Limiting global warming to 2°C: what do the latest mitigation studies tell us about costs, technologies and other impacts?

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Abstract:

There is now a wealth of model-based evidence on the technology choices, costs and other impacts (such as fossil fuel demand) associated with mitigation towards stringent climate targets. Results from over 900 hundred scenarios have been reviewed in the latest Intergovernmental Panel on Climate Change Assessment Report (IPCC AR5) including baseline scenarios under which no mitigation action is taken, as well as those under which different limits to global warming are targeted. A number of additional studies have been undertaken in order to assess the implications of global mitigation action. The objective of the paper is to provide a concise overview and comparison of major input assumptions and outputs of recent studies focused on mitigating to the most stringent targets explored, which means around the 2°C level of global average temperature increase by 2100. The paper extracts key messages grouped into four pillars: mitigation costs, technology uncertainty, policy constraints, and co-benefits. The principal findings from this comparison are that, according to the models, mitigation to 2°C is feasible, but delayed action, the absence or limited deployment of any of a number of key technologies (including nuclear, CCS, wind and solar), and limited progress on energy efficiency, all make mitigation more costly and in many models infeasible. Further, rapid mitigation following delayed action leads to potentially thousands of idle fossil fuel plants globally, posing distributional and political economy challenges.

1) Introduction:

In March 1994 the UNFCCC entered into force and recognised that it is necessary to stabilize atmospheric greenhouse gas (GHG) concentrations at a level that would prevent dangerous anthropogenic interference with the climate system [1]. A consensus between stakeholders in Copenhagen in 2009 [2] concluded that to comply with this goal the warming achieved should be limited to below 2°C compared with preindustrial times. In 2015, the Paris Agreement, to the surprise of many, included text on limiting warming to “well below” 2°C and to “pursue efforts” to limit it to less than 1.5°C [3].

There has been a great deal of analysis to consider whether the mitigation commitments (or ‘Copenhagen pledges’) made to date are consistent with achieving a 50:50 chance of limiting the surface temperature rise to 2°C (UNEP objective [4]) with the conclusion that the scenarios including these near term pledges are not least-cost optimal pathways [5]. Many authors argue that with further ambitious global policies, the target is reachable ([6]; [7]; [8]), although others suggest it could be too late, as we are already locked into a fossil based energy system under the weaker-than-optimal “Copenhagen pledges” ([9]; [10]).

Part of the reason for this dichotomy of views is that the complexity of the climate system, as well as the extent of uncertainties embedded in it, gives rise to a wide variety of possible emission trajectories that are consistent with a 2°C temperature rise. The additional uncertainties and complexities with modelling the global energy system lead to an even wider range of views on whether, or how, such cuts in emissions are possible.

This paper reviews recent major studies that analysed the latest GHG emission pathways that are compatible with limiting average global temperature rise to levels close to 2°C by the end of the 21st century. The objective of this paper is to provide a concise, systematic summary of key metrics on climate change mitigation to scholars, by extracting key messages under the following four pillars: mitigation costs (Section 4), technology uncertainty (Section 5), policy constraints (Section 6), and co-benefits (Section 7).

In section 2 we first present the studies covered and models and assumptions that have been used in the selected studies covered. In section 3 we examine the global pathways to comply with targeted temperature rise and survey the technologies needed as well as the implied rates of deployment for a number of key electricity decarbonisation technologies. In section 4 we consider the costs and feasibility of the target. In section 5 we study the target feasibility under restricted availability of specific technologies. In section 6 we focus on the effects of delay in beginning global mitigation action on the pathways, the technological development and the costs induced by the delay. In section 7 we discuss the wider impacts (particularly co-benefits) of mitigation, as well as suggesting areas worthy of further investigation. Section 8 concludes by highlighting the most policy-relevant points emerging from these studies.

2) Models and assumptions used for the different studies included.

2.1) Studies covered

A number of recent studies and model inter-comparisons are included in the analysis: Energy Modelling Forum 27 Study[1] (*EMF27*), Low climate IMpact scenarios and the Implications of required Tight emission control Strategies[2] (*LIMITS*), Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates[3] (*AMPERE*), Global Energy Assessment: Toward a Sustainable Future[4] (*GEA*), The Roadmaps towards Sustainable Energy futures[5] (*RoSE*) and TIAM-UCL global modelling studies: The CCC 2013 report[6] and UKERC Global study 2014[7] (*TIAM-UCL*) and the RCP 2.6 scenario[8] (RCP2.6). In addition to these studies, the evaluations of two large assessment reports are also used in this paper: Climate Change 2014, Mitigation of Climate Change[9] (*IPCC 2014*) and The UNEP Emissions Gap Report 2012[10] (*UNEP 2012*). The assessment reports compile and compare in detail and at length the results from different studies, most of them included in the list above. These results include reference scenarios (no mitigation policies) and different levels of climate targets from 1.5 to 4°C – although it should be noted that the majority of the most stringent scenarios are focused on 2°C, with very few achieving close to 1.5°C.

The results and conclusion of these major studies have been widely published in peer-reviewed papers as well as scientific and assessments reports. However, to our knowledge a comprehensive yet concise review of the key features of the model inputs and outputs has not yet been published. . This review paper focuses only on the 2°C target compared to the reference pathways, to reflect the policy-relevance of this target to international negotiations; it integrates the key components and discusses the main conclusions of these research studies.

For the specific target of 2°C, the majority of mitigation scenarios assessed over recent years have focused on GHG pathways broadly consistent with achieving atmospheric concentrations of GHGs between 450 ppm and 500 ppm [11]. However, as already discussed, there remains uncertainty in the relationship between atmospheric GHG concentrations and long-term temperature changes, broadly speaking the 450 scenarios are aimed at achieving an even or better chance of limiting surface warming to 2°C.

2.2) Models included in this review.

The models incorporated in the major studies analysing the transition pathways to the 2°C target are listed in Table 1, along with some of their characteristics. As seen in the last column of the table, some models have been involved in more than one study. The studies examined assumed a range of values for global population increase and economic growth, with a higher variation noted in the range of economic growth estimates than that of population between the studies. This is, in part, due to there being more uncertainties in estimating economic growth than population increase.

