].	WITCH sees almost flat final energy demand globally over the 21st century in the 2°C scenario with action delayed to 2020. This compares to a more-than-doubling of final energy demand in the reference scenario (see Section 3.4)
Quantity of CO_2 captured and stored	Implies successful large-scale deployment of CCS, overcoming technical, economic, legal and other barriers for CO_2 transport and storage [33]	MESSAGE-GLOBIOM and TIAM-Grantham see over 30GtCO_2/yr captured by 2080 in the 2°C scenario with delayed action to 2020 (see Section 3.7)
Timing of net global negative CO_2 emissions	Very large-scale deployment of negative emissions technologies (e.g. BECCS) poses technical, regulatory, infrastructure, economic challenges [34].	All three models see global CO_2 emissions at negative levels by 2080 in the 2°C scenario with delayed action to 2030 (see Section 3.7).

Table 7: Degree of challenge presented by 2^{O}C mitigation scenarios

Scenario	Models solve	CO_2 prices	CO_2 rate of change	Mitigation cost	Idling of coal plant	Technology deployment rates	Energy intensity improvement	CO_2 captured	Negative emissions	Overall
Delay to 2020	All models solve	1 model shows >$1,000/t$CO_2$ increase in CO_2 price per decade in period 2080-2100	2020-2030 period sees 2-9% average annual CO_2 reductions	2 models have cost as 1.3-1.7% of 21st century GDP. 1 model 8.0% of 21st century GDP	2 models have 1,400GW of idle coal plant by 2030	Over 300 GW each of nuclear, gas CCS, biomass CCS, onshore wind in 2020-2030	2.4-6.8% annual fall in primary energy/unit GDP in 2020-2030	2 models have >30 GtCO_2 captured in 2080	2 models see negative emissions by 2080	
Delay to 2020, late CCS	All models solve	1 model shows >$1,000/t$CO_2$ increase in CO_2 price per decade in period 2070-2100. and CO_2 price almost $10,000/t$CO_2$ by 2100	2020-2030 period sees rate 2-7% average annual CO_2 reductions	2 models have cost as 1.9-2.3% of 21st century GDP, 1 model 8.6% of 21st century GDP	2 models have 1,400GW of idle coal plant by 2030	Over 300 GW each of gas, biomass, nuclear, solar (PV, CSP) and offshore wind in 2020-2030	3.0-8.3% annual fall in primary energy/unit GDP in 2020-2030	1 model has >30 GtCO_2 captured by 2060	All models see negative emissions by 2090	
Delay to 2020, weak electrification	All models solve	1 model shows >$1,000/t$CO_2$ increase in CO_2 price per decade in period 2070-2100, and CO_2 price almost $9,000/t$CO_2$ by 2100	2020-2030 period sees rate 2-9% average annual CO_2 reductions	2 models have cost as 1.6-2.2% of 21st century GDP, 1 model 8.5% of 21st century GDP	2 models have 780-1,400GW of idle coal plant by 2030	Over 300 GW each of gas CCS, biomass CCS, onshore wind and nuclear in 2020-2030	2.6-7.1% annual fall in primary energy/unit GDP in 2020-2030	2 models have >30 GtCO_2 captured in 2080	2 models see negative emissions by 2080	
Delay to 2030	Only two out of three models solve	All models show >$1,000/t$CO_2$ increase in CO_2 price per decade in period 2090-2100. 2 models show CO_2 price >$7,000/t$CO_2$ by 2100	2030-2040 period sees rate 7-14% average annual CO_2 reductions	2 models have cost as 2.2% of 21st century, 1 model 9.6% of 21st century GDP	2 models have 800GW of idle coal plants by 2040	Over 300 GW of gas CCS, biomass CCS, solar (PV, CSP), onshore wind and nuclear in 2030-2040	1.9-8.9% annual fall in primary energy/unit GDP in 2030-2040	1 model has >30 GtCO_2 captured by 2060	All models see negative emissions by 2080	

Notes: Green = least challenging, red = most challenging; colours do not indicate absolute level of challenge, only relative level to each-other.

5 What are the key messages for policy-makers that follow from this analysis?

It is well-understood from the IPCC 5th assessment that mitigation to achieve the 2^{O}C target is still technically feasible, but that the challenges and costs increase with delayed action, absent or limited key supply-side technologies and low levels of energy efficiency improvements. This analysis highlights the additional challenges and costs of failing to achieve electrification in the energy end-use sectors, as well as the costs of failing to deploy CCS before 2050. Moreover, the analysis presented here highlights the multiple dimensions across which the challenge of achieving the most stringent mitigation scenarios should be considered. In summary, the 2^{O}C scenarios present particular challenges with respect to:

- ensuring that mitigation action at a global level in line with the target begins as soon as possible, given the significant costs of delays, particularly to 2030;
- achieving sustained energy efficiency improvements over the course of the century and very rapid near-term improvements, which though technically feasible, would be unlikely to occur without very effective policies;
- ensuring commercial-scale deployment of CCS is feasible as soon as technically and economically possible, such that hundreds of GW of CCS power stations can be deployed in the coming decades;
- developing supply chains for other low-carbon technologies such as wind, biomass, solar and nuclear to ensure that hundreds of GW globally can be deployed each decade in the near future;
- demonstrating the different aspects of BECCS technology and/or other negative emissions technologies so that global CO_2 emissions can become first neutral and then net-negative in the latter half of the century.
- increasing the penetration of electricity-using heating, transport and industrial process technologies throughout the end-use sectors;
- managing the political economy issues that would be associated with the early idling of coal-fired power stations without CCS fitted.

