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# Halving Global $CO_2$ Emissions by 2050: Technologies and Costs

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**ABSTRACT**

*This study provides a whole-systems simulation on how to halve global $CO_2$ emissions by 2050, compared to 2010, with an emphasis on technologies and costs, in order to avoid a dangerous increase in the global mean surface temperature by end the of this century. There still remains uncertainty as to how much a low-carbon energy system costs compared to a high-carbon system. Integrated assessment models (IAMs) show a large range of costs of mitigation towards the 2°C target, with up to an order of magnitude difference between the highest and lowest cost, depending on a number of factors including model structure, technology availability and costs, and the degree of feedback with the wider macro-economy. A simpler analysis potentially serves to highlight where costs fall and to what degree. Here we show that the additional cost of a low-carbon energy system is less than 1% of global GDP more than a system resulting from low mitigation effort. The proposed approach aligns with some previous IAMs and other projections discussed in the paper, whilst also providing a clearer and more detailed view of the world. Achieving this system by 2050, with $CO_2$ emissions of about 15Gt$CO_2$, depends heavily on decarbonisation of the electricity sector to around 100g$CO_2$/kWh, as well as on maximising energy efficiency potential across all sectors. This scenario would require a major mitigation effort in all the assessed world regions. However, in order to keep the global mean surface temperature increase below 1.5°C, it would be necessary to achieve net-zero emission by 2050, requiring a much further mitigation effort.*

## 1. INTRODUCTION

The decarbonization of the global economy by 2050 requires urgent actions across different sectors, such as buildings, transport, industry and electricity, with a broad range of associated costs, depending on the assumptions and trends adopted in the scenarios. The Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5) [1], for example, reported hundreds of mitigation scenarios, placing the cost of mitigation towards a 2°C-consistent level of emissions at around 2-6% of global Gross Domestic Product (GDP) in 2050 in its headline conclusions. Looking at 2050 specifically, the IPCC Representative Concentration Pathway (RCP) 2.6 scenario, which is deemed closest to a 2°C scenario, sees consumption losses of 1.7% of global GDP [2], hence at the lower end

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of the range. Integrated assessment models, from which these mitigation scenarios arise, are critical tools in helping to examine low-carbon transition pathways. However, their size and complexity can result in a relative lack of transparency, which has drawn recent criticisms regarding their "black box" nature [3], [4]. On the other hand, some recent studies contributed to transparently evaluate some climate change mitigation scenarios [5]-[8], but additional reviews and modelling approaches are needed to help inform future public policies and reduce uncertainties for decision making.

This article summarises the results of an extensive research project aimed at providing a broad cost and technology assessment on carbon mitigation pathways by 2050, compared to 2010. The research was based on a transparent set of assumptions so that researchers and policy makers can understand why it would cost of the order 1% of GDP to run a low-carbon, as opposed to high-carbon, energy system. It was conducted by the same authors of this article, whilst based at Imperial College London from 2012 to 2013, with the support of the Areva Group. The development of the modelling approach required a team with a multidisciplinary background; thus, most authors worked focused on their respective sectors and areas of expertise, whereas others compiled all sectors into a single global simulation matrix.

The modelling approach was then made publicly available as an executive report [9] and a full technical report, which also served as the executive report's annex [10]. Both reports were presented and discussed in a launching event held in London, in the presence of international authorities and experts in energy and climate change [11]. The event was fully recorded, and the video is publicly available online [12]. In addition, Imperial College prepared a short introductory video about the project, which is also available online [13] alongside these two reports. For the first time, this study is demonstrated through a scientific article, now including an updated critical discussion and current context of 2020. Scenarios for obtaining global net-zero emissions by 2050, for example, would demand a much further mitigation effort and different cost analysis than the proposed scenarios for halving global emissions, which are also ambitious whist compared to business-as-usual trends.

Therefore, the objective of this article was to present a comparative analysis of the main projected scenarios simulated through this research project by 2050, including some updated references, reviews and a sensitivity analysis. It is worth noting that it was not the objective here to validate the modelling approach, which was already presented, discussed and thoroughly explained in the reports already cited. Instead, the aim was to provide a contextual overview on this original research, followed by a critical discussion on key scenarios regarding the technologies and costs of different decarbonization pathways by 2050.