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[1] https://emf.stanford.edu/projects/emf-27-global-model-comparison-exercise
[2] http://www.feem-project.net/limits/
[3] http://ampere-project.eu
[4] http://www.globalenergyassessment.org/
[5] http://www.rose-project.org
[6] http://www.theccc.org.uk/wp-content/uploads/2013/11/TIAM-UCL_global_energy_modelling_2013.pdf
[7] http://www.ukerc.ac.uk/support/UK+Energy+in+a+Global+Context+Ext&structure=Research
[8] http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=welcome
[9] http://www.ipcc.ch/report/ar5/wg3/
[10] http://www.unep.org/pdf/2012gapreport.pdf

Table 1: List of models included in the review:

Model name	Model category	Solution Algorithm	Coverage of greenhouse gases	Study participation
AIM / AIM-Enduse[*]	Partial equilibrium	Recursive dynamic	All GHGs and other radiative agents	*EMF27, LIMITS, AMPERE*
BET	General equilibrium	Intertemporal optimization	CO_2	*EMF27*
China MARKAL[*]	Partial equilibrium	Dynamic linear optimisation	CO_2	*RoSE*
DNE21+[*]	Partial equilibrium	Intertemporal optimization	All GHGs and other radiative agents	*EMF27, AMPERE*
GCAM / GCAM-IIM	Partial equilibrium	Recursive dynamic	All GHGs and other radiative agents	*EMF27, LIMITS, AMPERE, RoSE*
EC-IAM	General equilibrium	Intertemporal optimization	Kyoto gases from fossil fuel combustion and industry	*EMF27*
ENV-Linkages[*]	general equilibrium	Recursive dynamic	Kyoto gases	*EMF27, UNEP2012*
FARM	general equilibrium	Recursive dynamic	CO_2 from fossil fuel combustion and industry	*EMF27*
GAINS	Partial equilibrium	Intertemporal optimization	All GHGs and other radiative agents	*UNEP2012E*
GEM-E3	general equilibrium	Recursive dynamic	All GHGs	*AMPERE*
GRAPE	General equilibrium	Intertemporal optimization	All GHGs and other radiative agents	*EMF27*
IMACLIM	general equilibrium	Recursive dynamic	CO_2 from fossil fuel combustion and industry	*EMF27, AMPERE*
IMAGE / TIMER/FAIR	Partial equilibrium	Recursive dynamic	All GHGs and other radiative agents	*EMF27, LIMITS, AMPERE, GEA, UNEP2012, RCP2.6*

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[*] The reported time horizon for these models is 2050 instead of the usual 2100; however the pathways to 2050 are in agreement with a 2°C target in 2100.

IPAC	Multi-model framework	links several models	All GHGs	*RoSE*
MERGE/MERGE-ETL	General equilibrium	Intertemporal optimization	All GHGs and other radiative agents	*EMF27, AMPERE, RoSE*
MESSAGE-MACRO	General equilibrium	Intertemporal optimization	All GHGs and other radiative agents	*EMF27, LIMITS, AMPERE, GEA*
Phoenix[*]	general equilibrium	Recursive dynamic	CO_2 from fossil fuel combustion and industry	*EMF27*
POLES	Partial equilibrium	Recursive dynamic	Kyoto gases from fossil fuel combustion and industry	*EMF27, AMPERE*
REMIND	General equilibrium	Intertemporal optimization	All GHGs and other radiative agents	*EMF27, LIMITS, AMPERE, RoSE*
TIAM-ECN	Partial Equilibrium	Intertemporal optimization	CO_2, CH_4, N_2O.	*LIMITS*
TIAM-UCL	Partial Equilibrium	Intertemporal optimization	CO_2, CH_4, N_2O.	*UKERC2014*
TIAM-World	Partial equilibrium	Intertemporal optimization	Kyoto gases with the exception of F-Gases	*EMF27*
WITCH	General equilibrium	Intertemporal optimization	Kyoto gases	*EMF27, LIMITS, AMPERE, RoSE, UNEP2012*
WorldScan	general equilibrium	Recursive dynamic	CO_2, CH_4, N_2O.	*AMPERE*

2.3) Socio-economic assumptions.

Estimated population growth

In most studies, 2050 population is estimated at around 9 billion while 2100 population assumptions vary from 9.1 billion (LIMITS and RCP 2.6) to 10 billion (AMPERE). Within the EMF 27 project variation in population growth assumptions exists between models, as no socioeconomic harmonisation was carried out. As reported in [12] the population and economic growth have been varied in combination with GDP within the RoSE project; the population varies from a scenario with peak at 9.4 billion in 2070 under a medium growth to a high growth scenario reaching 14 billion in 2100. Most of these studies did not explicitly discuss future urbanisation rates, which is one of the key drivers that contribute to increasing per capita energy consumption and consequently emissions, especially in the emerging economies in the near and medium term and in developing countries in the medium- and long-term. As of 2011, more than 52% of the global population lives in urban areas whilst in 2006, urban areas accounted for 67–76% of energy use and 71–76% of energy-related CO_2 emissions; by 2050, the urban population is expected to increase to 5.6–7.1 billion, or 64–69% of world population [13].

Estimated economic growth

Global studies such as UNEP Emissions Gap Report [5] and Global Energy Assessment 2012 [14]) assume per capita GDP growth of 2% per year to 2050, mostly driven by developing countries, while the TIAM-UCL and AMPERE studies assume slightly higher growth rates of 2.4% and 2.7% respectively. EMF 27 assumes an average growth rate of 1% per year to 2100. The RoSE project assumes 3 different growth rates (slow, medium and fast) ranging from 1.6% to 2.7% [15]. The projections of economic growth used in the studies for the mitigation scenarios (to 450 ppm) are presented in figure 1; the data have been extracted from the AR5 database described in [16].