In addition to these challenges, it should be noted that the models do not incorporate local and national fossil fuel subsidies, which means that the significant and rapid shift away from these in the mitigation scenarios modelled is hampered if the approximately $550 billion of global subsidies remain in force [18]. A rapid phase out of subsidies would help to boost renewable energy deployment and, in particular, energy efficiency and conservation efforts.

Further analysis in the AVOID 2 programme will build on these scenarios to stress-test the achievability of the 2^{O}C goal with constraints on technology take-up rates and deployment patterns (including for energy efficiency measures), as well as the impact of unconventional gas on the low-carbon transition.

References

[1] IPCC. Climate Change 2014: Working Group III: Mitigation of Climate Change. IPCC, United Nations; 2014.
[2] Dessens O, Anandarajah G, Gambhir A. Review of existing emissions pathways and evaluation of decarbonisation rates - AVOID 2 WPC1 2014.
[3] UNEP. The Emissions Gap Report 2014 2014.
[4] Riahi K, Kriegler E, Johnson N, Bertram C, den Elzen M, Eom J, et al. Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technol Forecast Soc Change n.d. doi:10.1016/j.techfore.2013.09.016.
[5] Loulou R, Labriet M. ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure. Comput Manag Sci 2007;5:7–40. doi:10.1007/s10287-007-0046-z.
[6] Loulou R, Labriet M, Kanudia A. Deterministic and stochastic analysis of alternative climate targets under differentiated cooperation regimes. Energy Econ 2009;31, Supplement 2:S131–43. doi:10.1016/j.eneco.2009.06.012.
[7] Messner S, Strubegger M. Model-based decision support in energy planning. Int J Glob Energy Issues 1999;12:196–207. doi:10.1504/IJGEI.1999.000837.
[8] Riahi K, Grübler A, Nakicenovic N. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol Forecast Soc Change 2007;74:887–935. doi:10.1016/j.techfore.2006.05.026.
[9] Riahi K, Dentener F, Gielen D, Grubler A, Jewell J, Klimont Z, et al. Chapter 17 - Energy Pathways for Sustainable Development. Glob. Energy Assess. - Sustain. Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria: 2012, p. 1203–306.
[10] Bosetti V, Carraro C, Galeotti M, Massetti E, Tavoni M. WITCH - A World Induced Technical Change Hybrid Model. Rochester, NY: Social Science Research Network; 2006.
[11] O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, et al. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim Change 2014;122:387–400. doi:10.1007/s10584-013-0905-2.
[12] Schweizer VJ, O'Neill BC. Systematic construction of global socioeconomic pathways using internally consistent element combinations. Clim Change 2014;122:431–45. doi:10.1007/s10584-013-0908-z.
[13] Rogelj J, McCollum DL, O'Neill BC, Riahi K. 2020 emissions levels required to limit warming to below 2 °C. Nat Clim Change 2013;3:405–12. doi:10.1038/nclimate1758.
[14] IPCC. Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change 2014.
[15] Elzen MGJ den, Vuuren DP van, Vliet J van. Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. Clim Change 2010;99:313–20. doi:10.1007/s10584-010-9798-5.
[16] Smil V. Energy Transitions: History, Requirements, Prospects. ABC-CLIO; 2010.
[17] IIASA. Global Energy Assessment. Cambridge University Press; 2011.
[18] IEA. World Energy Outlook 2014. IEA ; OECD; 2014.
[19] Energy Information Administration. Capital cost for electricity plants 2013.
[20] National Renewable Energy Laboratory. Transparent Cost Database (September 2013 Update) n.d. http://www.nrel.gov/analysis/tech_cost_data.html (accessed May 18, 2015).
[21] Eom J, Edmonds J, Krey V, Johnson N, Longden T, Luderer G, et al. The impact of near-term climate policy choices on technology and emission transition pathways. Technol Forecast Soc Change n.d. doi:10.1016/j.techfore.2013.09.017.
[22] Van Der Zwaan BCC, Rösler H, Kober T, Aboumahboub T, Calvin KV, Gernaat DEHJ, et al. A cross-model comparison of global long-term technology diffusion under a 2°c climate change control target. Clim Change Econ 2013;04:1340013. doi:10.1142/S2010007813400137.
[23] Pissarides C. Assessment of macro economic transmission mechanisms of carbon constraints through the UK economy - a report for the Committee on Climate Change 2008.
[24] Gambhir A, Schulz N, Napp T, Tong D, Munuera L, Faist M, et al. A hybrid modelling approach to develop scenarios for China's carbon dioxide emissions to 2050. Energy Policy 2013;59:614–32. doi:10.1016/j.enpol.2013.04.022.
[25] Gambhir A, Napp TA, Emmott CJM, Anandarajah G. India's CO2 emissions pathways to 2050: Energy system, economic and fossil fuel impacts with and without carbon permit trading. Energy 2014;77:791–801. doi:10.1016/j.energy.2014.09.055.

