Imperial College
London

Halving global CO_2 by 2050: technologies and costs

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Project lead: Nilay Shah
Project team: Lola Vallejo, Tim Cockerill, Ajay Gambhir, Andrew Heyes, Thomas Hills, Mark Jennings, Owain Jones, Nicole Kalas, James Keirstead, Cheng Khor, Chris Mazur, Tamaryn Napp, Alexandre Strapasson, Danlu Tong, Jeremy Woods

A study by the Energy Futures Lab and
Grantham Institute for Climate Change
at Imperial College London

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Imperial College Project Team

Tim Cockerill[a], Centre for Environmental Policy

Ajay Gambhir, Grantham Institute for Climate Change

Andrew Heyes[a], Department of Mechanical Engineering

Thomas Hills, Grantham Institute for Climate Change

Mark Jennings, Department of Civil and Environmental Engineering

Owain Jones[b], Centre for Environmental Policy

Nicole Kalas, Centre for Environmental Policy

James Keirstead, Department of Civil and Environmental Engineering

Cheng Khor, Department of Chemical Engineering

Chris Mazur, Grantham Institute for Climate Change

Tamaryn Napp, Grantham Institute for Climate Change

Nilay Shah, Department of Chemical Engineering

Alexandre Strapasson, Centre for Environmental Policy

Danlu Tong[c], Grantham Institute for Climate Change

Jeremy Woods, Centre for Environmental Policy

Lola Vallejo[d], Energy Futures Lab

Current affiliations:

[a] University of Leeds

[b] University College London

[c] BP

[d] Committee on Climate Change

1 Executive summary

There is still a chance to achieve a reduction in CO_2 emissions that would keep the world broadly on track to limit global warming to around 2 degrees Celsius (2°C) above pre-industrial levels. This study outlines how it could be done, by focusing on the technologies which in combination could cut energy and industrial process CO_2 emissions to a 2050 level consistent with a 2°C temperature rise (which we have interpreted as around 15 Gt/yr by 2050, a level about half that in 2008, when leaders at the Hokkaido Toyako G8 Summit in Japan agreed to support a goal to halve CO_2 emissions by 2050[1]). The approach considers only technologies which either currently exist at commercial scale, or which have been demonstrated at sub-commercial scale but which are still awaiting full-scale deployment.

The approach divides the world into ten geographical regions[2], and for each region projects how economic output and population could grow to 2050. It then considers how this growth will affect the future demand for energy services across each region in the buildings, transport and industrial sectors. By further considering how primary energy is converted into final energy which can be used in these sectors, through electricity generation and other energy transformation processes, a complete, high-level picture of each region's energy system is produced.

The study specifies the technologies that would be employed in this energy system in a reference scenario (the "low mitigation scenario", LMS) in which no concerted action on climate change is undertaken, and in a range of low-carbon scenarios (LCS) in which emissions reductions would be broadly in line with a 2°C global warming target. In this way the study sets out the major technologies needed for this energy system transformation, with associated costs.

A number of implications follow from the analysis. The first is that, with challenging but feasible penetrations of a range of low-carbon technologies, an energy and industrial system transformation is possible which would result in CO_2 emissions in 2050 being 15 Gt/yr rather than the reference level of around 50 Gt/yr. Such a fundamental change in the production and use of energy would result in a cost differential (considering capital, operational and fuel costs) between the LCS and the LMS of the order 1% (results range from 0.2% to 0.9%) of 2050 GDP (on a current PPP basis[3]). It is not necessarily surprising that this cost – though potentially almost (2010 US) $2tn per annum by 2050 – is a relatively small share of projected 2050 GDP ($235tn on a current PPP basis or $111tn on a current exchange rate basis), given that a large part of the transformation comes from deploying new technologies which save energy, avoid increasingly expensive fossil fuels, and in many cases are projected to fall in cost over time. Indeed, under a high fossil fuel price scenario, this cost differential drops to around $400bn per year in 2050.

Our estimates of the operational (excluding capital but including fuel) energy system costs as a proportion of GDP are 3.5% (2010), 3.9% (2050, LMS, high fossil fuel prices), 2.8% (2050, LMS, low fossil fuel prices), 2.9% (2050, LCS, high fossil fuel prices) and 2.6% (2050, LCS, low fossil fuel prices). Our analysis therefore indicates that the transition is affordable.

The second implication is that decarbonising the world's electricity generation system is fundamental to achieving such significant emissions reductions. A number of regional analyses over the last few years have also demonstrated that – according to our best estimates of future technology costs and our knowledge of what is technically feasible – this is the most economic strategy to pursue. This study suggests that the globally-averaged CO_2 intensity of electricity generation can be reduced from a projected level of around 500 g/kWh in 2050 to less than 100 g/kWh, through the use of zero-carbon (operationally), or near-zero-carbon generation technologies including carbon capture and storage (CCS), nuclear and renewables. The precise mix of these technologies will require further analytical considerations, including how intermittent renewable sources, base-load nuclear sources and more load-variable fossil fuel sources are balanced. These results are robust across four different scenarios of power mix ("balanced", "high renewable", "high nuclear", "high CCS"). Nevertheless, the large-scale development and commercial deployment of CCS, biomass, solar, wind, and nuclear sources should be high on every government's policy agenda.

The third implication is that – in conjunction with the decarbonisation of electricity – there needs to be a shift towards electrification of industrial manufacturing processes, building heating systems, and vehicle propulsion systems. A range of technologies will be required to achieve this, including increased penetrations of electric arc furnaces in steelmaking, heat pumps in buildings, and battery electric and hybrid vehicles in road transport. Considerable investment in developing new technologies, with associated infrastructure, needs to begin now in order to enable the penetrations of these technologies that are required by 2050. Electricity's share of end-user energy increases from around 20% in the LMS to around 32% in the LCS in 2050 (the latter figure is over 60% on a primary energy basis).

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[1] This is, of course, dependent on emissions levels before and after 2050, since cumulative emissions (rather than emissions in any given year) affect levels of global warming. For comparison purposes, the IEA's (2012) Energy Technology Perspectives shows 2050 energy-related CO2 emissions levels at around 16 GtCO2 in a scenario where there is an approximate 80% chance of limiting global warming to 2°C.

[2] The ten geographical regions used are: OECD Europe, Eastern Europe, OECD North America, Latin America, China, India, OECD Asia Pacific, Other Asia, Middle East and North Africa, and Sub-Saharan Africa.

[3] PPP is Purchasing Power Parity, a method of expressing the relative value of currencies which accounts for the purchasing power of each currency within its country of use.

The fourth implication is that energy efficiency will need to improve in order to achieve relatively low-cost CO_2 reductions which will help keep the overall energy system transition cost manageable. As such, we would envisage (by 2050, when comparing the LCS with the LMS) a 19% improvement in industrial energy efficiency, and a 33% improvement in both the transport and buildings sectors.

The fifth implication is that following the LCS would see the world shift from its current overwhelming reliance on fossil fuels (especially in transportation), although these will still be a significant part of the non-transportation 2050 energy mix. The total amount of petroleum products consumed as final energy demands in the 2050 LMS scenario is 185EJ, while in the LCS it is 44EJ. This decreasing reliance is important if we are concerned about uncertainty around future fossil fuel prices, or indeed about rising fossil fuel prices. In a higher fossil fuel price world, the total LCS energy system cost would only be around 0.2% of 2050 GDP (in current PPP terms) higher than the reference (LMS) case, compared to 0.9% higher in a lower fossil fuel price world. For even higher fossil fuel prices, the transition to a low-carbon energy system might pay for itself over the long run. There are clearly strong economic as well as climate benefits from reducing dependence on fossil fuels; evidence for this is the persistence of relatively high oil prices since the global financial crisis began in 2008[4].

The major sources of primary energy supply on which a low-carbon world could rely by 2050 include bioenergy, renewables such as wind and solar, abated fossil fuels (i.e. combined with CCS) and nuclear. This will raise its own implications in terms of the degree of investment needed to deploy the relevant technologies to the scale required. For example bioenergy, which by 2050 could account for 160 EJ per year of primary energy demand, will require concerted R&D, investment and infrastructure planning to ensure that its use is genuinely renewable and does not hamper food production and alternative land use functions in an increasingly population- and climate-stressed environment. Such considerations have been taken into account in assessing the contribution of biomass, which is nevertheless significant. The LCS uses 0.44GHa globally for bioenergy, equivalent to 8.8% of the total global arable and pasture land.

The analysis highlights a number of uncertainties that mean any representative low-carbon pathway must be treated with caution. These include the future growth of world output and economic structures, particularly in least-developed regions where economic growth has huge future potential, and considerable risk of lock-in to high-carbon energy sources.

Another area of uncertainty is the relative costs of technologies, as well as any constraints on the rate of deployment, which are critical drivers in defining a future technology mix. This has been represented through the use of scenarios which consider varying resource constraints around the major low-carbon technologies including nuclear, CCS and renewables in power generation. Whilst these do not appear to greatly affect the overall estimated energy system cost, they do imply very different requirements for planning around the energy system mix, including electricity grid balancing, R&D into new storage technologies, demand management, and the need to map and plan CO_2 storage and transport networks fully.

Importantly, this study assumes that future GDP growth is the same in the LMS and the LCS, which implies that investments in low-carbon technologies do not affect other investments outside of the energy sector, such that the overall effect of investment patterns on growth is the same in both scenarios. Moreover, the study does not consider the economic damages that might result from taking no concerted mitigation action (as in the LMS), nor does it quantify the co-benefits of the LCS, such as enhanced energy security and reduced air pollution. As such, the LCS presented here is not about imposing additional economic costs, but rather on investing in order to reap several benefits, in particular reduced climate damages and risks. In addition, the study does not include analysis of potentially very powerful interventions around land use, both in terms of better urban planning and better management of non-urban areas (e.g. reforestation).

The energy system transition discussed in this study is, by nature of its scale and significance, likely to prove very challenging in technological, operational, social and political terms. It is not unachievable, nor economically prohibitive, but it will require governments to implement a technology development agenda consistent with achieving such a low-carbon energy system by 2050.

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[4] See Murray and King (2012) for a detailed analysis of the rising costs of fossil fuels

2 Objective of study

This study assesses the technologies which in combination could cut energy and industrial process CO_2 emissions to around 15 Gt/yr by 2050 – a level which, depending on the pathway to get there and the emissions levels thereafter, would keep the world on track to limit global warming to 2˚C above pre-industrial levels. The approach considers only technologies which either currently exist at commercial scale, or which have been demonstrated at sub-commercial scale but which are still awaiting full-scale deployment.

The particular objectives of the study are to:

- Identify the combination of interventions and technologies that will reduce final energy demand and direct emissions from the three major energy end-use sectors (industry, buildings and transport);
- Explore options for decarbonising the energy chains that feed these end-use sectors and hence reduce the direct and indirect emissions associated with them;
- Base this exploration on a geographically-explicit (using ten world regions) and technologically-rich analysis, building on Imperial College's strengths in technology and systems modelling and analysis;
- Quantify the cost implications of concerted, deep decarbonisation activity globally, to achieve a 2050 emissions target consistent with a 2˚C global average temperature rise;
- Analyse the potentially feasible and cost-effective technology mixes and develop a set of high level findings to support policy development;
- Ensure robustness of the findings by identifying alternative technology solutions and using two scenarios (a high and low case) for future fossil fuel prices.