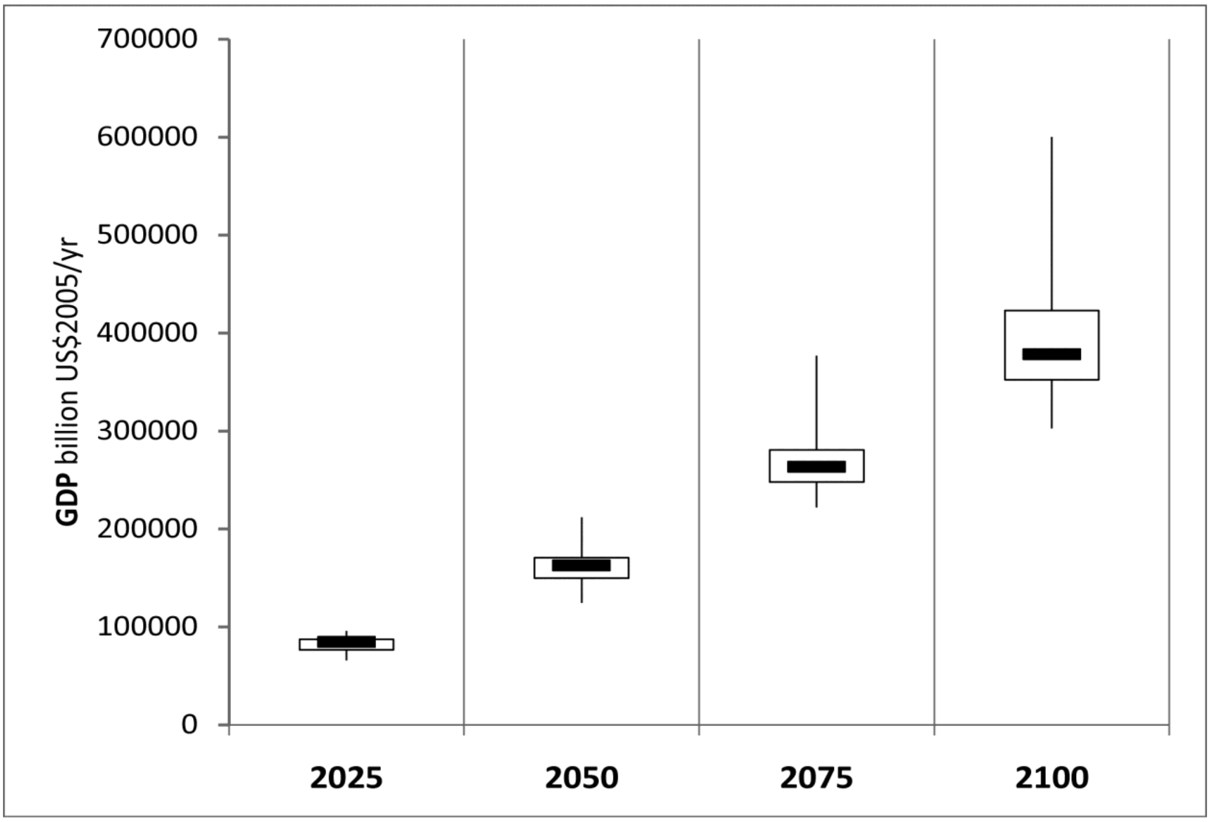

Figure 1: Projected total world GDP in the AR5 database (represented: median, 25% and 75% percentile and minimum maximum).

3) Is the 2°C target achievable? What are the technologies needed?

We have studied the scenarios that are broadly consistent with a 2°C target. It should be noted that all these scenarios represent ambitious goals with dramatic changes in anthropogenic GHG emissions. There are however limitations to comparing scenarios. Comparing the findings of different scenarios can be difficult; in part due to the variety of ways the targets within different studies are set. Targets used by studies include:

- a maximum temperature in 2100 [4];

- a Representative Concentration Pathway (RCP2.6) describing the radiative forcing [17];
- a maximum concentration of GHGs (LIMITS [18]; RoSE [19]; EMF27 [20]);
- an emissions pathway [7] ;
- a carbon budget (AMPERE [21]).

Another possible limitation in comparing the scenarios of different studies is the diverse socio-economic storylines that supports scenario developments for modelling already discussed in the previous section.

3.1) Pathways broadly consistent with meeting 2°C or below

In this section we study pathways that are consistent with international climate policy focusing on the 2 °C temperature limits. To concentrate on temperature change we have to be able to link equilibrium temperature increase to the GHG concentration level or to the radiative forcing achieved. The ability to draw such links in a simple and transparent way in models rests on the definition of equilibrium climate sensitivity. This parameter is a critical source of uncertainty in long-term temperature projections and is largely determined by internal feedback processes that amplify or dampen the influence of radiative forcing on climate. Large spread in model climate sensitivity is one major factor contributing to the range in projections of future climate changes [22]. According to the latest reviews [23], equilibrium climate sensitivity is likely in the range 2.1°C to 4.7°C and very unlikely greater than 6°C. A multi-model ensemble value is usually applied to calculate the temperature change within the models presented in the previous chapter and as a consequence the high values, high impacts but low probability climate change temperature realisations are not included in the review.

Based on 2°C target studies (listed in table A-1; Appendices section) and discussed as part of [11], it seems that 500 ppm is the maximum permissible CO_2-eq concentration in 2100, with emissions peaking in 2030-2035 at the latest; the later peaking dates prove less cost-effective and rely heavily on CO_2 removal technologies such as bio-energy with carbon capture and storage (BECCS). Most of these scenarios also exhibit net negative global CO_2 emissions at the end of the century.

A few of these scenarios indicate an expected temperature change below 2°C in 2100 (between 1.5 and 1.8°C): RCP2.6 and EMF27-450. Generally the mean annual GHG emissions reduction rate, following the peak, is between 2 to 5% when the peak year is around 2020 [21]. Later peaking pathways will lead to larger rates of GHG emission reduction (from 6 to 8% per year) and require net negative emissions at the end of the period to comply with the target, albeit with a temporary overshoot. Although the rapid reduction in global emissions in some scenarios is technically and economically feasible within the modelling framework, political decisions, social acceptance and institutional factors will also play a major role in the real world – elements which are not part of the modelling framework, other than through the mechanism of delayed or regionally fragmented action. Focussing at national level, some examples of very rapid emissions reductions can be found in the recent past: during the 1980s France was reducing emissions at a rate of 3% per year as a result of the large-scale deployment of new nuclear power plant facilities; the UK sustained a reduction reaching 2% per year in the 1970s decade by a strong switch from coal to gas in electricity production. These examples highlight the practical rates achievable through technical changes;

however the recorded reductions lasted only a decade or less, and were at country levels as opposed to the global level required in the scenarios discussed in this paper. In the literature maximum possible global reduction rate can be extracted; for example maximum annual rates of 3.5% [2] and 4.3% [24] taking into account assumptions on technological development, economic costs, and/or socio-political factors. In some scenarios analysed for this study the emission reduction rates reach 8 to 10% per year are largely exceeding these regarded as possible maximum values [7

3.2) Role of low carbon technologies within the 2°C pathways.

This section highlights the technologies included in the different scenarios. Table A-2 (in Appendices section) summarises some key data concerning technology development for the scenarios achieving the 2°C target. The usual approach in the majority of the projects included in this review is to use a business-as-usual or reference scenario to compare to a series of mitigation scenarios (of different levels of stringency) involving a large portfolio of technologies available at specified costs. These "full technology portfolio" scenarios usually allow strong and rapid developments in renewable or other low-carbon technologies in the power sector as well as the deployment of new technologies such as CCS. Energy efficiency improvement options in final energy demand sectors are also included, but treated as separate from the group of energy generating technologies. In these "full portfolio" modelling exercises technology cost changes over time can occur through two channels: learning-by-doing (experience gained during development) or learning-by-searching (research and development activities). These improvements can induce new dynamics between technology adoptions and create divergences among model results (LIMITS and EMF27). However in most model scenarios, technology costs are specified as a set of input assumptions.