[26] Anandarajah G, Gambhir A. India's CO2 emission pathways to 2050: What role can renewables play? Appl Energy 2014;131:79–86. doi:10.1016/j.apenergy.2014.06.026.
[27] Clarke L, Edmonds J, Krey V, Richels R, Rose S, Tavoni M. International climate policy architectures: Overview of the EMF 22 International Scenarios. Energy Econ 2009;31, Supplement 2:S64–81. doi:10.1016/j.eneco.2009.10.013.
[28] Johnson N, Krey V, McCollum DL, Rao S, Riahi K, Rogelj J. Stranded on a low-carbon planet: Implications of climate policy for the phase-out of coal-based power plants. Technol Forecast Soc Change n.d. doi:10.1016/j.techfore.2014.02.028.
[29] IPCC. Special Report on Carbon Dioxide Capture and Storage: Summary for Policymakers 2005.
[30] National Energy Technology Laboratory. Carbon Sequestration Atlas of the United States and Canada-Third Edition 2010.
[31] Vuuren DP van, Stehfest E, Elzen MGJ den, Kram T, Vliet J van, Deetman S, et al. RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. Clim Change 2011;109:95–116. doi:10.1007/s10584-011-0152-3.
[32] Sorrell S. The Economics of Energy Efficiency: Barriers to Cost-effective Investment. Cheltenham ; Northampton, Mass: Edward Elgar Publishing Ltd; 2004.
[33] IEA. Technology Roadmap: Carbon Capture and Storage 2013 2013.
[34] McGlashan N, Shah N, Caldecott B, Workman M. High-level techno-economic assessment of negative emissions technologies. Process Saf Environ Prot 2012;90:501–10. doi:10.1016/j.psep.2012.10.004.
[35] Havlík P, Schneider UA, Schmid E, Böttcher H, Fritz S, Skalský R, et al. Global land-use implications of first and second generation biofuel targets. Energy Policy 2011;39:5690–702. doi:10.1016/j.enpol.2010.03.030.
[36] Rao S, Riahi K. The Role of Non-CO2 Greenhouse Gases in Climate Change Mitigation: Long-term Scenarios for the 21st Century. Energy J 2006;27:177–200.
[37] Amann M, Bertok I, Borken-Kleefeld J, Cofala J, Heyes C, Höglund-Isaksson L, et al. Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. Environ Model Softw 2011;26:1489–501. doi:10.1016/j.envsoft.2011.07.012.
[38] Rafaj P, Rao S, Klimont Z, Kolp P, Schöpp W, Amann M. Emissions of air pollutants implied by global long-term energy scenarios. IIASA Vienna 2010.
[39] Messner S, Schrattenholzer L. MESSAGE–MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. Energy 2000;25:267–82. doi:10.1016/S0360-5442(99)00063-8.
[40] Meinshausen M, Raper SCB, Wigley TML. Emulating IPCC AR4 atmosphere-ocean and carbon cycle models for projecting global-mean, hemispheric and land/ocean temperatures: MAGICC 6.0. Atmospheric Chem Phys Discuss 2008;8:6153–272.
[41] Winiwarter W, Höglund-Isaksson L, Schöpp W, Tohka A, Wagner F, Amann M. Emission mitigation potentials and costs for non-CO2 greenhouse gases in Annex-I countries according to the GAINS model. J Integr Environ Sci 2010;7:235–43. doi:10.1080/19438151003774430.
[42] Höglund-Isaksson L, Winiwarter W, Purohit P, Rafaj P, Schöpp W, Klimont Z. EU low carbon roadmap 2050: Potentials and costs for mitigation of non-CO2 greenhouse gas emissions. Energy Strategy Rev 2012;1:97–108. doi:10.1016/j.esr.2012.05.004.
[43] Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma MLT, Lamarque J-F, et al. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Clim Change 2011;109:213–41. doi:10.1007/s10584-011-0156-z.
[44] Bernie D, Lowe JA. Analysis of climate projections from the IPCC working group 3 scenario database. AVOID2 deliverable WPA.1 2014.
[45] Taylor KE, Stouffer RJ, Meehl GA. An Overview of CMIP5 and the Experiment Design. Bull Am Meteorol Soc 2012;93:485–98. doi:10.1175/BAMS-D-11-00094.1.
[46] Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, Knutti R, et al. Greenhouse-gas emission targets for limiting global warming to 2 °C. Nature 2009;458:1158–62. doi:10.1038/nature08017.
[47] Allen MR, Frame DJ, Huntingford C, Jones CD, Lowe JA, Meinshausen M, et al. Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature 2009;458:1163–6. doi:10.1038/nature08019.
[48] Matthews HD, Gillett NP, Stott PA, Zickfeld K. The proportionality of global warming to cumulative carbon emissions. Nature 2009;459:829–32. doi:10.1038/nature08047.