The proposed approach complements existing tools and models, which are equally important, especially for assessing specific sectors in greater detail and projecting scenarios under different assumptions and types of simulation (*e.g.* econometric models, agent-based models, system dynamics models). This approach was not designed to assess long-term dynamic pathway modelling and, hence, it does not capture the intertemporal mitigation choices. Moreover, it was not calibrated to simulate net-zero emission pathways, which would require a different approach. The aim was to project pathways that could halve global $CO_2$ emissions by 2050, whilst also keeping a similar level of annual final energy consumption of 2010. Thus, technology improvements and fuel shift are some of the key strategies here discussed.

## 2. METHODOLOGY

This section provides an overview on the methodological approach involved in the original assessment on "Halving Global $CO_2$ by 2050: Technologies and Costs", whilst also including a description on the projected scenarios and sensitivity analysis.

### *2.1 Assumptions*

The original assessment was based on a vast number of assumptions, equations and references used to model each sector of the global economy. A step-by-step description of all the equations and estimates involved in this assessment are publicly available in its full report [10], as already mentioned, but a brief explanation about its main aspects is following described.

The study used a framework based on a bottom-up, technologically-rich and region-specific engineering assessment of the key technologies in each major sector of the economy. The calculations were made using spreadsheets and sectorial simulations [10]. Differently to past studies [14], [16], this study provides a more detailed view of the world, and especially the individual power sectors and solutions – with content experts having delivered customized model approaches for each of these sectors reflecting their unique conditions. This contrasts with other approaches that are driven by model experts. As a result, the various different end-use sectors and power sources have been described individually offering a higher granularity.

The focus of this study was on the cost of mitigation through simulating different technological pathways by 2050 in a low-carbon world, and what they would cost compared to high-carbon technologies. To keep the analysis simple and tractable, no long-term dynamic pathway modelling is undertaken. Rather the costs in 2050, a key year of analysis in most long-term studies of decarbonisation, are used to elucidate the economic impacts of choosing a low-carbon over a high-carbon pathway. This removes the complex dynamics of inter-temporal mitigation choices as well, so that a clearer feel for the comparative costs of low- and high-carbon energy systems can be gleaned.

### *2.2 Carbon Mitigation Pathways*

The methodology is based on two comparative scenarios:

- *Low Mitigation Scenario* (LMS), which represents a reference scenario, analogous to a business-as-usual pathway, but including some level of mitigation effort;
- *Low Carbon Scenario* (LCS), which is the simulation pathway aimed at having global $CO_2$ emissions from human activities by 2050, by limiting them to around 15 Gt per year by 2050.

The analysis started from the major end-use sectors (industry, transport and buildings) in 10 world regions, developing a reference scenario (*i.e.* the LMS), for which 2050 regional energy demand and emissions data were determined. The world regions were comprised of OECD Europe, Eastern Europe, OECD Pacific, China, India, Middle East and North Africa (MENA), Other Developing Asia, Sub-Saharan Africa (SSA), OECD America, and Latin America. For each region and end-use sector, this was done by defining the relevant drivers of energy demand (for example GDP, population, urbanisation, travel demand and industrial share of GDP), their historical relationship to energy demand, and projections of these drivers to estimate future energy demand in 2050. The LMS assumes that there are no fundamental shifts in the energy carrier mix, such that if historically energy demand increases have been satisfied through the use of fossil fuels, then this will continue into the future. The supply side of the system for each region was 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 was made assuming no concerted action on climate change mitigation using past trends as a guide to the future.

In contrast, the LCS is arrived at by defining a set of viable low-carbon technology mixes, which together limit energy and industry-related $CO_2$ emissions to about 15 $GtCO_2$ in 2050 whilst satisfying the energy services demand derived for the LMS. 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 the LCS versus the LMS in 2050. A range of scenarios is considered, including variations in 2050 fossil fuel prices, as well as the mix of power generation technologies in each region. These steps are further explained in the full research report [10], including all the assumptions and methodology used to assess each sector of the economy (*e.g.* buildings, transport, industry, electricity and other energy supply) and the major assumptions in economic evaluation (*e.g.* capital and operational costs, fossil fuel prices, among other variables).