In the baseline scenarios the energy demand increase is met primarily with carbon intensive fossil fuels; generally the CO_2 emissions for 2050 reach 2 to 3 times the 2010 levels. Within the full technology portfolio scenarios decarbonising the electricity generation sector is one of the main approaches to achieving the targets. The share of low-carbon generation in the electricity supply increases from 30% today to 80-100% in 2050 (depending on the stringency of the climate target). Within the total primary energy sources, low-carbon sources represent only between 60% and 70% in these scenarios highlighting the difficulty of decarbonisation of other sectors (such as transport) compared to electricity generation. Renewable technologies such as wind and solar commonly take the largest share of low-carbon electricity generation in 2050. The share of CCS in electricity generation in 2050 varies from 8% to 32%. This is partly driven by assumptions on CCS deployment, which starts in or after 2025 in all the scenarios where CCS is considered, and assumptions on deployment of renewable technologies. However this fact changes during the second half of the century when CCS technology becomes more mature and renewable generation reaches saturation; this is particularly the case in scenarios with stringent targets or overshoots when BECCS (bio energy with CCS) in the second part of the century is needed to achieve negative emissions.

The pathways indicate that the energy transformations need to be initiated without delay, gain momentum rapidly, and be sustained for decades. This implies the rapid introduction of policies and fundamental governance changes toward integrating climate change into local and national policy priorities. A range of measures is required in each sector. For example, as discussed in the GEA [14], rather than aiming for buildings that use zero fossil fuel energy as quickly as possible, an economically sustainable energy strategy would implement a combination of the following: reduced demand for energy; use of available waste heat from industrial, commercial, or decentralized electricity production; on-site generation of combined heat and electricity production; and off-site supply of electricity. Some assessments, notably the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [25] and the GEA [14], emphasize the great importance of accelerating demand-side efficiency and conservation measures for future reductions of GHG emissions.

4) Mitigation costs implications of the 2°C target

There is some variation in total energy system costs at a regional level. In 2020, overall costs are higher in high-income regions since these are required to meet their Copenhagen Accord emissions reductions. This switches after 2020, with a greater proportional cost in middle and low-income regions [26]. For middle-income regions, the rapid increases in energy-services are predominantly met through an increase in coal consumption. Given that coal consumption needs to be severely restricted in 2°C scenarios even under the availability of CCS technology [27], [28], these regions require a greater level of investment to meet the emissions reductions required. Low-carbon technologies (including CCS) are characterised by large up-front investments, and low-income regions have higher capital costs [29]. These low carbon technologies are consequently more expensive to deploy in the developing world than in the high-income regions even when factoring the lower operating and maintenance costs expected from cheaper labour costs.

According to GEA [14], in order to achieve the 2°C target, at least a 60–80% share of global primary energy will need to come from zero-carbon options by 2050; the electricity sector in particular will need to be almost completely decarbonized by mid-century (low carbon shares of 75–100%). Getting to that point requires in general a complete phase-out of coal power without CCS by 2050 with strong bioenergy growth in the medium term. There is however less agreement in the contribution of natural gas or oil as a bridging or transitional technology in the short to medium term to provide back up for intermittent renewables [28]. In these scenarios nuclear energy is a choice, not a requirement.

As explained in IPCC 2014 [11] and [13], substantial reductions in emissions would require large changes in investment patterns. Mitigation scenarios in which policies stabilize atmospheric concentrations (without overshoot) in the range from 430 to 530 ppm CO_2-eq by 2100 lead to substantial shifts in annual investment flows during the period 2010–2029 compared to baseline scenarios. Over the period 2010 to 2029, annual investment in conventional fossil fuel technologies associated with the electricity supply sector is projected to decline by about US$ 30 (with a range of 2–166) billion (median: -20% compared to 2010) while annual investment in low-carbon electricity supply (i.e., renewables, nuclear and electricity generation with CCS) is projected to rise by about US$ 147 (with a range of 31–360) billion (median: +100% compared to 2010).

Under climate mitigation policies fossil fuel consumption in high-income regions consequently falls, leading to downwards pressure on fossil fuel prices. Cheaper resources are therefore available to the middle and low-income countries and so there is almost no additional cost to these regions in 2020 (while marginal, the change in cost is still positive), however fossil fuel exporters suffer from the variation of the price. The assumption of perfect foresight in most models means that some of the middle and low-income regions do show some reduction in their emissions through the first half of the century (albeit at a much lower level of ambition than in high-income regions) [27], [30].

Carbon prices are assessed for the mitigation scenarios and presented in Figure 2. The carbon price tends to rise over time when emissions mitigation effort increases, reflecting that further mitigation is more expensive to achieve. The inter-model spread in carbon price increases as the required emissions reduction effort increases, because the models have different technical capabilities and costs for deep levels of mitigation. The target analysed here corresponding to temperature goals lower than 2°C is stringent and as a consequence the carbon price reported can diverge significantly amongst models within the same project. The carbon prices interquartile range for the 2°C target pathways, in the optimum case scenarios of early adoption of mitigation policy and availability of all key low-carbon technologies in the models (right panel of Figure 2), span between US$15-US$115 per ton of CO_2 in 2025 and increase to $100-$500 in 2050 and US$1100-US$9000 in 2100 (prices in US$2010). These values are presented for the optimal case scenarios; any delays in policy adoption or failure in one of the low-carbon technologies assumed will rapidly change and increase these prices (included in the left panel Figure 2).

Some studies (for example AMPERE [31]) reported macroeconomic costs of climate change mitigation policies. Generally macroeconomic costs increase with the stringency of the target and are higher for the pledge pathways. Delayed action, in general, increases the global mitigation costs and also leads to a possible fossil fuel lock-in of the electricity system, creating large and expensive unusable assets. As such the most cost-effective scenarios to achieve the 2°C target are characterised by early mitigation creating clear signals for low-carbon technology investments and a near term peak in emissions (with the latest possible peaking dates occurring between 2025 and 2030, and with peak GHG emissions in the range of 30 to 50 $GtCO_2$-eq). In the optimal policy scenarios (AMPERE [31]), consumption losses (2010-2100) are between 0.5-3.1 percent of global GDP. The comparable range (extracted from the models that solve the three scenarios) of the early action scenarios is between 0.6-3.9 percent, and for the late action scenarios between 0.7-4.3 percent. Consumption losses for the least cost pathways to reach the 2°C target in 2100, with the assumption that all mitigation technologies are available (including all major renewables, nuclear and CCS), are in the range of 2 to 6% in 2050 and 3 to 11% in 2100 relative to the no mitigation (or “business as usual”/baseline) scenarios (Table A-2).