Annex A: Regional CO_2 emissions in 2020 and 2030 for moderate action

There are four categories of country to consider for the weak Cancun pledges scenario:

1. Countries which have offered unilaterally to meet an absolute CO2 or GHG emissions reduction on a specified base year

The EU, for example, has pledged that its 2020 GHG emissions are 20% below 1990 levels by 2020. The 2020 emissions cap given such pledges is determined simply by taking the specified emissions reduction from the specified base year. In the case of the EU, unfortunately neither TIAM, WITCH nor MESSAGE represent the region distinctly, with countries spread over a Western and Eastern European region. As such, an assumption has been made that those countries in Western Europe would have a target of 25% below their 1990 value, whilst those in Eastern Europe would have a target of 5% below their 1990 level. This differentiation is in line with the effort share principles upon which the non-traded (i.e. non EU ETS) sectoral emissions target in the EU is distributed between Member States. The specific % reductions chosen follow from Croatia (an Eastern European country) having a target to achieve a 5% reduction on its 1990 emissions levels. The combination of the 25% Western European countries target with the 5% Eastern European countries target yields an average reduction across all EU28 countries of just less than 20%, so this simplified burden split is deemed an acceptable approximation.

2. Countries which have offered unilaterally to meet an emissions intensity reduction on a specified base year

This category applies to China and India, which have offered a 40% and 20% reduction on their 2005 emissions intensity respectively. The 2020 absolute emissions level under this weaker pledge is calculated by multiplying the 2005 absolute emissions level by the projected GDP growth over the period 2005-2020 (using SSP2 GDP projections) and then subtracting the specified % reduction.

3. Countries which have made a pledge based on capping emissions at a specified %age below a 2020 business as usual level

Countries such as Brazil and Indonesia have made such pledges. In the case of these countries an appropriate BAU estimate is required. This has been calculated by first taking the 2005 emissions level, and then by applying an emissions growth factor over the period 2005 to 2020. The latter factor has been derived from den Elzen (2012), itself based on BAU projections from OECD (2012), with both of these studies covering all GHG emissions and land use change (whereas this study is focused on energy and industrial CO2 only). Strictly speaking, the use of this factor could account for the fact that the economic growth projected in this study, using SSP2 figures, is different to that projected using OECD (2012) figures. However, many factors affect emissions growth, not just GDP, and so a simplifying assumption has been made to use the same factor.

4. Countries which have not made a pledge

This category applies to countries such as the USA, whose Cancun pledge is contingent on international action, and the majority of non-Annex I countries, who have stated qualitatively a series of nationally appropriate mitigation actions (NAMAs). In many cases, it makes most sense to simply not impose a cap on regions representing these countries – or combinations of these countries – in the TIAM, WITCH and MESSAGE models. However, in some cases regions represented by the models include a combination of countries form this category, and countries from other categories. In these cases a projection of BAU emissions for these countries is required, before emissions for the different countries within the region can be aggregated up to a regional estimate of 2020 emissions. As for category 3, this category of countries therefore requires an assumption of BAU emissions in 2020, and the 2005-2020 emissions growth factor derived from den Elzen (2012) has again been applied to 2005 emissions.

Details of Cancun pledges (where quantified) – Annex I

Country/region	Weak pledge	Strong pledge
Australia	GHG 5% below 2000 by 2020	GHG 25% below 2000 by 2020
Belarus	Emissions 5% below 1990 by 2020	Emissions 10% below 1990 by 2020
Canada	None	GHG 17% below 2005 by 2020
Croatia	Emissions 5% below 1990 by 2020	Emissions 5% below 1990 by 2020
EU	GHG 20% below 1990 by 2020	GHG 30% below 1990 by 2020
Iceland	GHG 15% below 1990 by 2020	GHG 30% below 1990 by 2020
Japan	None	GHG 25% below 1990 by 2020
Kazakhstan	15% below 1992	GHG 25% below 1990 by 2020
New Zealand	GHG 10% below 1990 by 2020	GHG 20% below 1990 by 2020
Norway	GHG 30% below 1990 by 2020	GHG 40% below 1990 by 2020
Russian Federation	GHG 15% below 1990 by 2020	GHG 25% below 1990 by 2020
Switzerland	GHG 20% below 1990 by 2020	GHG 30% below 1990 by 2020
Ukraine	GHG 15% below 1990 by 2020	GHG 20% below 1990 by 2020
USA	None	GHG 17% below 2005 by 2020

Source: http://unfccc.int/resource/docs/2011/sb/eng/inf01r01.pdf

Details of Cancun pledges (where quantified in % reduction terms) – Non-Annex I

Country/region	Weak pledge	Strong pledge
Brazil	GHG 36.1% below 2020 BAU by 2020	GHG 38.9% below 2020 BAU by 2020
Chile	GHG 20% below 2020 BAU by 2020	GHG 20% below 2020 BAU by 2020
China	GHG intensity 40% below 2005 in 2020	GHG intensity 45% below 2005 in 2020
India	CO2 intensity 20% below 2005 levels in 2020	CO2 intensity 25% below 2005 levels in 2005
Indonesia	None	GHG 26% below 2020 BAU by 2020
Israel	GHG 20% below 2020 BAU by 2020	GHG 20% below 2020 BAU by 2020
Mexico	None	GHG 30% below 2020 BAU by 2020
Papua New Guinea	None	GHG 50% lower by 2030
South Korea	GHG 30% below 2020 BAU by 2020	GHG 30% below 2020 BAU by 2020
Rep of Moldova	GHG 25% below 1990 by 2020	GHG 25% below 1990 by 2020
Singapore	None	GHG 16% below 2020 BAU by 2020
South Africa	None	GHG 34% below 2020 BAU by 2020

Source: http://unfccc.int/resource/docs/2011/awglca14/eng/inf01.pdf

For categories 3 and 4, in many cases the pledges result in emissions higher than the BAU projected in den Elzen (2012). In such cases the pledge has been assumed to be the BAU in 2020.