### 2.3 Sensitivity Analysis

The energy demand and energy mix in the end-use sectors were assumed to be sensitive only to energy technology penetration rates, and not to fossil fuel prices. In fact, 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, resulting in different LCS simulations. 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 Carbon Capture and Storage (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 it was chosen to neglect a potentially important price feedback in that it was 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 the view that future fossil fuel prices are highly speculative, and the desire to show the cost of decarbonisation given certain future fossil fuel price projections.

A final sensitivity analysis to the cost of decarbonisation was undertaken using both fossil fuel price scenarios and exploring the effect of tightening and relaxing the annual $CO_2$ budgets by approximately 15.3Gt, *i.e.* between 13.8 Gt and 16.8 Gt annual emissions suggested by IEA [17]. It is worth noting that the global carbon budget to meet either 2ºC or 1.5ºC target has been periodically updated according to new data and revised statistical estimates, for example, as recently published by Matthews *et al.* [18]. Moreover, future fossil fuel prices are largely uncertain and tend to remain volatile through to 2050. The recent coronavirus pandemic, for instance, has abruptly affected both carbon emission and oil price globally with impacts on global energy demand [19].

Finally, potential limitations and future improvements to the approach include:

- The use of a full pathway model to describe and evaluate in more detail the transitions required over time;
- Interaction with a dynamic electricity sector model to explore in more detail the feasible levels of renewables in different scenarios;
- Addition of detail to the potential interventions in the industrial sector model.

To aid this level of transparency, a number of simplifications were made as follows:

- Firstly, the analysis is limited to $CO_2$ emitted from fossil fuel combustion and cement production, representing about 70% of total Greenhouse Gas (GHG) emissions annually;
- Secondly, the calculation is based on the annual cost of the energy system in 2050, with no consideration of the pathway from now until 2050. As such, the calculation does not consider the cumulative costs of transitioning from a high-carbon to low-carbon energy and industrial system over the whole period to 2050;
- Thirdly, carbon dynamics from land use change was not included in the assessment, because the focus was on energy issues. However, land use may play a substantial role on climate change mitigation, too, including through soil carbon dynamics and above ground carbon sequestration via afforestation and/or reforestation, as demonstrated in related studies at international level [20], [21]. The impacts related to land use change on land price and food market by 2050 are subject to large uncertainties and regional variations;
- Fourthly, this study does not consider costs related to climate change adaptation, which are also subject to many uncertainties depending on the level of climate change impact expected by 2050. It is generally assumed that even high costs for climate mitigation are likely to be lower than the potential costs for adaptation, particularly those related to sea level rise, changes in dry/wet season, poverty, migration, regional conflicts, insurance market, food security, biodiversity loss, among other issues.

## 3. RESULTS AND DISCUSSION

The following sections present the main results of our simulations for a Low Mitigation Scenario (LMS) and a Low Carbon Scenario (LCS). Further results and discussions are available in both the executive [9] and full report [10].

### *3.1. Energy Demand and GHG Emissions*

In the LMS, global annual $CO_2$ emissions are projected to reach around 50 $GtCO_2$ by 2050, compared to about 30 $GtCO_2$ in 2010. This projection compares to the IEA's [17]. 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. 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 (about 7.7bn in 2019) to 9.3bn in 2050, based on medium estimates suggested by the United Nations [22], as well as a corresponding growth in GDP per capita from a global average of (US 2010, *i.e.* values in US dollars based on year 2010 reference) US$ 10,600 to US$ 26,900 for the same period, based on projections from IEA [17] and World Bank [23]. In contrast, the LCS is constrained to be within annual emissions of 15.3 $GtCO_2$ by 2050. This level sits between the 14 $GtCO_2$ of the IEA's Energy Technology Perspectives "BLUE Map" scenario [17] and around the 15 $GtCO_2$ of the IEA's Energy Technology Perspectives "2DS scenario" [24], both of which would be broadly consistent with achieving a stabilisation of atmospheric GHG concentrations of 450ppm, as part of a pathway which limits global warming to 2ºC.