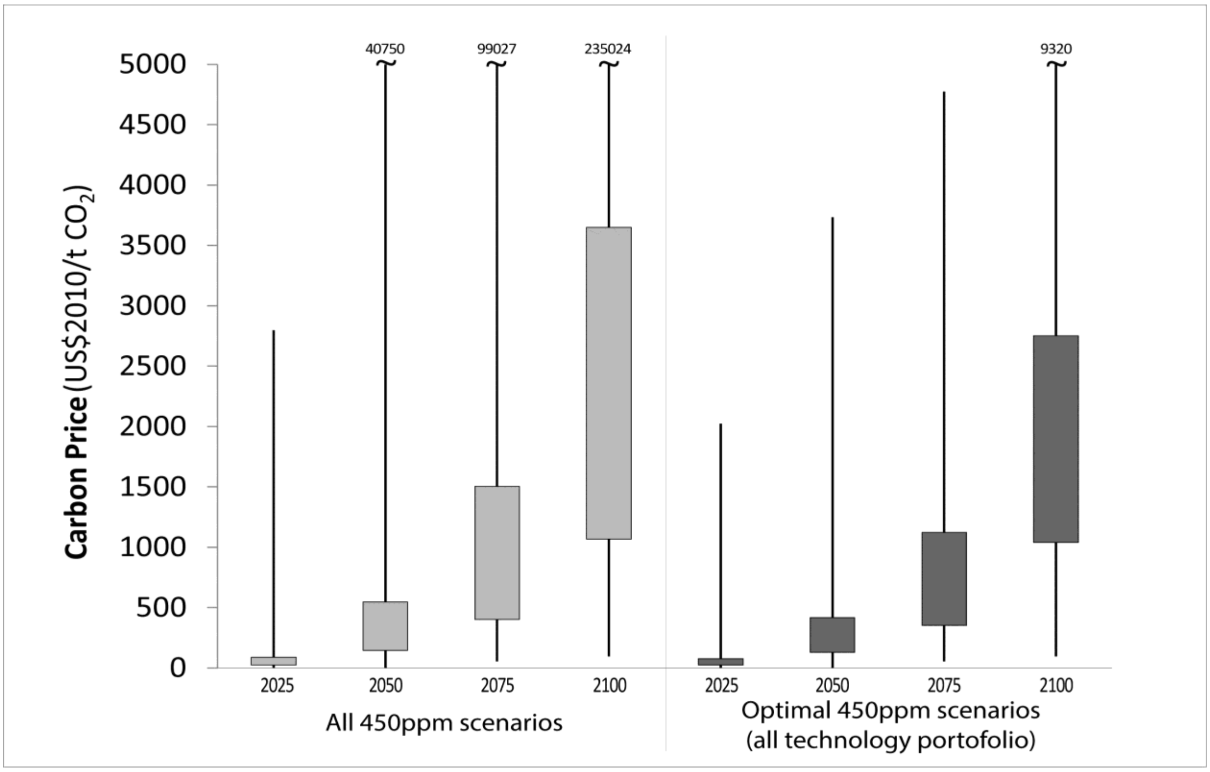

Figure 2: Carbon price for 450ppm scenarios for 2025, 2050, 2075 and 2100 in US$2010/t$CO_2$. Left panel: all 450ppm pathways; right panel: optimal full-technology 450pmm scenarios only.

5) Can we reach the target in the case of technological failures or limitations?

It was found that in order to remain under the 2°C target early action and a full portfolio of low-carbon technologies is needed in order to keep global mitigation costs down. Therefore the availability, cost and future performance of key technologies has an important role in achieving this stringent climate target.

Technological challenges are studied in a series of scenarios including limitations on the availability of specific technologies or groups of technologies. The usual technology restrictions (which are assumed to follow from technical limits or political decisions to restrict technology deployment) in these alternative scenarios are: a nuclear phase out, no CCS development, reduced deployment of wind and solar because of intermittency limits, and finally reduced availability of biomass as an energy feedstock. Some scenarios are modelled with a combination of these restrictions. The results of these scenarios have been summarised in figure 3 presenting feasibility and cost of the 2°C target under restriction of specific technology: no CCS, EERE (low energy intensity, high renewable and neither CCS nor nuclear), Conv (conservative renewable availability), LowBIO (low biomass availability), LowSW (low solar and wind penetration), NoNuc (no nuclear) and finally LowEI (low energy intensity). The feasibility indicator in figure 3 is defined as the proportion of models solving the 2°C target from the total number of models in the evaluation group.

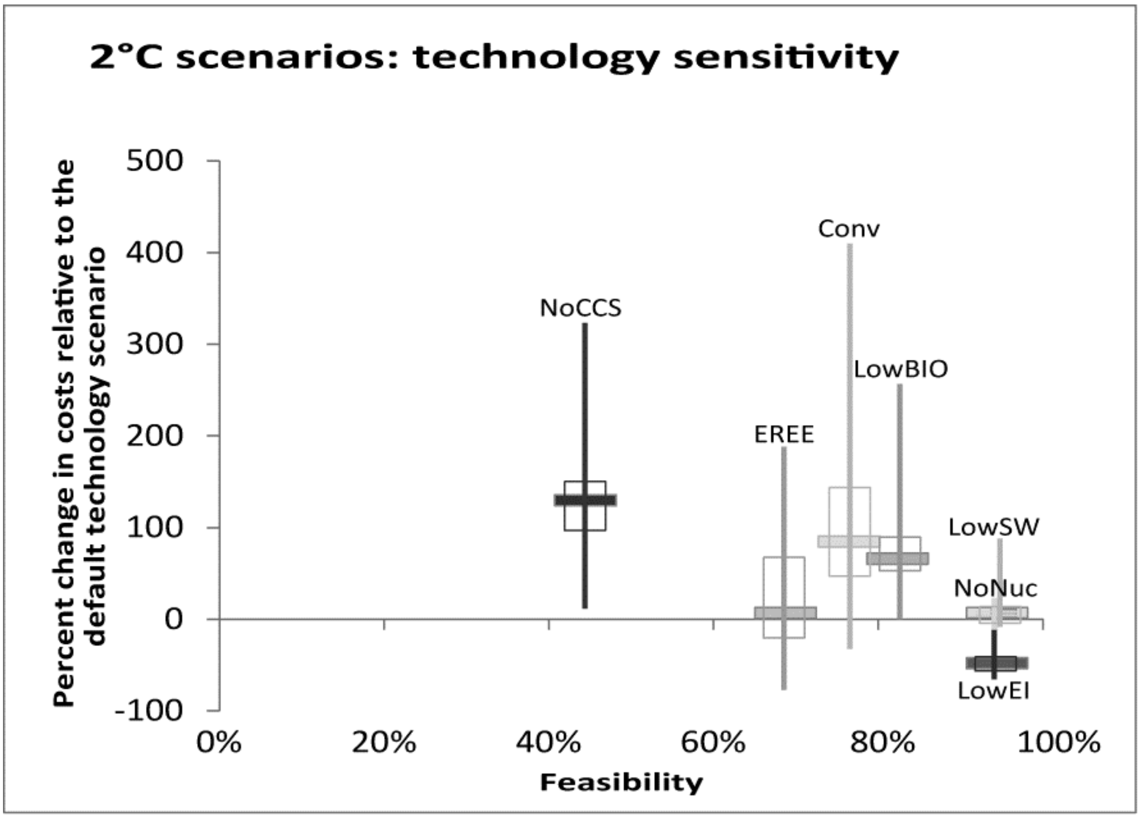

Figure 3: sensitivity on cost and feasibility to technology restriction of the 2°C target scenarios (represented: median, 25% and 75% percentile and minimum maximum) extracted from the AR5 database.