3 Methodology

The analysis starts from the end-use sectors and develops a reference scenario (which we call the Low Mitigation Scenario, or LMS) for which energy demand and emissions data are determined. We then identify viable low-carbon technology mixes in 2050 which together limit energy and industry–related CO_2 emissions to about 15 Gt (the Low Carbon Scenario, or LCS). The annual cost difference (including energy usage, annualised capital costs and operation and maintenance costs) between the LCS and LMS is then calculated, to show the annual cost of decarbonisation in 2050. The rest of Section 3 describes the methodology in further detail. For those readers content to understand the high-level methodology only, we recommend you skip to Section 4 which discusses our major results.

In detail, the steps of the methodology are to:

1. Start with a 2050 perspective and define the three major end-use sectors and ten geographical regions;
2. For each region and end-user sector, define the drivers of energy consumption (e.g. GDP, population, urbanisation, travel demand and industrial share of GDP);
3. Project the future values of the drivers based on our interpretation of published data and projections;
4. Use the projections to generate an energy system response under conditions whereby society does not make any effort to decarbonise – we call this the "low mitigation scenario (LMS)";
5. Determine the annual cost of operation of the energy system (considering both capital and operational expenditure, including energy costs) in 2050 under the LMS;
6. Set a target of 15 Gt CO_2 p.a. in 2050 for our Low Carbon Scenario (LCS) – the scenario under which aggressive global mitigation action is undertaken;
7. Undertake a series of end-user sector and energy chain analyses and design activities to arrive at viable technology mixes to achieve the LCS. These are in the form of a 2050 "snapshot" of the system rather than a complete pathway describing changes between now and 2050. Only technologies which either currently exist at commercial scale, or which have been demonstrated at sub-commercial scale and await full-scale deployment (e.g. CCS), are considered. Options have been appraised and chosen by combining screening of deployment options for demand sectors with a power systems optimisation tool, which deploys available generation plant according to a cost-minimising algorithm. The major low-carbon interventions considered in this study include:

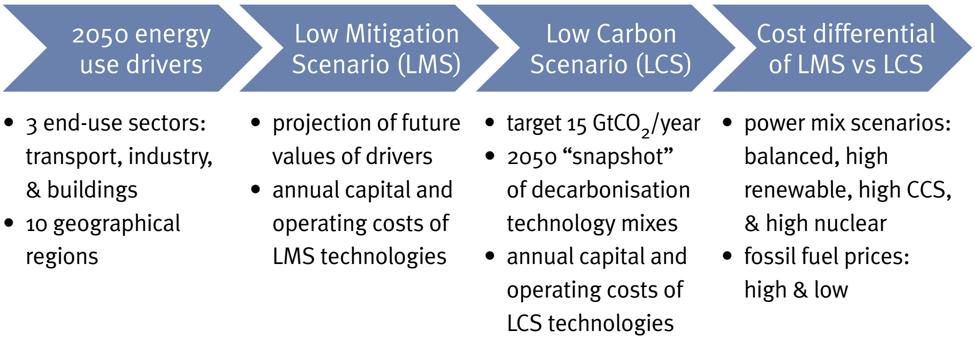
   7.1 For the power sector: fuel switching, use of renewables and nuclear power, and fossil fuels and biomass with CCS;

   7.2 For the industry sector: fuel switching, energy efficiency, and CCS;

   7.3 For the transport sector: hybrid, full electric, and fuel cell vehicles in road transport, electrification of rail, as well as energy efficiency and widespread use of bio-fuels across all modes;

   7.4 For the buildings sector: energy efficiency of building shells and appliances, increased electrification of heating and cooking, and other low-carbon heating options including CHP (combined heat and power).

Figure 1. Overview of methodology



- 3 end-use sectors: transport, industry, & buildings
- 10 geographical regions

- projection of future values of drivers
- annual capital and operating costs of LMS technologies

- target 15 $GtCO_2$/year
- 2050 "snapshot" of decarbonisation technology mixes
- annual capital and operating costs of LCS technologies

- power mix scenarios: balanced, high renewable, high CCS, & high nuclear
- fossil fuel prices: high & low

8. Calculate the costs of the interventions required in the end-user sectors to move from the LMS to the LCS, and the corresponding changes to the energy chains (e.g. decarbonising power) and express these costs on an annualised basis. Note that although we use a snapshot model, the amortisation of assets in operation in 2050 is counted into the cost and so investments in the run-up to 2050 are accounted for;
9. Establish the cost differential between the two scenarios and express this in terms of proportion of 2050 GDP;
10. Undertake the analysis for a range of power mix options and fossil fuel prices (to ensure robustness of the analyses), and also explore the cost implications on a regional and end-use sector basis;
11. Develop a set of high level insights consistent with our findings.

The specific steps in the construction of the LMS and LCS are described below.

3.1 Construction of reference scenario (LMS)

The objective of this task is to construct a self-consistent reference scenario for each region, for the major end-use sectors of the economy (buildings, transport and industry). This uses past relationships between socio-economic factors (demand drivers) and use of different energy types, projecting these forward to estimate future energy demand in a "top-down" fashion. More detail on each sector's drivers and the relationships are provided in an online annex to this report[5]. We then construct "bottom-up" activity models for each region and for each major sector (transport, buildings, industry) and sub-sector (e.g. road transport, aviation, residential buildings shells, commercial buildings appliances, steel industry, cement industry, etc.) to show which energy services are likely to be used in the future for each region, and to quantify the extent of demand. This is harmonised with the top-down estimates, in order to ensure that the bottom-up estimates of energy demand, split by energy carrier, are plausible in the light of past trends and future socio-economic projections.

The supply side of the system for each region is then designed based on the concept of energy chains (essentially fuels and power) and associated future energy supply technologies (e.g. electricity generation) required to meet the total energy demand from these sectors in each region. The selection of technology mixes is made assuming no concerted action on climate change mitigation – in this case, past trends in the energy mix serving each demand sector and energy efficiency improvements in each sector are taken as a guide to the future.

The cost of operating the energy system in 2050 is then evaluated once the energy system details are finalised. There are a number of key assumptions/conventions employed in the economic evaluation:

- All our figures are real, rather than nominal, and are in 2010 US Dollar ($) terms;
- Capital investments associated with all sectors including power generation, industry technologies, building technologies and transport modes are amortised over their "technical life" using a 3.5% real discount rate (based on UK Treasury "Green Book" guidance);
- Capital investments to improve industrial energy efficiency are more complicated to model because of the wide range of potential interventions possible. We therefore use an approach whereby the total investment cost is calculated by assuming that energy savings arise from the adoption of technologies with a payback time of up to 5 years (which is not a typical on average). This investment cost is annualised assuming a discount rate of 3.5% and a plant lifetime of 25 years;
- We have accounted for the annualised cost (capital, operation and maintenance, and fuel) of supplying and using energy in 2050 in both the LCS and LMS. This means that, regardless of when the investment in capital used in the 2050 energy system takes place, its annualised cost is still counted as part of the 2050 energy system cost (i.e. there is no energy capital with sunk costs that are no longer being counted as economic costs);
- We calculate the *difference* between the annual energy system costs of the LCS and LMS in 2050, which reduces the sensitivity of the cost to assumptions common to both scenarios;
- The 2050 GDP values for each region are independent of scenario i.e. we make the assumption that the LMS pathway will have the same GDP as the LCS pathway. This ignores any impacts on GDP of the higher levels of warming in the LMS scenario, as well as the impact on GDP of making low-carbon investments (as opposed to high-carbon investments) in the LCS scenario;

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[5] http://www3.imperial.ac.uk/climatechange/publications/halving-global-co2-by-2050

- We use two fossil fuel price scenarios[6]:

  o The “low” scenario, with the following prices (in 2010 USD by 2050):
    - Oil : \$100/bbl;
    - Coal : \$100/tonne;
    - Gas : \$1/therm (\$34/MWh).

  o The “high” scenario, with the following prices:
    - Oil : \$150/bbl;
    - Coal : \$150/tonne;
    - Gas : \$1.3/therm (\$44/MWh).

3.2 Construction of low-carbon scenarios (LCS)

The LCS development starting point is to establish regional and sectoral emissions budgets that aggregate to our overall target. We use a uniform per-capita emissions budget for 2050 to establish a regional emissions budget, based on projected population levels in each region by 2050 (using central UN (2010) population estimates). The next step uses the calibrated bottom-up sectoral models and estimates the penetration of low-carbon technologies and other interventions in each major sub-sector (industry, transport, buildings) of each region to estimate final energy demands (which are different from those in the LMS due to efficiency-related interventions) and energy supply mix. This helps to establish the direct emissions from in-situ combustion activities (accounting for emissions from the mining, refining and transportation of fuels to their site of combustion) as well as electricity demands. Biomass is also assumed to be available with appropriate emissions factors associated with production and logistics. The direct emissions are summed across sectors leading to a regional total. A regional power sector emission target is then used as a constraint and a power system optimisation tool[7] is used to develop appropriate regional power generation mixes and establish indirect emissions from power generation. A degree of iteration between the steps (in particular reviewing the disaggregation of the total emissions budget between sectors and regions) is required before a consistent scenario, which meets the established target for each region, is arrived at.

The energy demand and energy mix in the end-use sectors are assumed to be sensitive only to energy technology penetration rates, and not to fossil fuel prices. In reality, any increased costs of energy would see a demand response which could lower future energy demand, potentially lowering future emissions levels beyond those levels calculated in this study. However, the power generation mix is influenced by fossil fuel prices, since the power generation optimisation tool calculates a least-cost generation mix, based on the generation cost of each power technology. In addition, four different power system mix scenarios are used to shape the power systems optimisation exercise. These are:

- A “balanced” scenario, which uses a set of technological and geographical constraints on the level of penetration of different technologies in different regions and applies a variant of a least-cost optimisation algorithm to establish regional generation mixes;
- A “high renewable” scenario, which shifts the supply curve of renewable technologies such that more capacity is available at lower marginal cost;
- A “high CCS” scenario where build rate, capacity constraints and cost assumptions are relaxed;
- A “high nuclear” scenario where deployment constraints are relaxed.

An economic evaluation is undertaken for each LCS scenario and the annual cost of the energy system in 2050 is compared to that of the corresponding LMS scenario. Note that we have chosen to neglect a potentially important price feedback in that we have not adjusted fossil fuel prices in the LCS even though by 2050 the demand for such products is much lower than in the LMS (a 76% reduction). This reflects our view that future fossil fuel prices are highly speculative, and our desire to show the cost of decarbonisation given certain future fossil fuel price projections.

A final sensitivity analysis to the cost of decarbonisation is undertaken using both fossil fuel price scenarios and exploring the effect of tightening and relaxing the annual CO_2 budgets by approx. 1.4 Gt (13.9 Gt and 16.7 Gt annual emissions) – the aim being to understand the marginal costs of relaxing the 2050 target from the central figure of 15.3 $GtCO_2$.

Supporting data for our analysis can be found in the online annex at http://www3.imperial.ac.uk/climatechange/publications/halving-global-co2-by-2050.

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[6] For further background on fossil fuel price scenarios, see online annex and data sheets at: http://www3.imperial.ac.uk/climatechange/publications/halving-global-co2-by-2050

[7] This tool is described in detail in the online annex: http://www3.imperial.ac.uk/climatechange/publications/ halving-global-co2-by-2050

4 Results

4.1 Energy demand and emissions in the LMS and the LCS

In the LMS, the global annual emissions are projected to reach around 50 $GtCO_2$ by 2050, compared to about 30 $GtCO_2$ in 2010[8]. In the LMS, the fastest growth in emissions between 2010 and 2050 occurs in China, OECD North America and India. This growth is driven by increased usage of energy for heating, transport and industrial production, and indirectly by a growth in global population from 6.9bn in 2010 to 9.3bn in 2050 (based on central UN (2010) estimates) and a corresponding growth in GDP per capita from a global average of (US 2010) $10,600 to $26,900[9].