The deployment of efficiency interventions and low-carbon technologies in each sector causes a change in final energy demand, as well as the fuels 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 1 shows that final energy demand could remain almost flat between 2010 and 2050 if pursuing a low-carbon pathway. In final energy demand terms bioenergy is as important as electricity by 2050, given that modern biomass is expected to play a major role for mitigating emissions in transport, power, heating and cooking. This scenario is also consistent with ambitious bioenergy trends projected by other global models [20], [21]. Regarding energy efficiency, it is important not only to increase the efficiency of appliances (*e.g.* electronics, lamps, machines) but also the efficiency obtained through a more rational use of thermal energy in the energy mix, using a systems perspective [25].

Figure 2 shows that substantial emissions reductions are required in all sectors. In order to halve global $CO_2$ emissions by 2050, carbon mitigation efforts must address all sectors combined and intensively, across all the assessed world regions.

Figure 3 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.

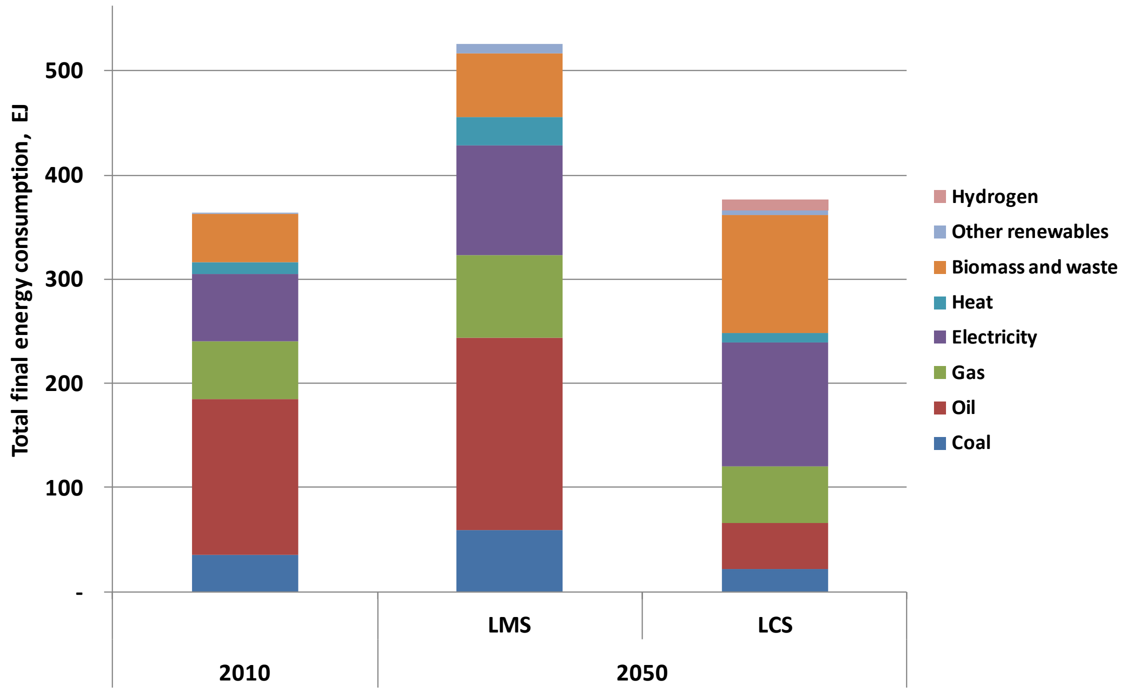


**Fig. 1. World total final energy consumption by energy vector.**

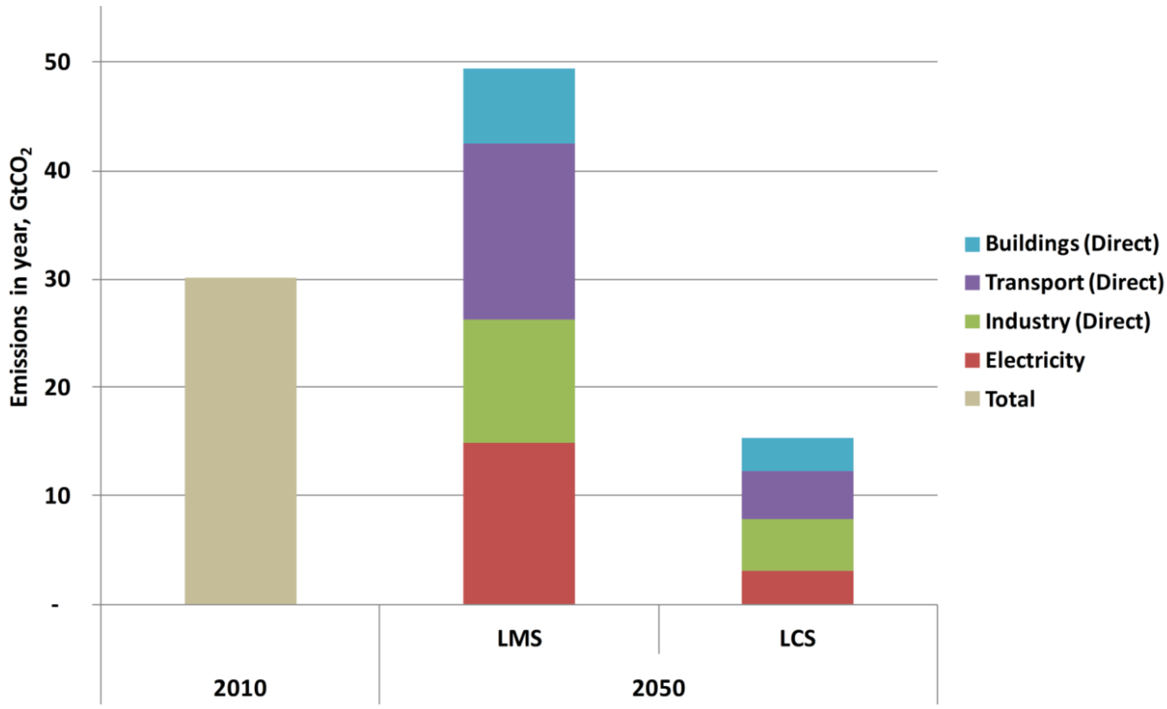


**Fig. 2. Annual $CO_2$ emissions by sector, and compared to total 2010 emissions.**

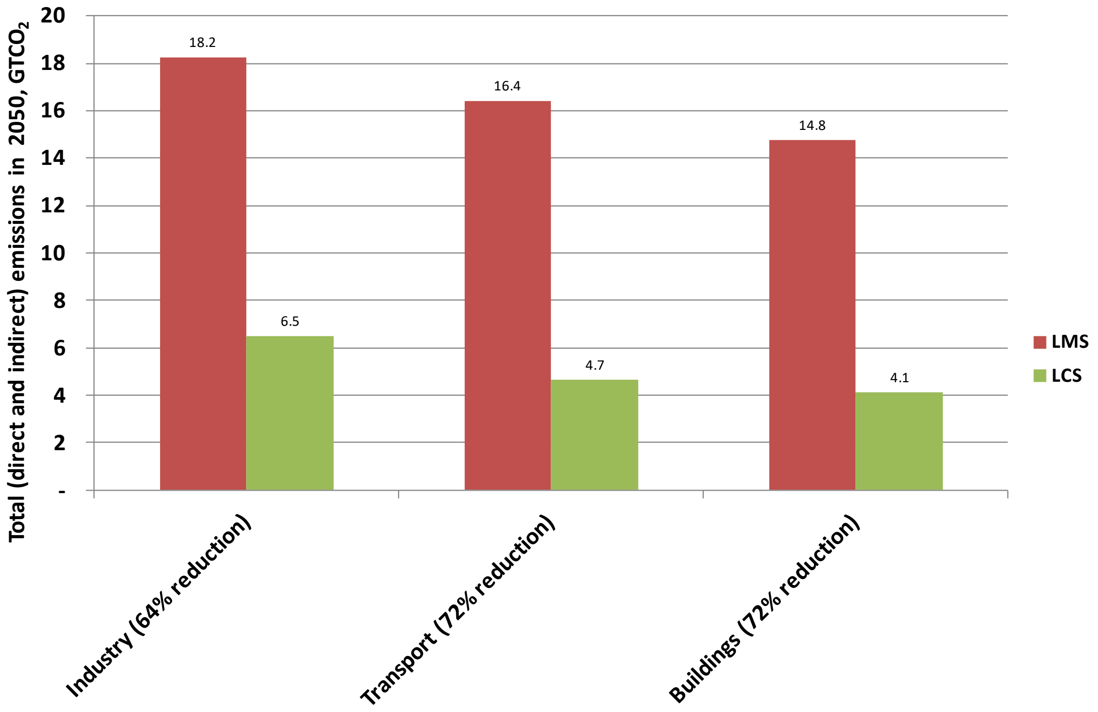


**Fig. 3. Total emissions (direct and indirect) by end-use sector for the LMS and LCS.**

Figure 4 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, too, 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.