Widespread electrification of the end use sectors combined with strong decarbonisation of electricity production occurs in most mitigation scenarios. Non-fossil energy sources replace coal in the near term and gas in the medium-and long-term in the electricity sector. Renewable electricity generation deployment is not by itself sufficient to achieve the required levels of electricity decarbonisation, and most of the 2°C scenarios also depend, during the second-half of the century, on the large-scale deployment of CO_2 capture technologies. In all of the scenarios the only geoengineering technology explored to mitigate climate change is bio-energy coupled with CCS (BECCS) that could results in net negative emissions during the end of the century. Particularly in scenarios with later peaking years, BECCS is therefore a critical technology, and its absence often results in an inability for models to meet the prescribed target where this is relatively stringent (i.e. consistent with 2 °C or less).

Under the absence or limited availability of certain technologies the mitigation costs can increase substantially. In some cases models could not achieve concentration levels below 450ppm CO_2-eq in 2100 under a scenario without access to CCS. The increase in total discounted mitigation costs relative to a limitation in a low-carbon technology can reach as high as 138% in the case of CCS and 64% in the case of limited access to bioenergy. In comparison nuclear phase out increases total costs by 7% and limited access to solar and wind 6% in the case of 450 ppm CO_2-eq target. These numbers show that key options for the 2°C target are biomass and successful deployment of CCS and their combination (BECCS). Nuclear or renewable (as solar and wind generation) taken separately within pathways can be considered a policy choices but not critical technologies to achieve the stringent climate goal.

Finally demand reduction can significantly reduce mitigation costs as well as the reliance on carbon capture and storage (CCS). In order to explore sensitivity of the results to demand assumptions, a scenario depicting stringent efficiency measures and behavioural changes to radically limit energy demand is explored [21] [32]. Unfortunately the demand side options are usually characterised with less detail than the supply side in the studies reviewed in this paper. Most models have a very limited accounting of demand side investments and costs [32]. The low energy intensity case, with a rate of energy intensity improvement about 50% higher than the historical rate of change, achieves the 450 ppm target with the lowest costs across all sensitivity cases and models, and it is also the only case where the target is found attainable by 90% of the models even in the case of delayed action (or near term low ambitions) pathways [21].

6) What are the consequences in delaying the decision to cut emissions?

Long infrastructure lifetimes mean that energy systems transition to a low carbon economy will take decades; so immediate action is needed to avoid lock-in of invested capital into existing energy systems and associated infrastructure that is not compatible with long-term climate targets [14]. Infrastructure developments and long-lived capital stocks that lock societies into GHG-intensive emissions pathways may be difficult or very costly to change, reinforcing the importance of early action for ambitious mitigation. This lock-in risk is compounded by the lifetime of the infrastructure, by the difference in emissions associated with alternatives, and the magnitude of the investment cost. As a result, lock-in related to infrastructure and spatial planning is the most difficult to reduce [13].

The largest threat of lock-in of technologies within the energy system regards electricity production from fossil fuel (for coal and gas) and has been considered in the case of a 2°C target following scenarios with different short term emission reduction goals within the AMPERE and the RoSE projects (Table A-2 – "delayed action"). Currently, about 90% of global primary energy supply comes from coal, oil and gas. Climate policy and pricing of CO_2 emissions are likely to make some of the fossil installations unprofitable, thus resulting in premature retirement of fossil capacities before the end of their technical lifetimes. In the AMPERE project, a range of GHG emissions targets are specified (from 50 to 60 $GtCO_2$-eq), with the long term target in all cases fixed below 2°C [27]. Scenarios with higher short term targets have to rely heavily on negative emissions at the end of the century to achieve the long term goal. More importantly, with these less stringent short term targets the phase-out of coal (and gas) capacity in electricity production is delayed until after 2030 and as a consequence fossil fuel generation capacity continues to be built in the period to 2030; in this case the phase-out of coal and gas based plants, to totally decarbonise the electricity system in 2050, creates stranded capacity in the electricity generation sector. In the worst case (the highest 2030 target) the stranded investment reaches globally US$ 60billion for the 2010-2030 period and almost US$ 450billion for the 2030-2050 period with a particularly large contribution from China and South Asia, which will have invested heavily in coal generation during the first period. The 2030-2050 costs for these two regions represent more than 10% of their total investment in electricity generation during the period. To avoid these future large stranded capacities, fixing short to medium term targets on electricity generation are effective in preventing their development in the first place (targets below 53 $GtCO_2$-eq in 2030 reduce the above costs by two thirds). Other less effective options available to avoid high costs from stranded capacity are reducing energy demand (increasing efficiency), retrofitting old coal and gas capacity with CCS (if available) and increasing the lifetime of existing coal capacity (instead of building new ones). The RoSE results for similar scenarios show that in 2030, between 600 GW and 1400 GW of fossil power generation capacity are idle in the best policy case with immediate action [33]. Early retirements peak at a higher level (up to 3,500 GW) in the delayed scenarios.

A second effect of delaying mitigation policies is the impact on the fossil fuel markets. The AMPERE project reported that fossil fuel revenue presents a short term increase when a delay in mitigation decision is applied in comparison to the optimal (i.e. 2010) start of global mitigation action. These short term gains have to be compared by the longer-term effect brought by the stringent climate target and lower carbon emissions to comply with the carbon budget. In [15] models show different results; some models show a compensation between the short term gains and long term losses however in certain results the short term higher use of coal (and the possible technological lock-in) leads to strong reallocation toward oil and gas use over the rest of the century maintaining strong fossil fuel revenue gains in the long –term as well.

As consequences of higher short-term GHG emissions and fossil fuel lock-in , higher CO_2 prices in 2050 are generated the longer the delay in implementing global emissions reductions (i.e. the later the date at which global emissions peak) and the greater the required level of emissions reductions [34].

7) Co-benefits and risks associated with climate action.

Co-benefits and risks are intrinsic to mitigation options chosen for the global transformation pathways implemented. The large reduction in GHG emissions necessary to fulfil the stringent target presented in the paper has a significant effect on the energy system (from primary energy mix to final demand levels). These changes to the energy system induce secondary impacts including possible health benefits, changes to energy security or impacts on biodiversity [35]. These effects are challenging to weight against the costs of mitigation as they apply to different systems (economic, social and environmental) and are measured in different units. Some integrated assessment models such as PAGE [36] or FUND [37] amalgamate some of these side-effects in a relatively simple manner to the global economic impact of the pathways but debates arise from the materialisation of such side-effects into monetary quantities. Within a small number of the studies included in the review two co-benefits to mitigation scenarios are reported: impacts on air pollution and energy security.