The LCS is constrained to be within annual emissions of about 15 $GtCO_2$ by 2050 (a precise level of 15.3 $GtCO_2$ is achieved) – a level which sits between the 14 $GtCO_2$ of the IEA's (2010) Energy Technology Perspectives "BLUE Map" scenario and the 16 $GtCO_2$ of the IEA's (2012) Energy Technology Perspectives "2DS scenario", both of which would be broadly consistent with achieving a stabilisation of atmospheric greenhouse gas concentrations of 450ppm, as part of a pathway which limits global warming to 2°C. It is also approximately central in the range of 450ppm scenarios modelled by different global integrated assessment models compared in the Stanford University Energy Modelling Forum (Clarke et al, 2009). A number of power generation system options (as discussed in Section 3.2), combined with assumptions on the use of final energy in each of the industry, transport and buildings sectors, have been generated so as to achieve this emissions level.

The deployment of efficiency interventions and low-carbon technologies in each sector causes a change in final energy demand, as well as the energy vectors that make up that demand, in each region, when comparing the LCS to the LMS. Some of the major technological shifts are electrification in vehicles, buildings and transport, energy efficiency and increased adoption of bioenergy (including in negative emissions power generation). This is coupled with deep decarbonisation of electricity using a range of technologies including different possible combinations of renewable (dispatchable and non-dispatchable), nuclear and fossil fuel generation combined with CCS.

Figure 2 shows that final energy demand could remain almost flat between 2010 and 2050 if pursuing a low-carbon pathway. Figure 3 shows that drastic emissions reductions are required in all sectors.

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[8] This compares to the IEA's (2012) Energy Technology Perspectives "6DS" scenario's annual emissions of 58 $GtCO_2$ by 2050, as part of a pathway which would see a mean global average temperature rise of at around 6°C in the long term

[9] GDP projections based on data from IEA (2012) and World Bank (2012)

Figure 2. Final energy demand by end-use sector. The totals are 526 EJ (LMS) and 376 EJ (LCS)

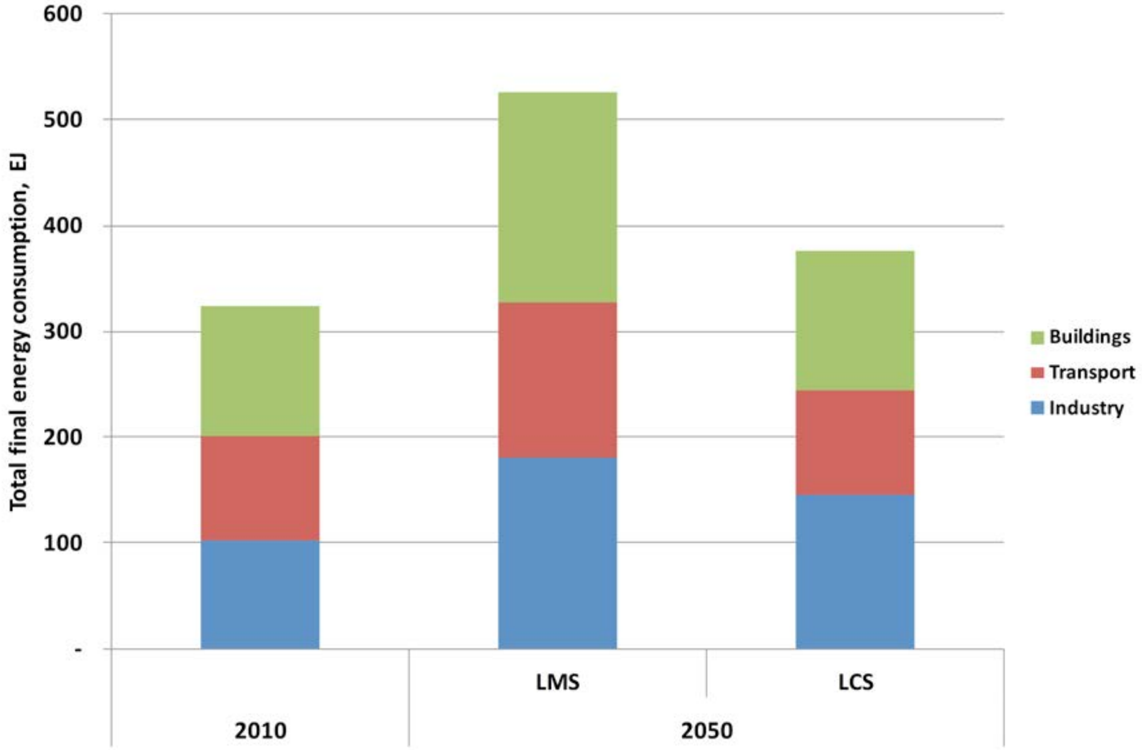


Figure 3. Annual CO_2 emissions by sector, and compared to total 2010 emissions

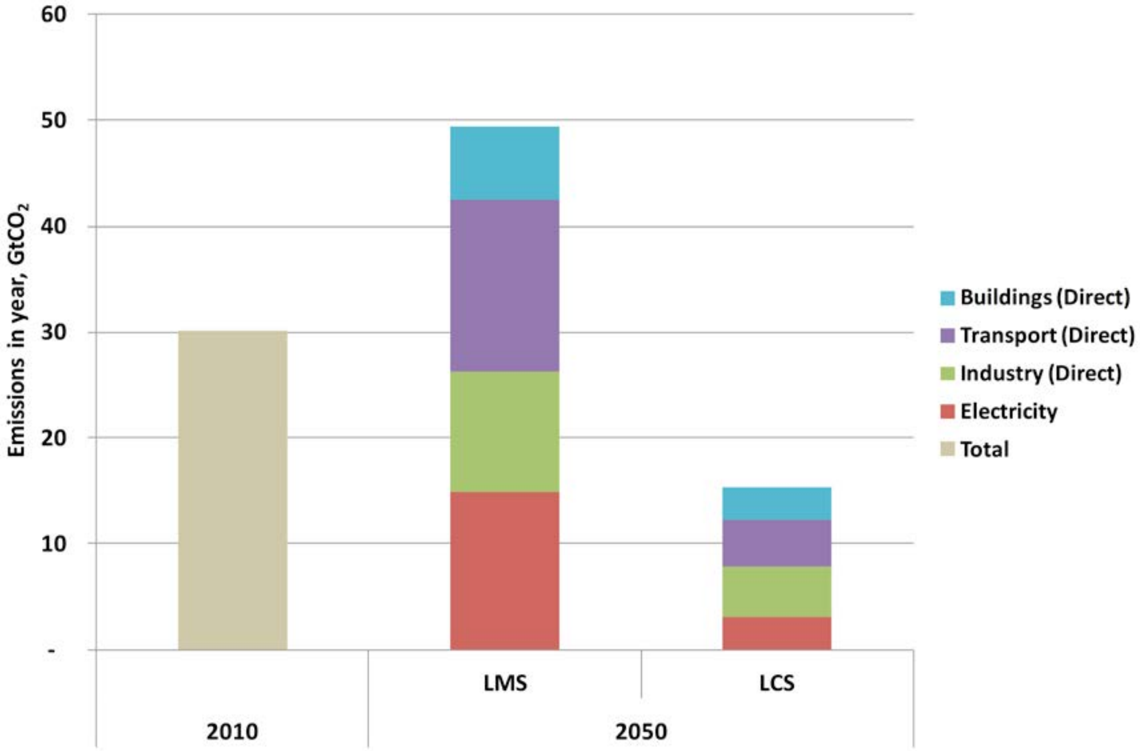


Figure 4. Final energy demand by vector. The totals are 526 EJ (LMS) and 376 EJ (LCS)

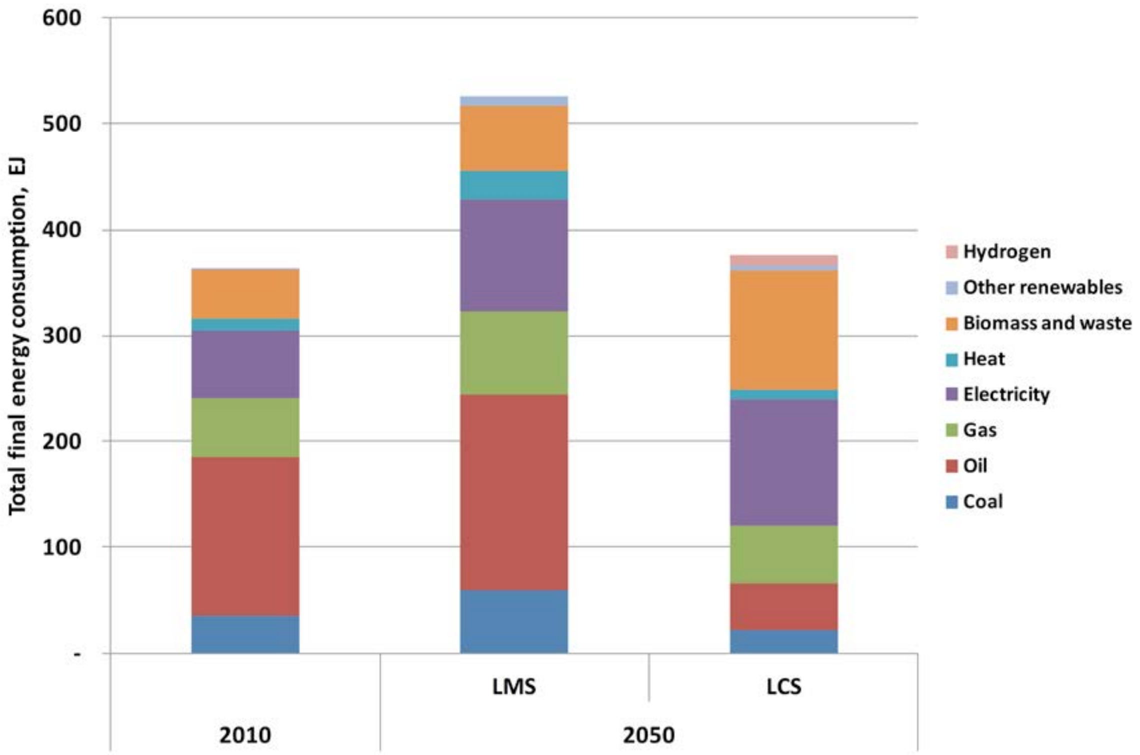


Figure 4 illustrates in greater detail the final energy demand by energy vector in the LMS and LCS. Of particular note are the large reduction in petroleum products consumption, a reduction in gas and coal consumption and an increase in hydrogen, electricity and (particularly) biofuels use. Consumption of biomass (by which we mean material which has been minimally processed as distinct from biofuels) is similar in both cases. This reflects the use of biomass heat and/or power in industry and buildings, a practice that is already prevalent today. However, we anticipate that in the future, biomass for buildings will come from increasingly efficient, commercial sources, as opposed to current rural biomass usage which is often from the informal sector using non-market biomass products such as agricultural wastes and residues.