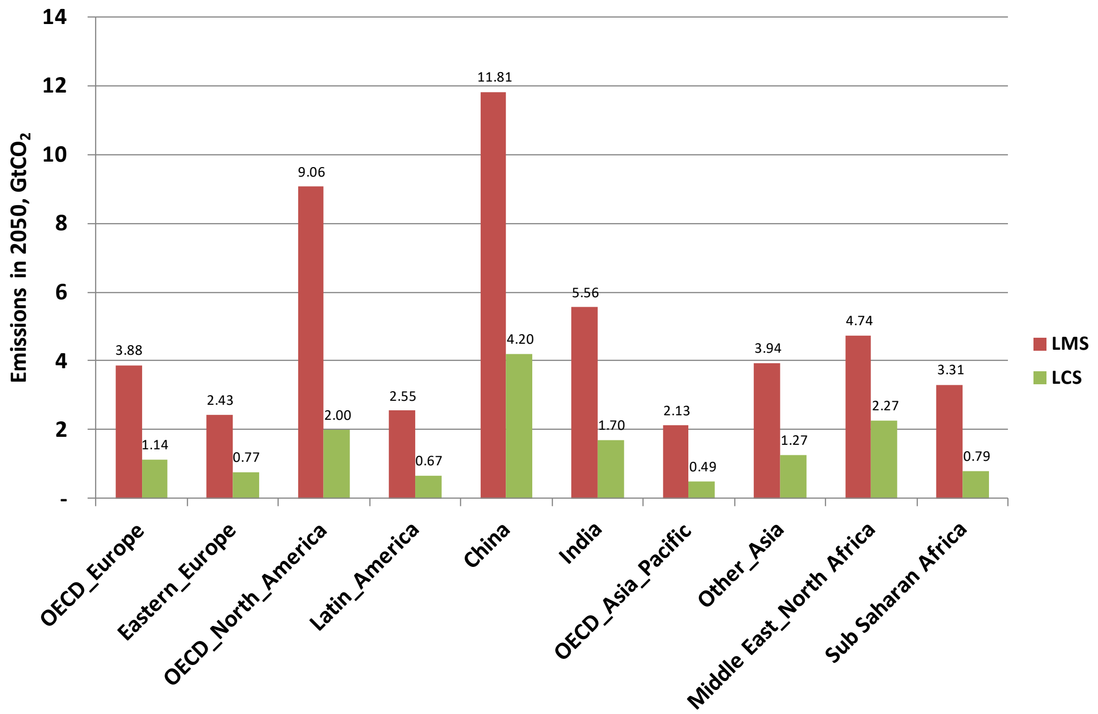


**Fig. 4. Variations in emissions by region for the LMS and LCS.**

### *3.2 Cost of the Low Carbon Scenario Compared to the Low Mitigation Scenario*

The cost of achieving the LCS, based on the cost differential against the LMS, is (2010 US) $0.33-2 trillion per annum in 2050, which translates to between 0.15%-0.9% of global GDP in 2050 in 2010 Purchasing Power Parity (PPP) terms, or 0.3-1.8% of GDP in 2050 on a 2010 exchange rate basis. Figure 5 shows the cost differential between the LCS and the LMS for three different global GHG emission targets where the central figure is 15.3 $GtCO_2$.