Discrepancies between calculated 2020 regional emission caps under weak policy and IEA WEO 2013 New Policy Scenarios weak caps.

IEA World Energy Outlook data for energy CO2 is provided for 2020 and 2030 for its New Policies Scenario, which assumes the weaker end of any pledges are implemented.

The following table compares derived values of weak policy according to interpretation of the Cancun pledges, as explained above, with IEA data.

Region (TIAM)	Derived 2020 CO_2 emissions (energy and industry, including bunkers) / $MtCO_2$	WEO 2013 2020 CO_2 emissions (energy only) / $MtCO_2$	Comment
USA	6,269	5197	Cement emissions about 60 MtCO2 in 2012. Bunkers about 100 MtCO2 in 2012. BAU Projections (e.g. Climate Action Tracker), WEO 2013 Current policy scenario see emissions broadly flat between 2012 (when they were 5194 MtCO2 for energy and cement) and 2020. Hence assume 5,400 MtCO2 to account for bunkers.
Canada + Mexico	1,089	1,029 (also includes Chile)	Chile 2012 emissions about 100 MtCO2 (energy and cement, from EDGAR). However, derived data includes bunkers and cement (which WEO 2013 does not) so derived data seems reasonable.
Japan	1,304	1,081	Derived data includes bunkers and cement, in total about 80 MtCO2 in 2012. EDGAR 4.2 shows Japan emissions currently 1,324 MtCO2 without bunkers. Assume derived data is more realistic than WEO.
W. Europe	2,727	3,493	WEO 2013 OECD Europe definition includes Czech Rep, Hungary, Israel, Slovenia, Slovakia, Turkey, with combined emissions of over 600 MtCO2 in 2012. So W.Europe value seems sensible (and is derived directly from a 2020 pledge based on 1990 data).
E. Europe + Former Soviet Union	4,150	2,829 (for E.Europe / Eurasia)	WEO 2013 region excludes Czech Rep, Estonia, Poland, Slovenia, Slovakia, together accounting for about 600 MtCO2 in 2012. Suggested cap on E. Europe (1,000 MtCO2) seems credible given it is close to 1990 levels. Suggested cap (3,150) on Former Soviet Union may be too high in which case models will follow BAU.
Australia, New Zealand, Oceania (excluding Japan) + S Korea	884	1,010	Region emissions dominated by Australia and South Korea, whose combined energy and cement CO2 in 2012 was 1,068. Given that South Korea is on track to achieve mild emissions reductions, and Australia's unilateral pledge to 2020 (-5% on 2000 levels) still stands, the original assumption seems reasonable.
Middle East	2,378	1,918	Derived Middle East value includes Turkey and Israel (which aren't in the WEO figures and accounted for 534 MtCO2 in the derived projection – without these this would be 1,843, which is reasonably close to the WEO estimate.
Latin America	1,386	1,329	Sufficiently close to require no further analysis.
Other developing Asia	2,215	2,267	Sufficiently close to require no further analysis.
Africa	1,394	1,204	Sufficiently close to require no further analysis.
China	13,147	9,617	EDGAR 4.2 shows China energy and cement emissions were 9,864 in 2012, and if CO2 intensity falls by 4% per year (as per recent trends) whilst economy grows at 7% per year, then emissions will grow by 34% to 13,000 MtCO2 – so the derived figure looks sensible.
India	2,967	2,318	India's energy and cement CO2 was 1,967 Mt in 2012, and if energy intensity falls at 3% per year whilst economy grows at 7% per year, then in 2020 emissions would be 2,900 – so the derived figure looks sensible.

In summary, the regional figures all look sensible in comparison with WEO 2013 data, with the following exceptions:

1. US, where the WEO 2013 data looks more realistic according to recent trends in US emissions. Hence, replace derived value with a 2020 cap of 5,400.
2. Former Soviet Union, where the derived 2020 cap may be too high (but in the case the models will allow this region to run at BAU which is probably realistic as it is unlikely to undertake significant climate action in a weak international scenario)
3. China and India, where the WEO 2013 figures seem unrealistically low compared to the weak Cancun pledges.

Comparison of estimates of 2030 emissions levels

Because of its relative granularity in terms of regions described, the IEA WEO 2013 data has formed the basis of finding a ratio of 2030 emissions / 2020 emissions in a weak policy scenario (what the WEO 2013 calls the "New Policies Scenario". WEO regions which are broadly the same as those in the TIAM model have been used to derive the uplift (or downward shift) in emissions from 2020 to 2030. This results in the following emissions levels globally, with comparisons to the Ampere study made.