Figure 5 aggregates the global direct and indirect emissions by sector and presents the overall emissions attributable to each sector in the LMS and LCS. The industry sector takes the lowest burden in terms of emissions reductions, which follows from our relatively conservative assumptions regarding the potential for changes in fuel mix, the degree of electrification, and the use of CCS to capture emissions. Nevertheless, steep reductions are necessary (and possible) in all sectors.

Figure 6 illustrates the regional variations in emissions between the LMS and LCS. It is clear that in relative terms the burden must be borne to a significant extent by all regions, but with a need for large absolute reductions in OECD North America, China and India. By 2050, Sub-Saharan Africa's emissions are such that without considerable mitigation in this region the global target will not be hit. This is a point worth making since it is often considered less important to focus on currently lower emitting regions with fewer economic resources. In reality the most likely way of meeting such a low 2050 CO_2 target is to achieve emissions reductions (relative to the LMS) in all regions. Similarly, figure 7 shows that the challenge extends far beyond the OECD, India and China.

Figure 5. Total emissions by end-use sector for the LMS and LCS

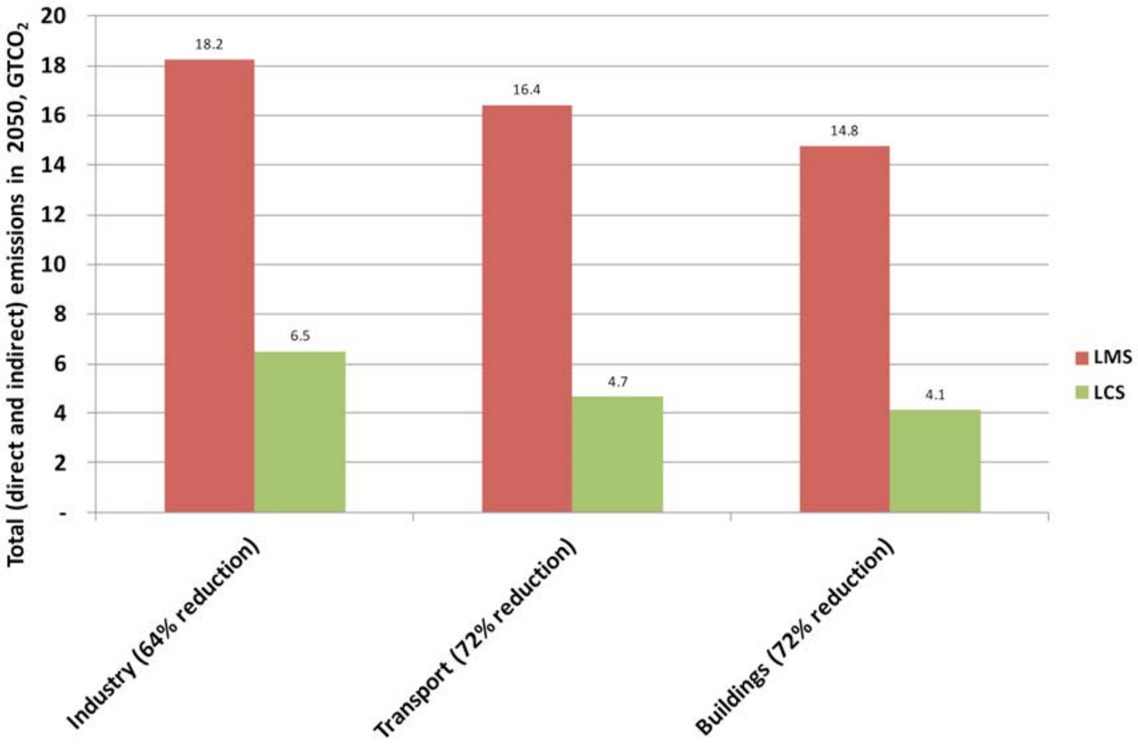


Figure 6. Variations in emissions by region for the LMS and LCS

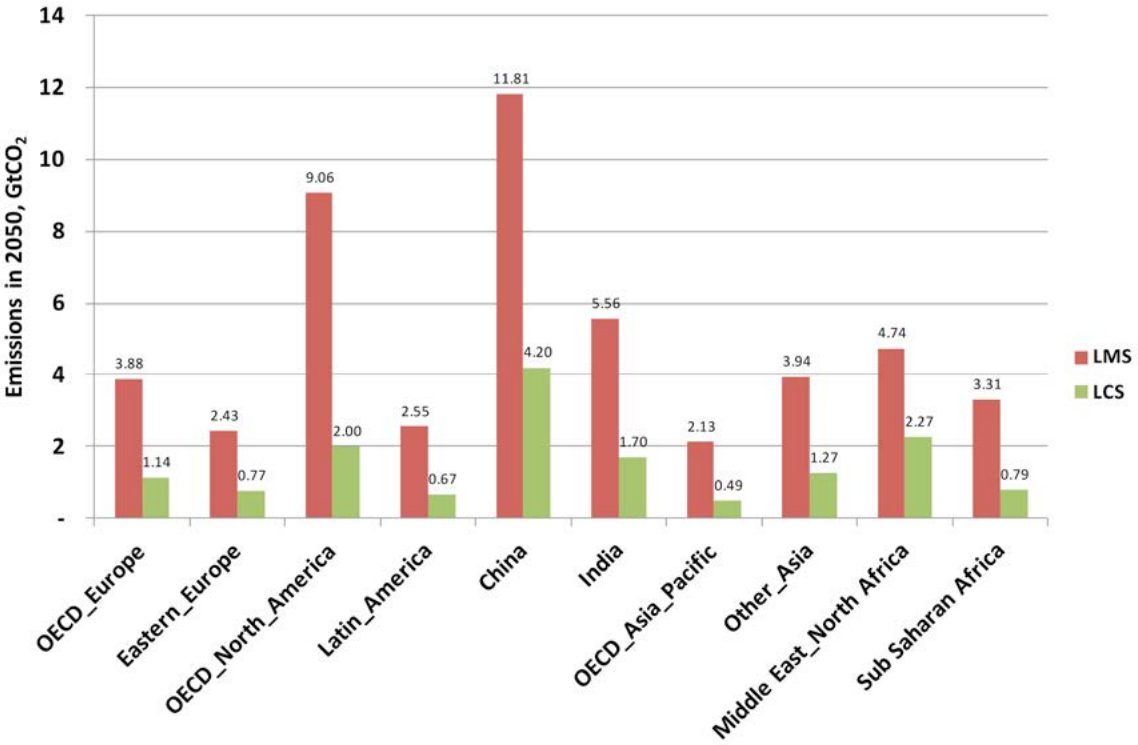
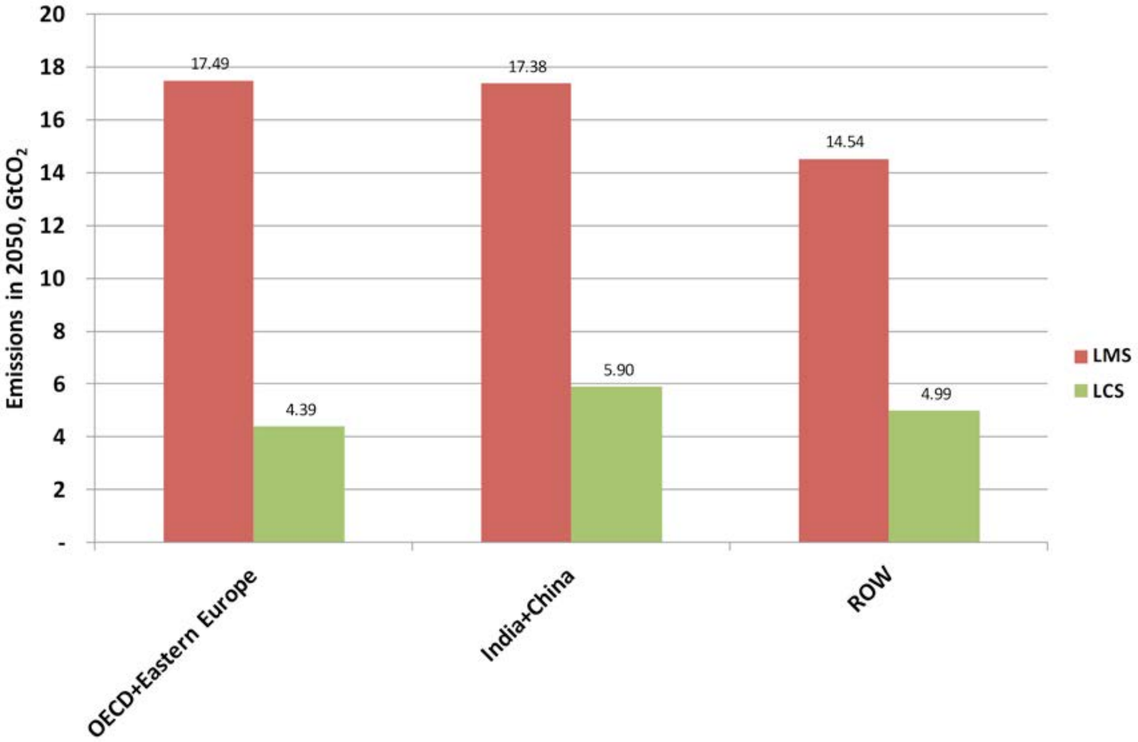


Figure 7. Variations in emissions by bloc for the LMS and LCS



4.2 Cost of the LCS compared to the LMS

The cost of achieving the LCS, based on the cost differential against the LMS, is (2010 US) \$0.33-2 trillion per annum, which translates to between 0.15%-0.9% of global GDP in 2050 (in 2010 PPP terms), or 0.3-1.8% of GDP (on a 2010 exchange rate basis). Figure 8 shows the cost differential between the LCS and the LMS for three different global GHG emission targets where the central figure is 15.3 $GtCO_2$. The marginal abatement cost based on the cost reduction in increasing or decreasing the emissions level corresponds to about \$39/tCO_2 (low fossil fuel prices) and \$30/tCO_2 (high fossil fuel prices).

Figure 9 shows how the cost differential between the LCS and LMS is made up of technology and fuel cost differences, and how this varies by sector. In the transport and buildings sectors, the energy efficiency gains in the LCS result in net fuel savings, which in the case of the transport sector largely offset the additional technology costs. The cost differential for fuel is positive for the industry sector because, despite efficiency gains, a switch to lower carbon fuels incurs a cost that more than compensates for this. Under a low fossil fuel price scenario, the cost of the transition is primarily associated with industrial production, where the cost of decarbonisation is estimated at 2.6% of the gross value-added (GVA) of this sector, and with decarbonising buildings, with an additional cost of \$267 per household per year, in 2050.

The transport cost differential between the two scenarios is very sensitive to the assumptions around fossil fuel prices. The global average cost per passenger-km is 3.6% higher in the LCS than in the LMS for low fossil fuel prices, and 7.3% lower than in the LMS for high fossil fuel prices. Note that no assumptions around demand management or improvements in land use planning are made for the LCS, and the passenger-km are the same in both the LMS and LCS.