Impacts on global air quality

The impact on air pollution is reported in AMPERE [38] and the RCPs scenarios [39] as avoided emissions of NO_x and SO_2, two important precursors to air quality pollutants: ozone and particulate matters. These two pollutants have negative impacts on human health, crop production and building preservation. The reduction in emitted quantities is reported due exclusively to climate considerations – no air quality policies are included. For mitigation scenarios achieving a concentration of 450ppm CO_2-eq, the models show strong reductions in NO_x (for example 60% below the baseline in 2050 for RCP 2.6) and more modest reductions for SO_2 (for example 20% below the baseline for RCP2.6). However, no direct effects on health and morbidity or on crop production are directly reported within the studies.

Impacts on energy security

Energy security is analysed for the mitigation scenarios compared to the baseline energy system. The reported information is orientated toward the qualitative analysis of energy system security. Within the RoSE project, study shows that mitigation policies in general increase national energy sufficiency and resilience via an increase and diversification of energy sources and carriers [40]. The 450ppm scenarios show radical reductions in energy trade (to almost zero in one for the models in the ensemble - WITCH), whilst energy diversity rises to mid-century, then declines as renewables start to dominate, although some regions' dependence on imported oil could increase if unconventional sources are not exploited in mitigation scenarios. However it is also remarked that the potential domination of the electricity sector by solar or the liquid fuel sector by biofuels may increase vulnerability. In LIMITS the analysis is primary focussed on the national level where energy security concerns are more relevant. The climate policy scenarios are combined with large reductions in fossil fuel dependence (and as a consequence imports) that increases energy security after 2030 at the regional level in major economy blocks [41].

Other impacts of mitigation options

Other potential side-effects from the climate mitigation scenarios have been highlighted in the assessments reports such as IPCC 2014 [13]; these include biodiversity and land use changes, water consumption, employment. No precise assessments have been found in the projects analysed.

8. Conclusion

This review paper summarises the characteristics of possible long-term transformation pathways of GHG emissions aimed toward stabilisation of climate change below the 2°C temperature target by the end of the century. The modelled scenarios indicate that it is still achievable. A large number of scenarios assessed share common views: mitigation to 2°C or below requires early action to keep costs down; at least a 60–80% share of global primary energy will need to come from zero-carbon options by 2050; the electricity sector in particular will need to be almost completely decarbonized by mid-century (low carbon shares of 75–100%); achieving a complete decarbonisation of the electricity sector will require a full portfolio of technologies. In particular, BECCS will be needed to achieve negative emissions later in the decade and coal power without CCS will need to be completely phased out by 2050; delays or removal of key technologies makes the requisite levels of mitigation harder to achieve and / or more costly.

However, a number of features of the models result in scenario “infeasibility” for some models. These include scenarios in which regional mitigation action remains relatively weak (in line with the less ambitious end of Cancun pledges) until 2030, before global coordinated mitigation action aimed at limiting atmospheric concentrations of GHGs to 450 ppm takes hold. Infeasibility also results from scenarios in which key low-carbon energy technologies, notably CCS with power generation, are not included in the technology mix. In this sense, model infeasibility means that the models do not have sufficient low-carbon technology options to provide a solution to the problem of meeting the world’s future energy needs (as derived from exogenous assumptions on economic growth, population growth and the elasticity of energy end-use demand to these factors) without exceeding a specified level of GHG emissions. Even in models which do meet the feasibility criterion, the consequences of delayed action are stark, with hundreds of fossil generation plants scrapped before the end of their useful lifetimes, and increased costs relative to an “optimal” scenario in which action began in the model base year (in most cases 2010).

As explained in the IPCC’s fifth assessment report [13], the integrated assessment models cannot define feasibility – they can only indicate it in terms of economic and technical factors. In reality the feasibility of stringent mitigation scenarios may be even lower as a result of societal and political barriers not represented in the models. Hence, the latest scenarios indicate that there is now an increasing risk that – under realistic assumptions where global coordinated mitigation action does not begin for several years - the achievement of 2 ° C is no longer realistically a feasible prospect. Furthermore, although there is emerging research that aims to further assess feasibility in terms of comparing required future low-carbon technology deployment rates with historical energy technology deployment rates, there is still much to be done to understand more accurately how important societal, institutional and political factors are to the lock-in of current fossil energy systems.

Considering the actions that would enhance the feasibility of achieving an emissions reduction trajectory in line with the 2 ° C target, it is clear from recent scenarios that energy efficiency is not just a low-cost option, but a risk-management strategy as well, where the specific risk is that there is a failure to be able to deploy a major low-carbon technology (such as CCS or large penetrations of intermittent renewables such as wind and solar). The enhanced energy efficiency cases in most models not only reduce the mitigation cost relative to the standard mitigation case, but allow the achievement of the 2 ° C target even when key technologies are excluded from the low-carbon set of options. As such, an enhanced focus on policies that drive rapid energy efficiency improvements is one of the most important near-term actions for governments. In addition, the criticality of deploying CCS to keep mitigation costs manageable and to allow the possibility of negative emissions in the latter half of the century cannot be overstated. As such, another key policy implication of these scenarios is the need to continue with demonstration projects until commercial-scale CCS is realised. A further policy implication is the need to plan and manage the inevitable shift from unabated coal and gas power stations that is likely to be necessary if mitigation action is further delayed, which will result in the early retirement of a number of such plants. Policies which can accommodate the complex distributional dynamics of this write-off of high-carbon assets will need careful preparation and stakeholder engagement.

Finally, GHG emission reductions are a source of possible co-benefits, which has not always been quantified in monetary terms. These co-benefits include air quality, health benefits, sustainable development, and green employment. Moreover, under higher levels of warming, systems such as the climate or the natural environment may be affected by large amplifying feedbacks that could trigger tipping points and extreme events. Taking into account these strong feedbacks and possible high damages from changing climate could be important for high-end scenarios such as, in general, the “business as usual” case used as a reference to calculate consumption losses due to climate mitigation policies. In most studies the baseline or BAU is assumed to see GDP grow continuously to 2100, unaffected by climate damages.

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Appendices:

Table A-1: physical climatic parameters for the pathways by studies.