Study	2020 global emissions from fossil and industry	2030 global emissions from fossil and industry	Comment
AVOID 2	38.981	41,422	2030 emissions 6% higher than 2020
WEO 2013	34,595	36,493	2030 emissions 5% higher than 2020 (Excludes cement)
Ampere WITCH	39,731	46,406	2030 emissions 17% higher than 2020
Ampere MESSAGE	38,182	42,344	2030 emissions 11% higher than 2020

The AVOID 2 assumptions, based on WEO 2013, show a relative flattening of global emissions between 2020 and 2030, when compared to the WITCH and (to a lesser extent) MESSAGE Ampere studies. However the SSP2 growth rates at a global level are reasonably close to those used in WEO 2013, and there are few other regionally disaggregated sources of information on 2030 emissions pledges under a weak policy scenario. Finally, the differences between these assumed rates of emissions growth between 2020 and 2030 are likely to be relatively trivial when compared to the significant deviation from the weak policy pathway in order to achieve the 2 degrees C pathway.

Annex B: Capped electrification rates for different regions in each model

In order to simulate a scenario in which limited progress is made in developing electric end-use technologies in the transport, buildings and industrial sectors, caps have been placed on the share of total final energy demand in each end-use sector in each region. The table below shows the caps applied in each case. These were derived with reference to recent (2011) shares of final energy demand made up by electricity for each region and sector, as well as those shares in 2035 in scenarios where only current policies are implemented, as gleaned from the IEA's World Energy Outlook 2013.

TIAM-Grantham				MESSAGE-GLOBIOM				WITCH			
Region	**Industry**	**Transport**	**Buildings**	**Region**	**Industry**	**Transport**	**Buildings**	**Region**	**Industry**	**Transport**	**Buildings**
Africa	30	5	20	Africa	30	5	20	SSA	30	5	20
Australia, New-Zealand, Oceanía	40	5	60	Pacific OECD	40	5	60	KOSAU	40	5	60
Canada	40	5	60					CAJANZ	40	5	60
China	40	5	50	Central and Planned Asia	40	5	50	China	40	5	50
Central & South America	30	5	60	Latin America & Caribbean	30	5	60	LACA	30	5	60
Eastern Europe	30	10	30	Central & Eastern Europe	30	10	30	Eastern Europe	30	10	30
Former Soviet Union	30	10	30	Former Soviet Union	30	10	30	TE	30	10	30
India	30	5	40	South Asia	30	5	40	SASIA	30	5	40
Japan	40	5	55								
Middle East	20	5	60	Middle East & North Africa	20	5	60	MENA	20	5	60
Mexico											
Other Developing Asia	40	5	40	Other Pacific Asia	40	5	40	EASIA	40	5	40
South Korea											
USA	40	5	60	North America	40	5	60	US	40	5	60
Western Europe	40	5	40	Western Europe	40	5	40	Western Europe	40	5	40

For the buildings and industry sectors, in all cases the current share of electricity in each end-use sector in each region has been rounded up to the nearest 10%. For transport, in almost all regions a cap of 5% has been opposed, reflecting the fact that the current and (in current policies scenarios) future share of electricity in transport remains very small (at 1 or 2%). The exception is in the Former Soviet Union and Eastern European countries, where the electricity share of transport final energy demand is between 5 and 10%.

Annex C: Description of IAMs used in this study

IIASA operates the **MESSAGE-GLOBIOM** integrated assessment modelling framework. MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is an energy engineering model based on a linear programming (LP) optimization approach which is used for medium- to long-term energy system planning and policy analysis [7], [8], [9]. The model minimizes total discounted energy system costs, and provides information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, and inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. MESSAGE is coupled to GLOBIOM (Global Biosphere Management Model, [35]) to analyse the competition for land use between agriculture, forestry, and bioenergy, which are the main land-based production sectors. It accounts for the 18 most globally important crops, a range of livestock production activities, forestry commodities, first- and second-generation bioenergy, and water. The comprehensive coverage of all energy and land sectors allows assessing emissions and mitigation options for the full basket of greenhouse gases and other radiatively active substances [36]. To estimate regionally-aggregated, sector-based air pollutant emissions and related pollution control costs, MESSAGE has been linked to the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model [37],[38]. For the estimation of price-induced changes of the energy demand, MESSAGE-GLOBIOM is iterated with the macro-economic model MACRO [39]. In MACRO, capital stock, available labour, and energy inputs determine the total output of the economy according to a nested constant elasticity of substitution (CES) production function. Through the linkage to MESSAGE-GLOBIOM, internally consistent projections of GDP and energy demand are calculated in an iterative fashion that takes price-induced changes of demand and GDP into account. Furthermore, MESSAGE-GLOBIOM is used in conjunction with MAGICC (Model for Greenhouse gas Induced Climate Change) version 6 [40] for calculating internally consistent scenarios for climatic indicators such as atmospheric concentrations, radiative forcing, annual-mean global surface air temperature and global-mean sea level implications.

TIAM-Grantham is the Grantham Institute, Imperial College London's version of the ETSAP-TIAM model, which is the global, 15-region incarnation of the TIMES model generator [5], [6], as developed and maintained by the Energy Technology Systems Analysis Programme (ETSAP). The model is a linear programming tool representing in rich resource and technological detail all elements of the reference energy system (RES) for each region represented, mapping energy commodity flows all the way from their extraction and refining to their distribution and end-use. TIAM has the ability to optimise the energy system for given climate constraints through either minimising the total discounted energy system cost over a given time-horizon, or through minimising total producer and consumer welfare when (optionally) accounting for elastic demand responses to energy prices. In the latter case, the model is solved as a partial equilibrium. There is no linkage to a macroeconomic model to observe full equilibrium impacts of changes in energy prices. The model uses exogenous inputs of factors such as GDP, population, household size and sectoral output shares to project future energy service demands across the agricultural, commercial, industrial, residential and transport sectors in each region. Energy system data such as technology costs, resource supply curves and annual resource availability are also input into the model. In solving, the model allows trade in energy commodities between regions.