Figure 8. Cost differential between LCS and LMS for different CO_2 targets and fossil fuel prices – 2010 PPP basis

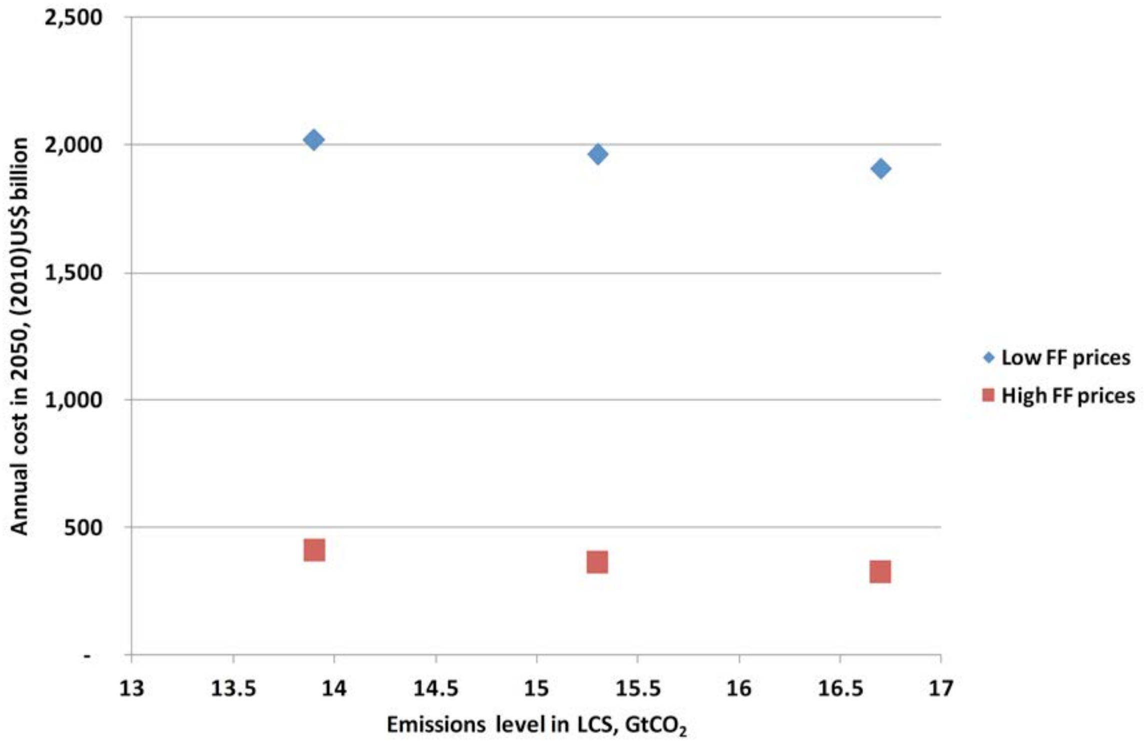
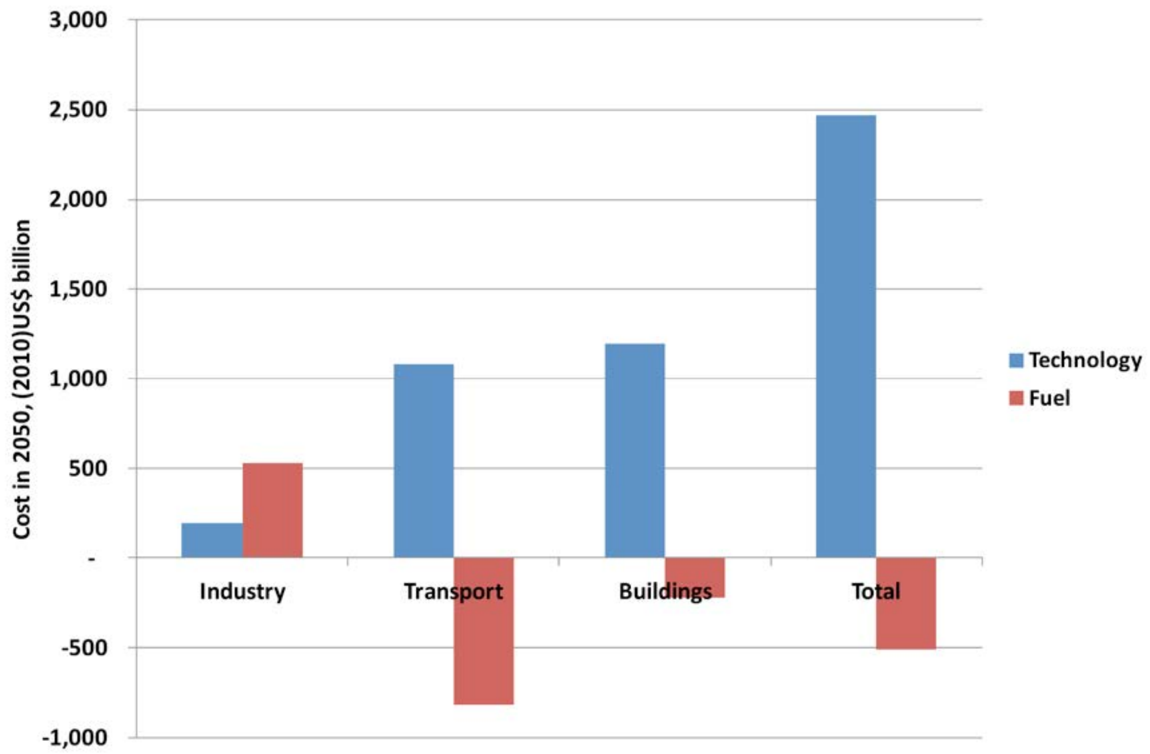


Figure 9. Cost differential between LCS and LMS (low fossil fuel prices) – 2010 PPP basis



4.3 Specific insights – Power mix

Analysis of final energy demand from the end use sectors, and the mix of technologies and fuels to meet that demand, is used to generate electricity demand levels for each region in both the LMS and LCS, and set overall carbon budgets for the power sector for each region in the LCS. For the LMS, an overall power generation mix is estimated for 2050 with regard to current fuel mix and projections from a variety of literature sources[10]. For the LCS, the power systems optimisation tool is used to generate four different generation mix options to meet these needs. These are the “Balanced”, high nuclear (“Hi-Nuc”), high CCS (“Hi-CCS”) and high renewable (“Hi-Ren”) options; the latter three reflect different potential societal preferences or responses to technological advances. Each of these LCS generation mix options would cut the world’s average CO_2 intensity of electricity by more than 80%, from 508 gCO_2/kWh in the LMS, to 94 gCO_2/kWh in the LCS, in 2050.

The global power generation mixes for these different cases are illustrated in figure 10. Note that the total generation (including transmission and distribution losses) is 117 EJ in the LMS and 147 EJ in the LCS by 2050. This compares to a figure of about 60 EJ in 2010, and so represents at least a doubling of global power generation over the next four decades in both the LMS and LCS cases. The cases all indicate a relatively low global share of unabated fossil fuel generation by 2050 and a significant role for the other technologies.

For the “Balanced” scenario, the LCS is associated with a 37-73% increase in world average levelised cost of electricity over the corresponding cost in the LMS, with the lower figure representing a higher fossil fuel price scenario. For the lower fossil fuel price scenario, the cost increase would mean that worldwide wholesale electricity unit costs were (US2010) 0.085 $/kWh in the LCS, compared to (US2010) 0.049 $/kWh in the LMS, by 2050. Despite this increase, the proportion of household expenditure on electricity would fall in the LCS compared to the 2010 figure because GDP per capita increases from (US2010) $10,600 (in 2010) to (US2010) $26,900 (in 2050) on a PPP basis. In addition, the quantity of electricity used per household is 26% lower in the LCS compared to the LMS.

However, disparity in electricity cost increases exists on a regional scale. For the low fossil fuel price case, where the average global electricity cost increase is 73%, four regions (OECD North America, India, China, and Other Asia) would see cost increases in excess of 80%, when comparing the LCS with the LMS, in 2050. This is largely due to the assumption that these regions would remain highly reliant on fossil fuel generation sources in the LMS, so that the significant decarbonisation of the electricity sector in the LCS would be more costly.

For the other scenarios, the average global cost of electricity in 2050 is of a similar magnitude to the “Balanced” scenario. The “Hi-Nuc” case would see a 9% reduction in electricity costs, and the “Hi-CCS” and “Hi-Ren” cases a 1% decrease in electricity costs, relative to the “Balanced” scenario in the low fossil fuel price case. A 10% reduction in the 2050 CO_2 emissions target, to 13.9 $GtCO_2$ (where additional emissions reductions over and above the central emissions target scenario are achieved through decarbonising the electricity sector even further) leads to a 2% increase in the electricity cost in the “Balanced” scenario. Since there is uncertainty about the future costs of different low-carbon electricity generation sources, we take these modest variations in electricity cost as a sign that it is possible to achieve electricity decarbonisation through a range of power technology mixes, without a significant impact on the average electricity cost, so long as no technological or resource constraints are reached.

As indicated in several other studies (IEA, 2010, 2012; IIASA, 2012), increased electrification is a critical element of decarbonisation. The projected growth in power generation in the ten regions is illustrated in figure 11. This is a stylised representation since our analysis is a 2050 snapshot analysis.

The contribution to power from intermittent renewables (including solar thermal which in practice has some storage capacity) is subject to constraints on capacity and the need for balancing plant; resulting in the global distribution shown in figure 12.

This overall picture could be disrupted (allowing further decarbonisation at a reasonable cost) by breakthroughs in solar PV generation, especially if combined with energy storage and demand management technologies.

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[10] See online annex for details, available at: http://www3.imperial.ac.uk/climatechange/publications/halving-global-co2-by-2050

Figure 10. Summary of power generation mix scenarios (low fossil fuel prices)