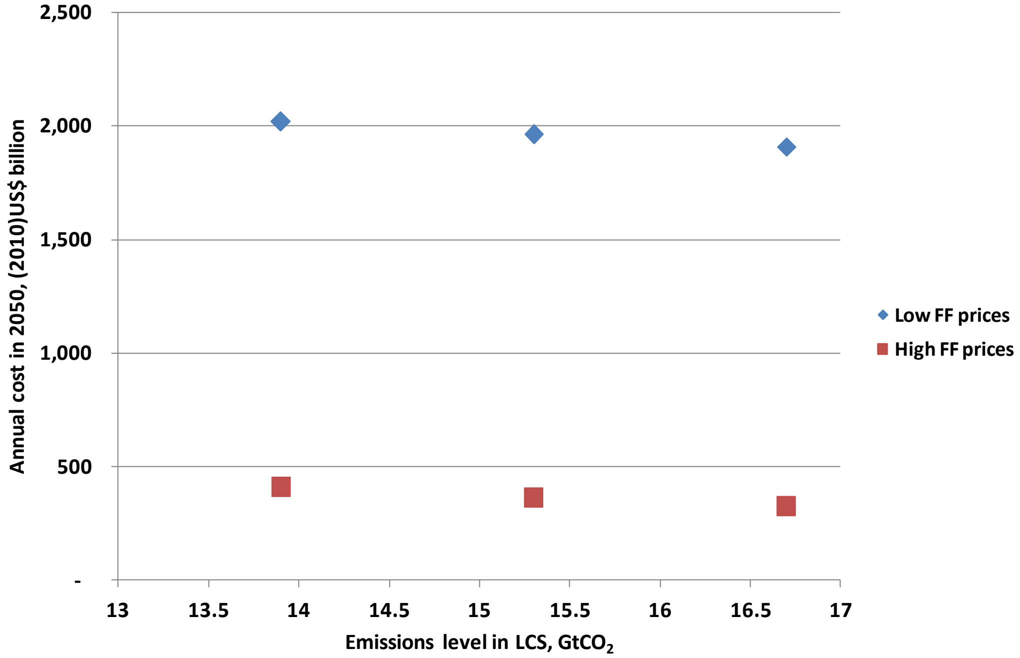


**Fig. 5. Cost differential between LCS and LMS for different CO2 targets and Fossil Fuel (FF) prices, 2010 PPP basis.**

### *3.3 The Role of the 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 with all references available in the full report [10]. For the LCS, the power systems optimisation tool was used to generate four different generation mix options to meet these needs. These were 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 6 Note that the total generation (including transmission and distribution losses) is 117 EJ in the LMS and 147 EJ in the LCS in 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. Both cases 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 other scenarios, the average global cost of electricity in 2050 is of a similar magnitude to the “Balanced” scenario. As indicated in several other studies [17], [26], [27] increased electrification is a critical element of decarbonisation, when associated with renewable-based electricity. Regarding the role of nuclear and CCS, Akashi *et al.* [28] similarly accessed scenarios for halving global GHG emissions by 2050 but without depending on nuclear and CCS. These authors concluded that, although this target is technologically feasible, the costs would become very high if nuclear and CCS are limited.

This overall picture could be disrupted (allowing further decarbonisation at a reasonable cost) by breakthroughs in solar photovoltaics (PV) generation, especially if combined with energy storage and demand management technologies. In the preparation of the research from which this article derived, the PV costs used for modelling were relatively high against other low carbon energy sources; however, in recent years PV costs came down much faster than expected [29], contributing to a large increase in its installed capacity to date, including in countries like China and several OECD nations, such as the United States and Germany. The algorithm used in the original research, as described in its full report [10], was a least-cost optimisation and, therefore, this type of uncertainty is intrinsic to the modelling approach. The full report also includes some discussions on $CO_2$ intensity in the electricity sector for the different world regions, as described in the Methods section.