Study / scenario	GHG concentration in 2100	Temperature change above pre-industrial by 2100	GHG pathway: peak year &level 2100 level	Rate of emissions reduction after peak
EMF27 450	450ppm	1.5-1.8°C (target on RF=2.6 Wm^{-2})	2025=20to35 GtCO$_2$eq 2100=-20to0 GtCO$_2$	2020-30=2.8,2030-40=5.3,2040-50=5.2%/y mean ensemble
LIMITS FP7 450ppm	450ppm	1.7±0.1°C	2020=53±1 GtCO$_2$eq 2100=0±1 GtCO$_2$	2020-30=2.8,2030-40=5.3,2040-50=5.2%/y mean ensemble
EMF27 G8	480 to 500ppm	1.8-2.3°C	2020to2030=25to35 GtCO$_2$eq 2100=0to20 GtCO$_2$	Not specified
LIMITS FP7 500ppm	500ppm	1.9±0.15°C	2020=53±1 GtCO$_2$eq 2100=1±1 GtCO$_2$	2020-30=2.7,2030-40=3.8,2040-50=4.2%/y mean ensemble
AMPERE 450 immediate action	450ppm	1.9°C (1.7–2.5) probablity >2°C=36%	2020=45±5 GtCO$_2$eq 2100=2±2 GtCO$_2$eq	2030-50=4%/y mean ensemble (3 to 4.5)
RCP 2.6	427ppm	1.9°C (0.9-2.3°C min to max range CMIP5)	2020= 37.6 GtCO$_2$ 2100=-1.5 GtCO$_2$	Not specified
RoSE Immediate action	450ppm	2°C with 50% chance	2010= 45 GtCO2eq, (one model peaks in 2035, at 50Gt CO$_2$eq)	1 to 3%/y
RoSE delayed action to 2020	450ppm	2°C with 50% chance	2020=50-57 GtCO$_2$eq 2100=5 GtCO$_2$eq	Not specified
RoSE delayed action to 2030	450ppm	2°C with 50% chance	2030=55-65GtCO$_2$eq 2100=0-5 GtCO$_2$eq	10%/y between 3030-2040 (maximum rate)
AMPERE 450 delayed action	450ppm	2.1°C (2.0–2.5) probability >2°C=60%	2020to2030=45±5 GtCO$_2$eq 2100=0±2 GtCO$_2$eq	2030-50=7.5%/y mean ensemble (6.5 to 8.5)
UNEP Emissions Gap Report 2013	highest 450ppm	Target 2°C with likely chance >66%	2010-2020=36to47 GtCO$_2$eq2100:1/3models negative emissions	2030-2050=2to4.5%/y (late action=6to8.5%/y)

UNEP Emissions Gap Report 2013	highest 450ppm	Target 2° C with medium chance (50to66%)	2010-2020=44to49 GtCO$_2$eq 2100:1/3models negative emissions	Not specified
UNEP Emissions Gap Report 2013	highest 450ppm	Target 1.5°C with medium chance (50to66%)	2010-2020=37to44 GtCO$_2$eq 2100:few scenarios negative emissions	2030-2050=2to4.5%/y (late action=6to8.5%/y)
Global Energy Assessment	Not available	2°C with at least 50% chance	2020 Peak year. Negative in 2100.	Not specified
CCC2013-UCL	440ppm	2° C	2016=36 GtCO$_2$. 2100=5.0 GtCO$_2$	4.00%
CCC2013-UCL	450ppm	2.1° C	2025=41GtCO$_2$. 39.9 GtCO$_2$ 2100=5.0 GtCO$_2$ in	4.50%
CCC2013-UCL	465ppm	2.15° C	2025=41GtCO$_2$. 2100=5.6 GtCO$_2$	2.00%

Table A-2: technologies and other economic indicators for the scenarios included.

Study / model / scenario	**Share of fossil fuels in primary energy by 2050, 2100**	**GW deployed of key technologies (solar, wind, CCS, nuclear)**	**Change in energy intensity of GDP, 2011-2050**	**Consumption losses in 2020, 2030, 2050, 2100**	**Reduction in primary energy relative to baseline by 2050/2100**
EMF27 450	N/A	S=30 (10to35), W=33 (20to35), N=67 (11to214) EJ/y Renewable electricity: =32% (28 to 36) / 55% (40 to 60) & Non-Electricity RE =6% (4 to 8) / 22% (10 to 26) & Nuclear electricity = 18%	15 to 50% rel. to BAU	0.8 to3.2 % loss (cumulative 2010-2100 with 5% discount rate) + one model 11.7%	N/A
LIMITS 450 ppm	N/A	2010-30(25,60,15,25);2030-50(170,140,105,45)GW/y	N/A	Cumulative 2010-2050: $45trillion comp to base	N/A
AMPERE 450 immediate action	N/A	Renewable share of primary energy 2050=30%, 2100=55%	N/A	0.6 to 4 % loss (cumulative 2010-2100 with 5% discount rate)	N/A
RCP 2.6	30% (2050) 10% (2100)	N/A	N/A	0.3% (2020) 0.9% (2030) 1.7% (2050) 0.8% (2100)	Primary energy reduced 20% compared to baseline in 2100
RoSE 450 ppm immediate action	54-61% (2050) 18-23% (2100)	Up to 240 EJ/year of nuclear in 2100 Up to 106 EJ/year of fossil with CCS in 2100 Up to 300 EJ/year biomass (of which 195 EJ/year with CCS) in 2100 Up to 285 EJ/year of solar in 2100	2.0-2.6% per year to 2050	1.4-2.5% GDP loss cumulatively over the period to 2100	23-45% below BAU (2050) 32-52% below BAU (2100)
RoSE 450 ppm delayed action to 2020	50-61% (2050) 15-22% (2100)	Up to 240 EJ/year of nuclear in 2100 Up to 97 EJ/year of fossil with CCS in 2100 Up to 290 EJ/year biomass (of which 195 EJ/year with CCS) in 2100 Up to 275 EJ/year of solar in 2100	2.0-2.7% per year to 2050	1.5-2.5% GDP loss cumulatively over the period to 2100	23-47% below BAU (2050) 36-53% below BAU (2100)

RoSE 450 ppm delayed action to 2030	42-58% (2050) 10-20% (2100)	Up to 130 EJ/year of wind in 2100 Up to 257 EJ/year of nuclear in 2100 Up to 280 EJ/year of biomass in 2100 (of which up to 196 EJ/year with CCS) Up to 309 EJ/year of solar in 2100	2.0-2.9% per year to 2050	1.7-2.9% GDP loss cumulatively over the period to 2100	25-50% below BAU (2050) 34-54% below BAU (2100)
AMPERE 450 delayed action	N/A	Renewable share of primary 2050=18% (≈2010) / 2100=65%	N/A	0.5 to 3.7 %	N/A
GEA 2012	N/A	Nuclear 75-1850 GW in 2050. Renewable (164-651 EJ) 30-75% of primary energy in 2050.	1.5-2.2% annually to 2050	N/A	N/A
CCC 2013-UCL: 440ppm	N/A	N/A	N/A	N/A	N/A