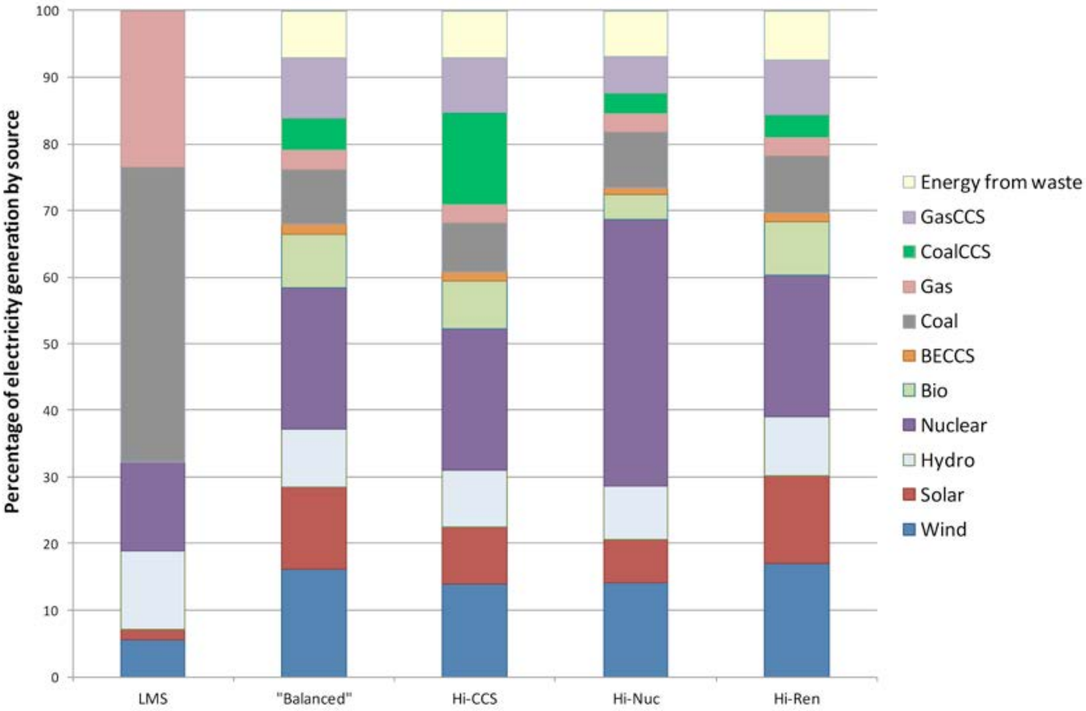


Figure 11. Growth in total power generation by region

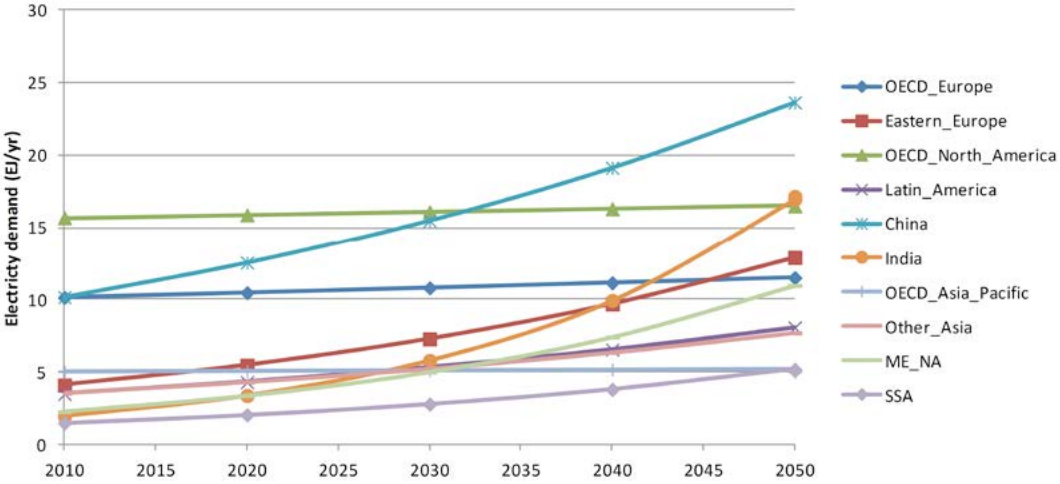
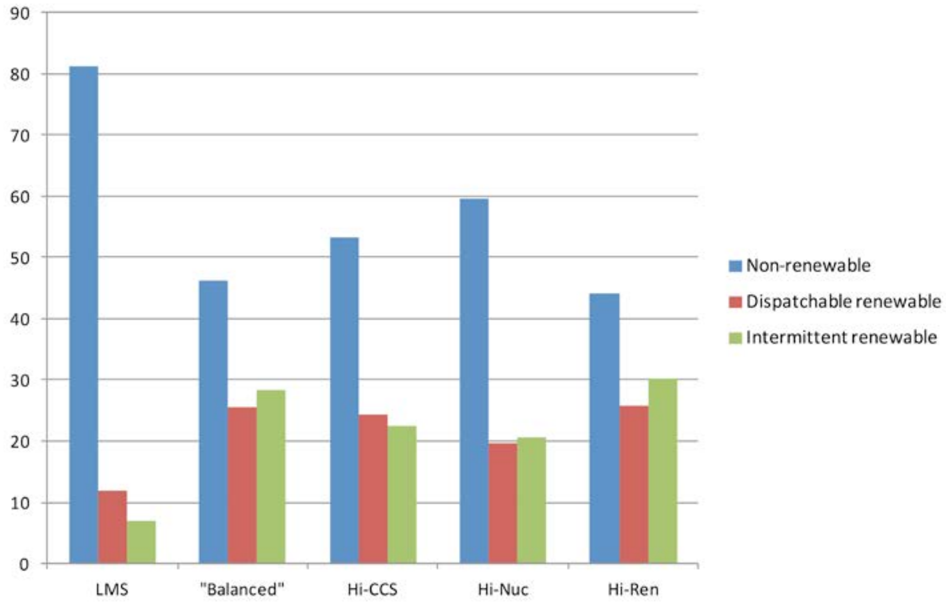


Figure 12. Share of power generation (%) by generation type; dispatchable renewable includes hydro and biomass



4.4 Specific insights – Industry

The industrial analysis is driven by estimates of manufacturing's value added proportion of GDP. Figure 13 shows the industrial energy demand, split by fuel type, in both the LCS and LMS, as well as the 2010 figures. As can be seen from figure 13, the LMS assumes a fairly similar fuel mix by 2050 as is currently used in industrial production, whereas the LCS assumes a far greater use of electricity, in place of coal combustion (for example, as a result of an increased share of electric arc furnace steel production, in place of blast furnace production). In addition, there is a significant (19%) energy demand reduction as a result of the use of more energy efficient technologies.

Overall, the industrial sector is responsible for 18.2 $GtCO_2$ emissions in the LMS and 6.5 $GtCO_2$ in the LCS in 2050 (a 64% reduction). The geographical distribution of the emissions is shown in figure 14. China is the largest emitter at more than double that of the subsequent main emitting regions comprising India, OECD North America, and Non-OECD Asia. The large emissions reduction observed in the LCS is primarily due to: (1) energy efficiency through adopting Best Available Technologies (BAT); (2) fuel switching away from coal and oil; (3) decarbonisation of the electricity generation sector and (4) Carbon Capture and Storage (CCS) applied directly to industrial emissions. Around 1.5 $GtCO_2$ is captured using CCS in this way; this figure is equivalent to 23% of the total emissions in the LCS.

The additional cost (annual cost difference between the LCS and LMS) is (US2010) $720 billion in 2050 (low fossil fuel price case), which corresponds to 2.6% of industry's 2050 projected gross value added (in 2010 PPP terms) – a proxy for the increase in the price of goods that might result from this level of decarbonisation in the sector. Three measures contribute to this cost: 1) the cost of energy efficiency, split into capital expenditure and fuel costs, 2) the cost of switching to less carbon intensive fuels and 3) the capital, operational and fuel costs of CCS[11]. For high fossil fuel prices, which place a greater value on energy savings resulting from energy efficiency, the additional cost of the LCS compared to the LMS is about (US2010) $440 billion in 2050, or about 1.6% of global manufacturing gross value added in 2050.

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[11] Further detail on the costs of the industrial sector are given in the online annex available at: http://www3.imperial.ac.uk/climatechange/publications/halving-global-co2-by-2050

Figure 13. Industrial final energy demand in the LMS and LCS by energy vector

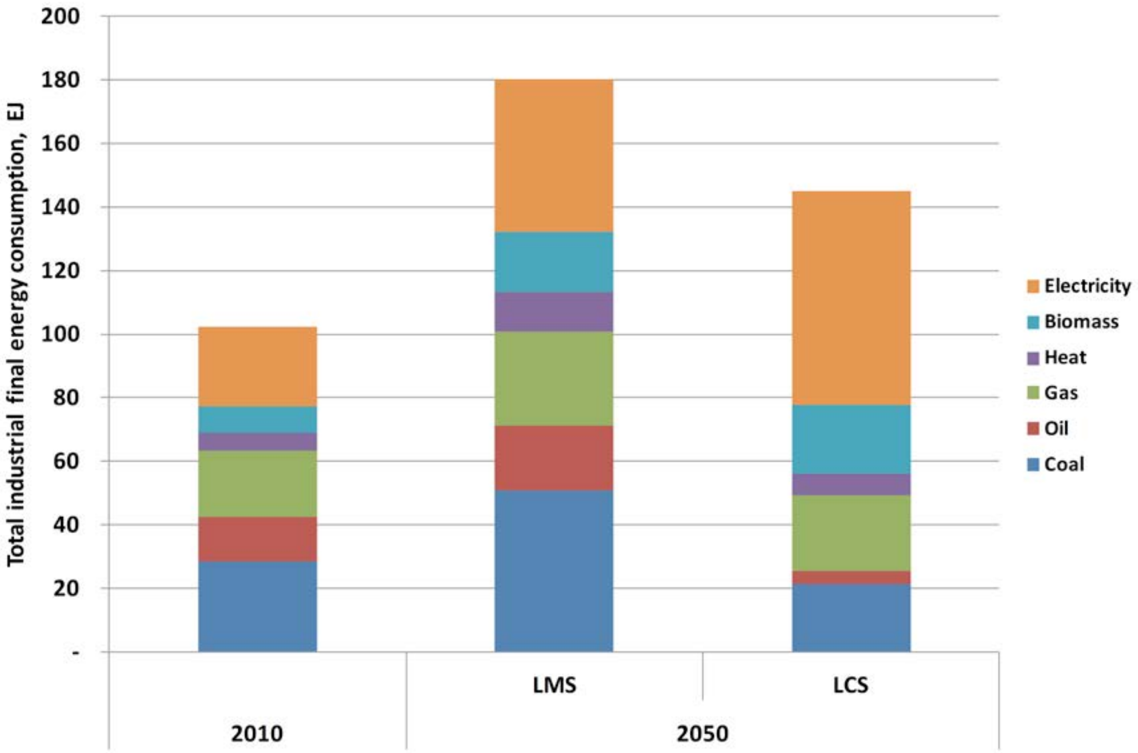
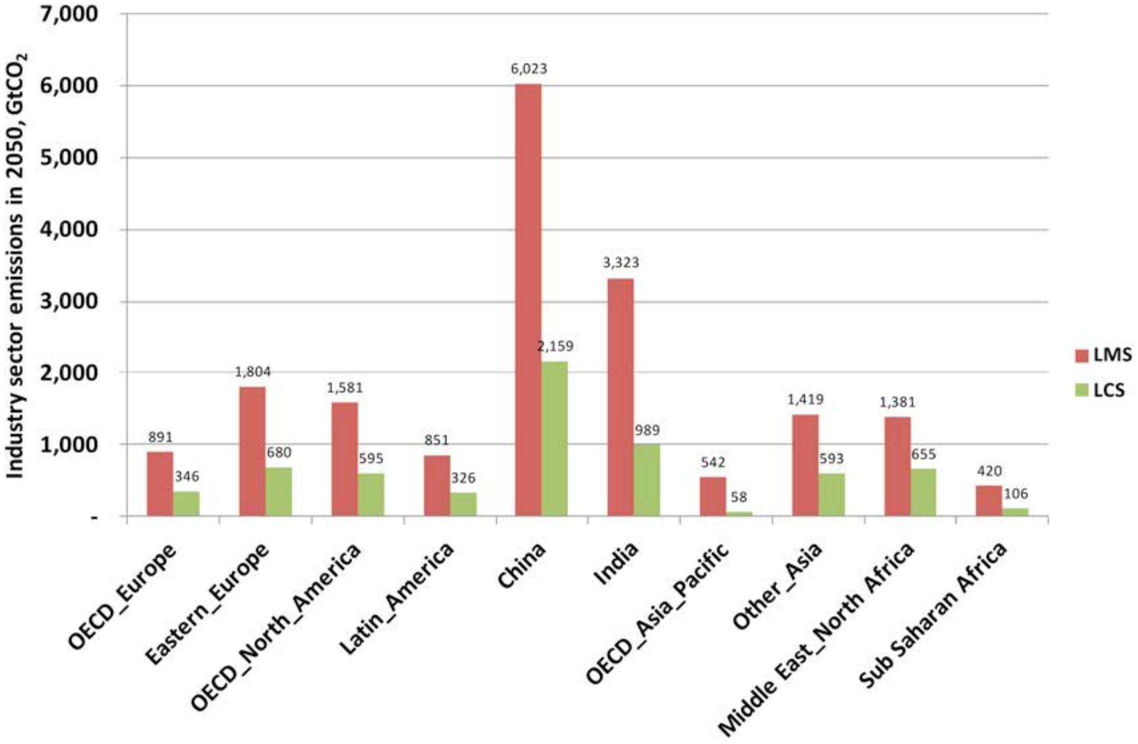


Figure 14. Industrial emissions (direct and indirect) by region in 2050



4.5 Specific insights – Buildings

Energy use in buildings includes space heating and cooling, cooking and the operation of appliances. Buildings are currently point sources of direct emissions and therefore present unique decarbonisation problems, particularly in the supply of heat.