WITCH is a dynamic global model that integrates the most important elements of climate change in a unified framework [10]. The economy is modelled through an inter-temporal optimal growth model which captures the long-term economic growth dynamics. A compact representation of the energy sector is fully integrated (hard linked) with the rest of the economy so that energy investments and resources are chosen optimally, together with the other macroeconomic variables. WITCH represents the world in a number (in this study, 12) of representative native regions (or coalitions of regions); for each it generates optimal mitigation and adaptation strategies for the long term (2005 to 2100), as a result of a maximization process in which the welfare of each region (or coalition of regions) is chosen strategically and simultaneously to other regions. This makes it possible to capture regional free-riding behaviours and strategic interaction induced by the presence of global externalities. In this game-theory set-up, regional strategic actions interrelate through greenhouse gas emissions, dependence on exhaustible natural resources, trade of oil and carbon permits, and technology research and development. The endogenous representation of research-and-development diffusion and innovation processes constitutes a distinguishing feature of WITCH. This approach gives the possibility to explore how research-and-development investments in energy efficiency and carbon-free technologies integrate the currently available mitigation options. The model features multiple externalities, both on the climate and the innovation side. The technology externality is modelled via international spillovers of knowledge and experience across countries and time. This formulation of technical change affects both decarbonization as well as energy savings.

Annex D: Deriving temperature goal-consistent 21st century CO_2 budgets and emissions profiles

The TIAM-Grantham and IIASA GAINS [41], [42] models are used to derive time profiles of emissions of CO_2, CH_4, N_2O and total F-Gas emissions from a given cumulative CO_2 budget for fossil fuels and industry (FFI) in order to meet a given long-term temperature goal (LTTG) – the temperature change in 2100. In order to make climate projections (verifying the CO_2 budgets) the total F-Gas emissions must be broken down into constituent species and emissions of other gases must also be estimated. The process of constructing the full set of emissions required and the iterative process used to determine the 21st century (i.e. 2000-2100) CO_2 FFI budget is detailed here. A schematic of the information flow through the RCPs, TIAM-Grantham, GAINS and Met Office Hadley Centre (MOHC) calculations is illustrated in figure A1.

1. Projections of global temperature change for the four RCPs is made using emissions relating to the RCPs [43]. Emissions are used rather than concentrations as this takes fuller account of uncertainty carbon cycle feedbacks. Following Bernie and Lowe [44], probabilistic projections are made using values of equilibrium climate sensitivity from models in the fifth Couple Model Inter-comparison Project (CMIP5) [45] along with uncertainty distributions of ocean mixing and carbon cycle feedbacks.
2. In each year land use emissions of CO_2 are linearly interpolated from the RCPs on the basis of each RCP's median 2100 projected temperature and the LTTG of the scenario.
3. Initial estimates of 21st century cumulative CO_2 emissions from the FFI sectors are also linearly interpolated from the RCPs on the basis of future temperature projections and the scenario LTTG.
4. The cumulative CO_2 FFI budget is then used to calculate emissions of CO_2 from FFI, CH_4, N_2O and F-gases:
    a. A time profile of CO_2 emissions from FFI is then calculated from the cumulative CO_2 FFI along with a carbon price profile;
    b. The CO_2 FFI emissions profile and aspects of the underlying energy system structure (in particular the fossil fuel energy mix) are then passed to GAINS to calculate non-CO_2 GHG no-mitigation baselines and corresponding MAC curves;
    c. The CO_2 FFI profile from TIAM-Grantham and the non-CO_2 GHG baselines and MAC curves from GAINS are then used to calculate the emissions of CH_4, N_2O and total F-Gas emissions, at different levels of CO_2e price applied to the non-CO_2 GHGs (using GWP100 values).
5. Individual F-gas emissions are then needed, but the constituent F-gases in the categories used by GAINS do not exactly match those used by MAGICC. Whilst this has a very small influence on the overall CO_2e emissions, the individual gas species are needed by MAGICC. To estimate emissions of individual F-gases it is assumed that the relative emissions rate of each F-gas to the total F-gas emissions will change with time in line with the "unmitigated" RCP 8.5 scenario. Based on this assumption the emissions of each F-gas in RCP8.5 are scaled by a ratio of the total F-gas emissions from GAINS to the total F-gas emissions in the unmitigated baseline. So for example if the F-gas emissions from GAINS are 20% of the unmitigated F-gas emissions for that scenario, then this factor is applied to emissions of each individual F-gas from RCP8.5. This approach

circumvents the issue of different gases being included in the calculation by GAINS and those needed by MAGICC. While other assumptions are possible, given the relatively small effect of differences in F-gas emissions between the RCPs, this an appropriate level of detail for the scope of the current study.