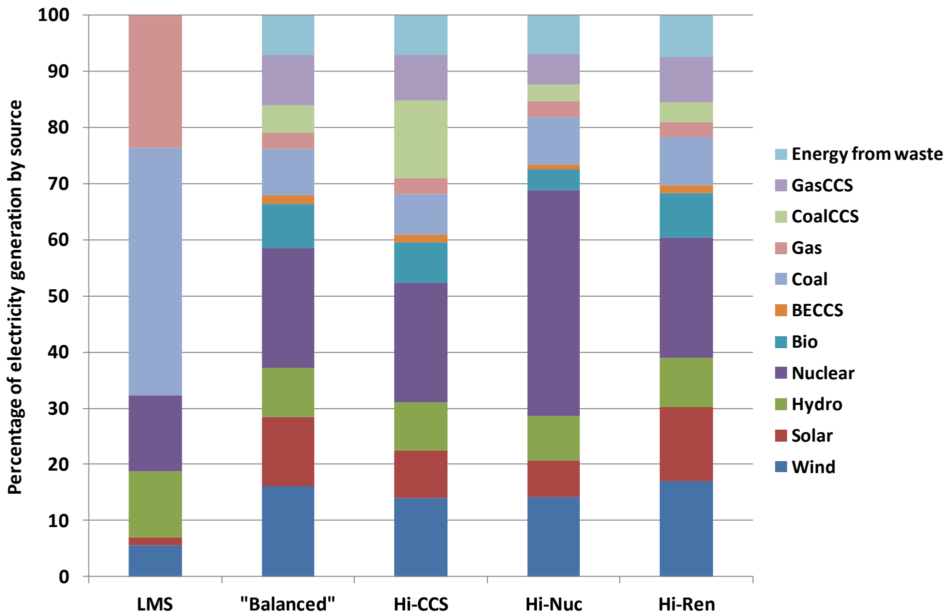


**Fig. 6. Summary of power generation mix scenarios (low fossil fuel prices).**

### *3.4 The Role of Industry*

The industrial analysis is driven by estimates of manufacturing's value-added proportion of GDP. 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. Detailed results are shown in the base reports [9],[10] of this study.

Overall, the industrial sector is responsible for 18.2 $GtCO_2$ emissions in the LMS and 6.5 $GtCO_2$ in the LCS (a 64% reduction). The large emissions reduction observed in the LCS is primarily due to: (i) energy efficiency through adopting Best Available Technologies (BAT); (ii) fuel switching away from coal and oil; (iii) decarbonisation of the electricity generation sector; and (iv) Carbon Capture and Storage (CCS) applied directly to industrial emissions. Around 1.5 $GtCO_2$ is captured using CCS in this way; which is equivalent to 23% of the total emissions in the LCS.

The additional cost (annual cost difference between the LCS and LMS) is (US2010) is $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). Three measures contribute to this cost: 1) the cost of energy efficiency, split into CAPEX and fuel costs; 2) the cost of switching to less carbon intensive fuels; and 3) the capital, operational and fuel costs of CCS.

### *3.5 The Role of the Building Sector*

To estimate the potential carbon savings in 2050, it was estimated 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); and 5) electricity grid decarbonisation.

Key assumptions in estimating the penetration of these measures included a reduction in space heating intensity from between 55 kJ/heating degree days (HDD).$m^2$ (for India) and 191 kJ/HDD $m^2$ (for OECD Europe) in the LMS to 52 kJ/HDD $m^2$ in most regions in the LCS. 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 further described in the full report [10]. 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 aspect, 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.

### *3.6 The Role of the Transport Sector*

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). 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 greater detail in the full report [10].

The overall reduction is from 16.4 $GtCO_2$ in the LMS to 4.7Gt $CO_2$.in the LCS. 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, as further described in the full report of this research [10]. There is, therefore, a potentially significant economic advantage from decarbonising the transport sector by reducing its reliance on fossil fuels.

## 4. CONCLUSION

This study analysed 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 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 current use 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.

The sensitivity analysis encompassing different future power generation mixes demonstrated that this level of decarbonisation is possible with a range of technologies, at similar cost increases. 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 (5Gha). 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.

On the other hand, recent GHG emissions trajectories have shown not to be sufficiently close to recommend pathways towards either 2ºC or 1.5ºC targets, requiring much further decarbonization actions, as recently highlighted by the IPCC [30] and Strapasson et al. [31].

In this context, the implementation of the Nationally Determined Contributions (NDCs) by the signatory parties of the Paris Agreement (including further actions) is fundamental to identify the necessary local and country-level measures to reduce emissions more rapidly. This includes net-zero targets by 2050 [32], [33], which are necessary to keep the global mean surface temperature increase below 1.5°C [32]. Delays in acting may increase these estimated costs for halving global $CO_2$ emissions by 2050 and even more to achieve a net-zero emission scenario by 2050, given the reduction of the existing carbon budget to meet these targets.

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