To estimate the potential carbon savings in 2050, we estimate the impact of five major interventions: (1) reducing residential space heating demand through efficiency measures; (2) introducing ground source heat pumps to the residential sector; (3) fuel switching from fossil fuels to biomass and electricity sources; (4) efficiency improvements in non-heat electrical demands (e.g. lights and appliances); (5) and electricity grid decarbonisation. Key assumptions in estimating the penetration of these measures include a reduction in space heating intensity from between 55 kJ/HDD m² (for India) and 191 kJ/HDD m² (for OECD Europe) in the LMS to 52 kJ/HDD m² in most regions in the LCS[12]. It is also assumed that 25% of OECD households benefit from improved external insulation and 50% of residential heat switches from fossil fuels to low carbon sources.

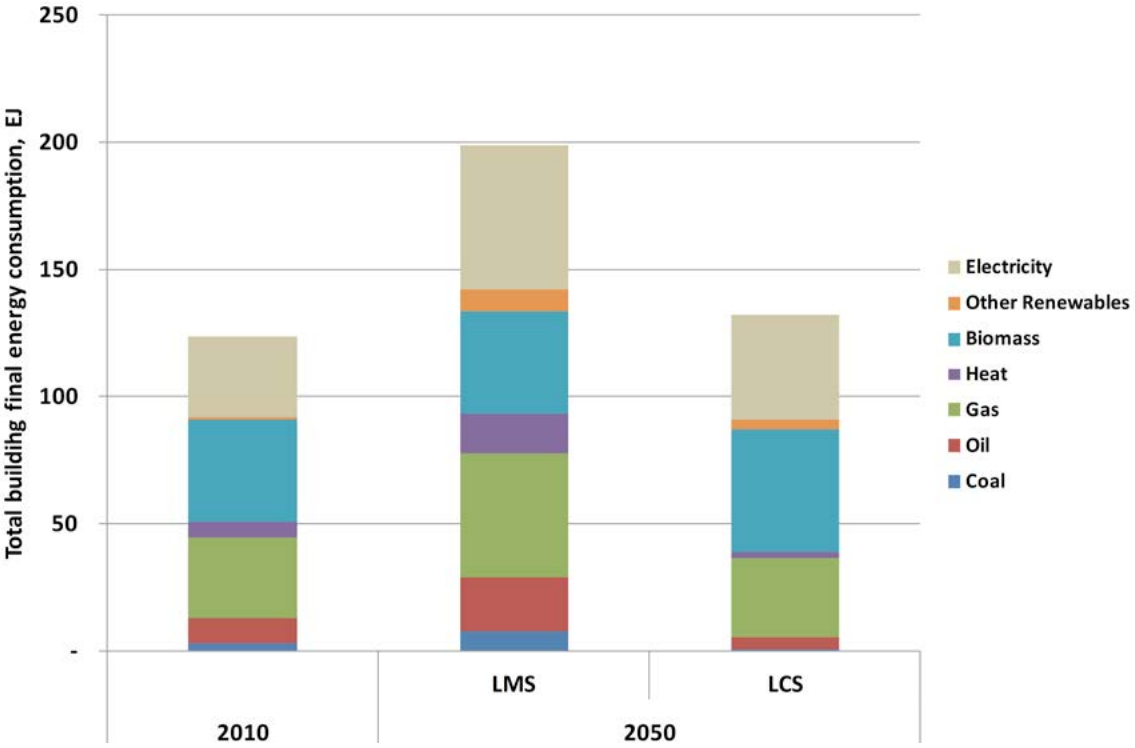
These assumptions result in a 33% reduction in energy demand and a change of fuel shares consumed in buildings as illustrated in figure 15.

The total emissions by region are depicted in figure 16. In all regions there is a significant reduction in emissions, in large part as a result of the use of decarbonised electricity in the LCS, as well as significantly reduced overall energy demand.

The exception is the Middle East and North Africa region, where increases in floor space are expected to exceed the efficiency and fuel switching gains. Residential heat demand is reduced from 66.5 EJ/y (LMS) to 24.8 EJ/y (LCS) by 2050, due to improvements in building shell design and uptake of available insulation opportunities. This, combined with low-carbon heat sources such as heat pumps, biomass heating, CHP and solar thermal heating, reduces heat-related emissions from 299 gCO_2/kWh_{th} (LMS) to 129 gCO_2/kWh_{th} (LCS) in 2050. Per capita global average emissions (direct and indirect) from the buildings sector are 1.61 t CO_2 per year in the LMS and 0.45 t CO_2 per year in the LCS, in 2050.

Figure 15. Buildings final energy demand in the LMS and LCS by energy vector

Other renewables is primarily solar thermal; "Heat" is provided by combined heat and power (CHP)



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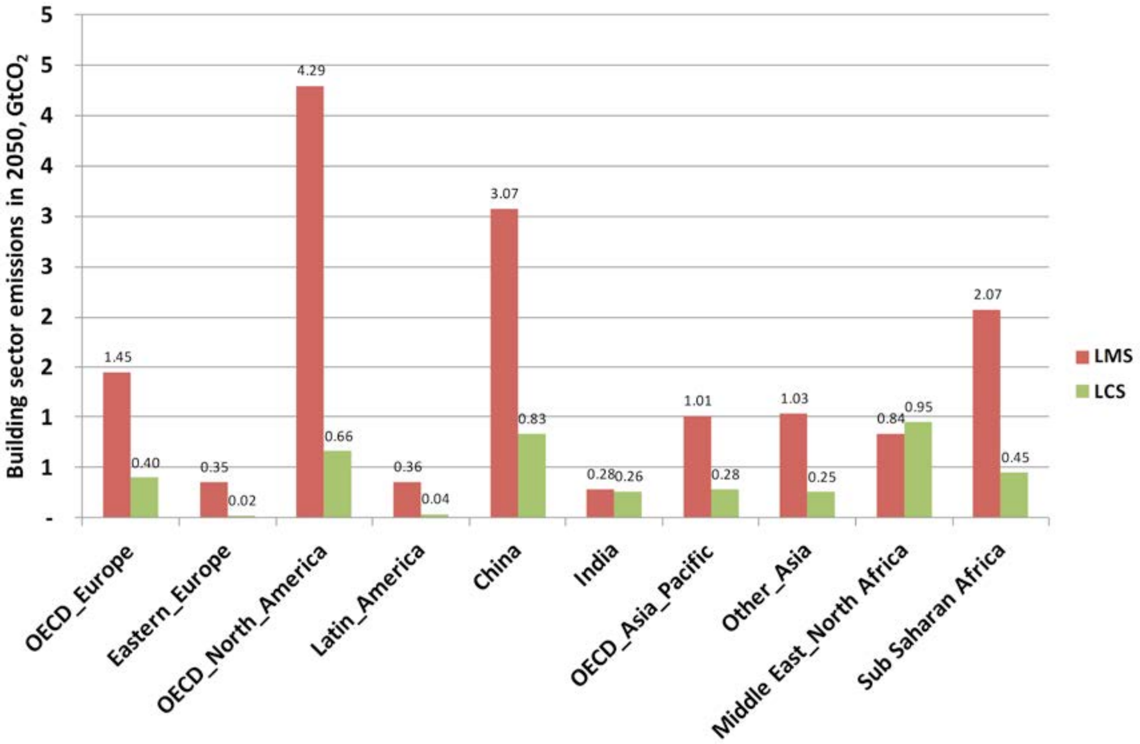
[12] HDD = Heating Degree Days. Further information on these assumptions is available in the online annex at: http://www3.imperial.ac.uk/climatechange/publications/halving-global-co2-by-2050

Figure 16. Building emissions (direct and indirect) by region in 2050



The total global additional cost of the LCS, compared to the LMS, is (US2010) $970 billion, or (US2010) $267 per household per year, in 2050, based on assumptions around the costs of the insulation, heat pumps, and other interventions, and including the increased electricity costs resulting from the use of low-carbon power generation sources in the electricity grid mix[13]. For a high fossil fuel price scenario, the additional economic benefit of energy efficiency measures leads to a total additional cost of (US2010) $540 billion, or (US2010)$150 per household per year.

4.6 Specific insights – Transport

The transport energy consumption in the LMS is dominated by fossil fuels with around 80% being gasoline and diesel and a further 17% aviation fuel (kerosene) in 2050. The LCS interventions do not assume any behaviour changes or reductions in demand from changing patterns of land use, but do include vehicle and aviation efficiency gains averaging 33% across the sector. This is combined with strong mitigation strategies involving significant changes to the fuel chain, resulting in a transition from gasoline, diesel and kerosene to electricity, hydrogen, road transport biofuels, and bio-kerosene in aviation. The mix of fuels in the LMS and LCS are compared in figure 17.

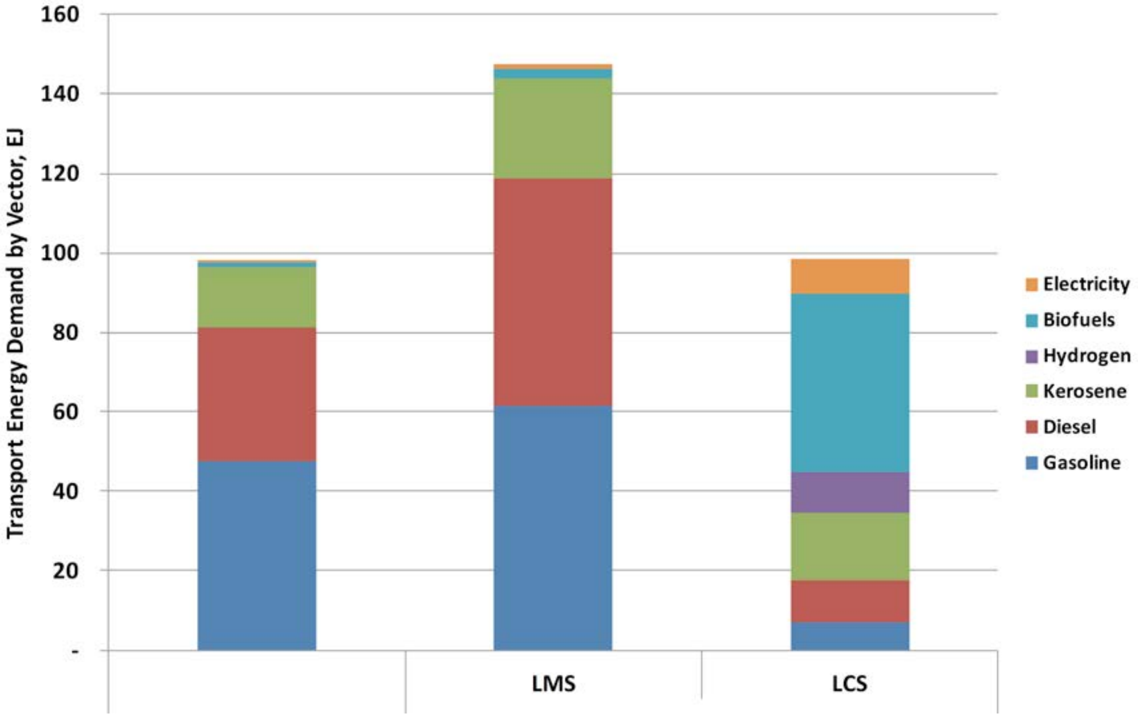
Overall, there are large reductions in transport emissions (figure 18) in all regions, with more or less uniform reductions in each region. The overall reduction is from 16.4 $GtCO_2$ in the LMS to 4.7Gt CO_2 in the LCS. The combination of increased use of electric vehicles, as well as hydrogen vehicles and the increased use of bio-fuels, sees average emissions from light duty vehicles decrease from an average 181 gCO_2/km (LMS) to 26 gCO_2/km (LCS) in 2050.