6. The emissions of non-Kyoto GHG and other gases needed by MAGICC (principally NOx, CO, NMVOC, SO_2) are all based on the ratio of the emissions of each gas to the emissions of CO_2 from the FFI sector in the RCPs being applied to the CO_2 FFI emissions from TIAM-Grantham. For example if the CO_2 FFI emissions from GAINS in a given year where 80% of the way between RCP4.5 and RCP6.0, the SO_2 emissions would be the product of the CO2 FFI from TIAM-Grantham multiplied by a weighted mean of the ratio of SO_2 to CO_2 FFI in those two RCPs, with 4 times more weight given to the ratio from RCP6.0.
7. Projected median 2100 temperature change is then calculated and if within 0.1 °C of the original LTTG, the CO_2 FFI budget is accepted, or else the CO_2 budget for the scenario is re-estimated, before repeating the above procedure to re-calculate 2100 median temperature change.

It should be noted again that the temperatures resulting from the emissions derived from a given budget are verified as meeting the target. With the cumulative CO_2 FFI being the only variable here the process used in iterating its value for each target warming level is unimportant. However, the use of a simple interpolation of cumulative CO_2 emissions to determine eventual warming is a notion that has become widely accepted in recent years [46], [47], [48]. Its use here to initially estimate the CO_2 budget for specific target warming levels implicitly assumes that the contribution of non-CO_2 gases to warming is linearly related to the emissions of CO_2. While this may appear to be broadly the case across the wide range of scenarios from the IPCC's AR5 WGII report [1], the wide spread in IAM construction and the experimental design across the scenarios available is likely to obscure more subtle relations from IAM scenarios constructed under specific sets of assumptions on constraints. For example two scenarios with similar CO_2 emissions profiles but which focus on either energy demand reduction or the heavy use of bio-energy with carbon capture and storage (BECCS) would likely have different non-CO_2 contributions to warming. Similarly, emissions scenarios with different climate targets derived from a common approach, such as here, would not necessarily produce a robustly linear relation of warming to CO_2 when the nuances of the underlying technological, economic and social assumptions and constraints are considered.

While the breakdown of the relation of cumulative emissions to temperature demonstrated by the need for iteration in developing these scenarios in small, it illustrates the inherent uncertainty in this relation and warrants careful verification of projections developed on this basis.

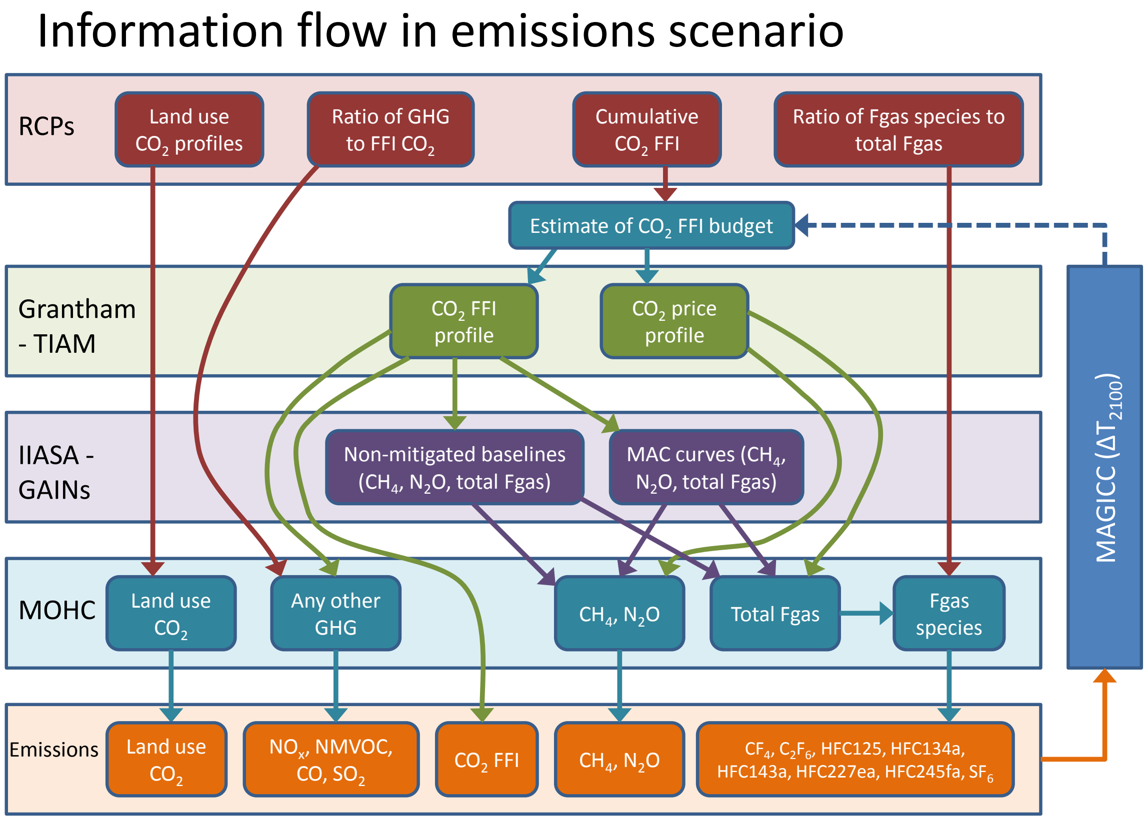

Figure A1: Schematic illustrating the process used to derive emissions scenarios from CO_2 budgets and iterate for target temperature levels where appropriate.