The additional cost of the LCS compared to the LMS is (US2010) $270 billion in the low fossil fuel price scenario. This is the least costly sector to decarbonise, owing to the very high energy efficiency improvements (33%) across the sector. In fact, with higher fossil fuel prices, the LCS would be considerably cheaper than the LMS for the transport sector – a saving of (US2010) $620 billion per year by 2050[14]. There is therefore a potentially significant economic advantage from decarbonising the transport sector, and shifting its reliance on fossil fuels.

[13] Further detail on these assumptions is available in the online annex at: http://www3.imperial.ac.uk/climatechange/publications/halving-global-co2-by-2050

[14] Further detail on cost assumptions is available in the online annex at: http://www3.imperial.ac.uk/climatechange/publications/halving-global-co2-by-2050

Figure 17. Transport final energy demand in the LMS and LCS by energy vector



4.7 Specific insights – Bioenergy

Bioenergy is not an end-use sector in its own right, but deserves a short discussion due to widely-aired concerns around availability of land and competition with food production. There have been a large number of recent studies on the global availability of bioenergy, most of which project at least 100-200 EJ in primary energy form available annually in 2050[15]. In our study, we anticipate a final energy demand derived from biomass and waste of 61 EJ in the LMS and 115 EJ in the in the LCS in 2050. The bioenergy chains are developed for each region and the regional land use implications also analysed to ensure feasibility. Finally, we do not consider bioenergy to be "carbon neutral" but rather have developed a set of lifecycle analyses to quantify the lifecycle emissions on a CO_2 equivalent basis. This is included in our overall emissions budget[16].

In relation to overall land use, the global land area is about 13 Gha, which is currently divided into: arable 1.5 Gha, pasture 3.5 Gha, forestry 4 Gha, and other 4 Gha (including deserts) (Slade, 2011). The total land area required for bioenergy would be equivalent to 6.4% (LMS) or 8.8% (LCS) of the total world arable and pasture lands (5 Gha). For comparison, the current amount of land devoted to growing energy crops for biomass fuels is only 0.19% of the world's total land area and only 0.5-1.7% of global agricultural land.

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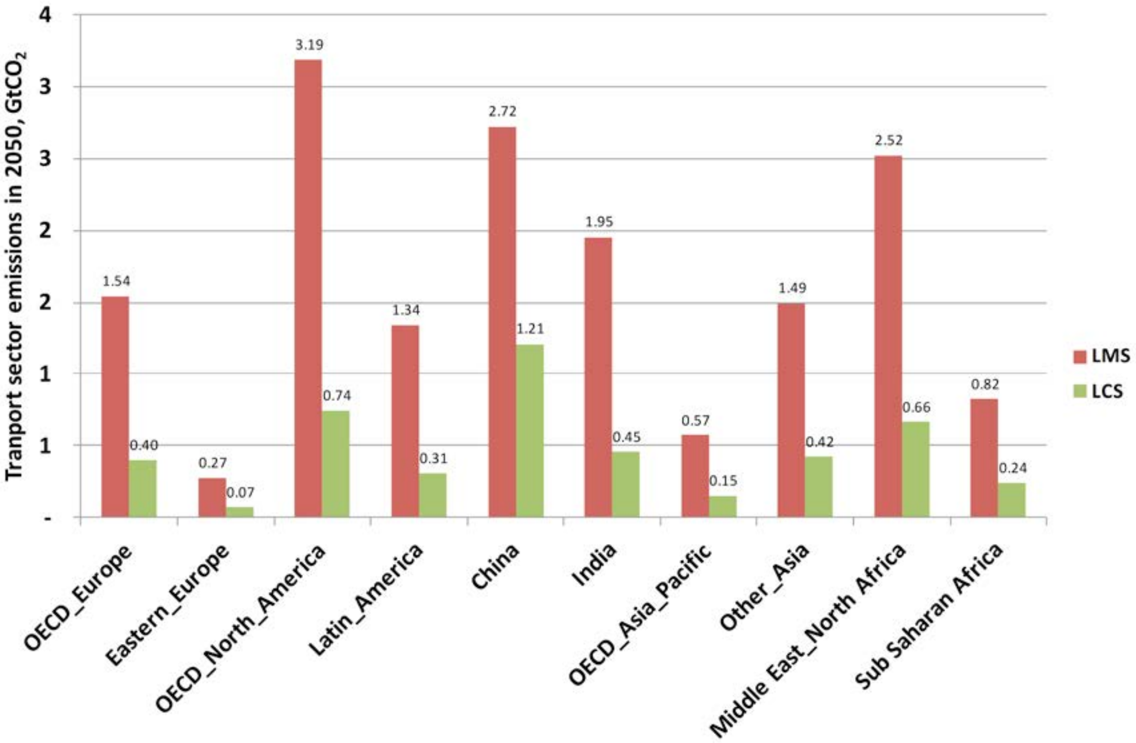
[15] See for example Slade (2011), Akhurst (2011)

[16] Details on the bioenergy emissions assumptions are available in the online annex at: http://www3.imperial.ac.uk/climatechange/publications/halving-global-co2-by-2050

Figure 18. Transport emissions (direct and indirect) by region in 2050



5 Overall conclusions

This study analyses the mix of low-carbon energy technologies in each world region that would together limit CO_2 emissions from energy use and industrial processes to around 15 Gt per annum by 2050, despite continued economic growth and development which would see world population increase to over 9 billion, and real per-capita incomes almost treble, between now and 2050. When comparing the low-carbon scenario (LCS) with a low-mitigation scenario (LMS) in which no further concerted action is taken to limit global warming, the overall additional annual costs (representing annualised capital expenditure and operation and maintenance of the low-carbon technologies implemented) would be significantly offset by fuel savings, as energy efficiency options are taken up at a large scale. As such, the overall cost to the world economy by 2050 would be of the order of 1% of 2050 GDP per year by 2050.

The major drivers of such a transition include the virtual decarbonisation of the electricity sector in each region by 2050, significant electrification of industry, transport and buildings, energy efficiency across all sectors, and increased use of low-carbon fuels such as bio-energy for heating and transport. None of these transitions are likely to happen without targeted policies to support the uptake of the major technologies, but neither are any of the technological transitions inconceivable – they all rely on technologies that are either in use today, or are close to deployment at commercial scales.

Underlying the decarbonisation of the economy for each region studied is the displacement of unabated fossil fuels in power generation with a mix of nuclear, renewables technologies (including hydro, wind, solar and biomass) and CCS applied to fossil and biomass fuels. This would cut the world's average CO_2 intensity of electricity by more than 80%, from a baseline of 508 gCO_2/kWh in 2050 in the LMS to just 94 gCO_2/kWh in the LCS. Achieving such a decarbonisation would lead to a 37-73% increase in the globally averaged cost of electricity generation in 2050, with the lower end of the range representing the higher fossil fuel price scenario. Disparity in the price increase also exists on a regional scale with OECD North America, China, India and Other Asia all experiencing a cost increase in excess of 80% in the lower fossil fuel price scenario. A sensitivity analysis encompassing different future power generation mixes demonstrates that this level of decarbonisation is possible with a range of technologies, at similar cost increases.

Immediate policy implications are the need to demonstrate and deploy CCS given its importance in future power generation mixes, as well as the creation of robust electricity grids which effectively balance supply and demand given a diverse mix of generation sources, including variable, non-dispatchable sources such as wind and solar.

In concert with this decarbonisation of electricity, each end-use sector would see an increasing use of electricity in its fuel mix. For example in the industry sector, the share of electricity in the final energy mix would increase from 27% (LMS) to 47% (LCS) by 2050. The share of electricity in transport would increase from 1% (LMS) to 9% (LCS) by 2050. In buildings, the share of electricity increases from 28% (LMS) to 32% (LCS) by 2050. A number of technologies and processes will need to be supported by specific policies to ensure that electric vehicles, electrical building heating and electrical industrial process heating technologies become economically feasible over time, and are supported by an appropriate infrastructure.

Also central to the decarbonisation of each region is the uptake of all feasible energy efficiency options, which sees total final energy demand in 2050 in the LCS at 376 EJ, compared to 526 EJ in the LMS, in spite of no reduction in the level of energy services (e.g. passenger-km travelled, heating degree days of building heating, lumens of light) provided. This reduction results from a 19% energy efficiency improvement in the industrial sector and a 33% improvement in both the transport and buildings sectors, in 2050 when comparing the LCS with the LMS.

Achieving energy efficiency is economically highly attractive, but at the same time very challenging, as it will require the encouragement of very high vehicle and building design standards, as well as the replacement of older, less efficient industrial plant technologies with those using best available techniques (BAT). Ensuring that capital replacement and refurbishment opportunities are met with the uptake of these more efficient designs will be critical.

Bioenergy has a strong role to play across sectors, and the total land required for bioenergy would be equivalent to 6.4% (LMS) or 8.8% (LCS) of the total world arable and pasture lands (5 Gha). By 2050 its importance becomes comparable to that of electricity when viewed from a final energy demand perspective and in primary energy terms it is the single biggest source by 2050.

The economic analyses show significant sensitivity to future fossil fuel prices, but are much less sensitive to the performance of any particular technology. The sensitivity analysis around our emissions target indicates a relatively shallow dependence of the decarbonisation cost around this figure.

In summary, this study shows that:

- Without concerted action and a continuation of historic trends in energy usage, global CO_2 emissions are likely to increase to around 50 Gt per year by 2050, and global fossil fuel consumption will increase by 50% compared to current levels.
- Achieving a much lower level of CO_2 emissions in 2050 (around 15 Gt per year, which is broadly consistent with a 2˚C global warming limit) will cost of the order 1% per year of global GDP by 2050 in a low fossil fuel price case, and much less than this if fossil fuel prices are higher.
- Such a transition will require a broad range of low-carbon technologies deployed across all sectors of the economy, underpinned by the decarbonisation of the power sector, within which the precise mix of technologies does not affect the overall cost significantly. In each low-carbon scenario the unit electricity costs increase by about 40% (in the high fossil fuel price case) to about 70% (in the low fossil fuel price case) compared to the low mitigation scenario, but even in the low carbon scenarios, electricity cost increases would not keep pace with increases in per capita GDP to 2050.
- As well as electricity decarbonisation, achieving energy efficiency across the whole economy is critical, with our low-carbon scenario showing an approximate 30% reduction in end-use energy demand in 2050, compared to the low mitigation scenario.
- In the low-carbon scenario, fossil fuel demand would reduce by almost 40% in 2050, compared to the low mitigation scenario.

Finally, our analysis shows that every one of the ten regions studied makes a significant contribution to the overall achievement of the low-carbon transition. We believe this transition to still be achievable and affordable.

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