Co-impacts of climate change mitigation

Pathways to co-impacts: final report

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CS-NOW

Climate services for a net zero resilient world

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About CS NOW

Commissioned by the UK Department for Energy Security & Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5.5 million research programme, that uses the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation and resilience ambitions.

CS-N0W enhances the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It contributes to evidence-based climate policy in the UK and internationally, and strengthens the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by **Ricardo** and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

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Acronyms

Acronym	Definition
APS	Announced Pledges Scenario
BMK	Benchmark
BRT	Bus Rapid Transit
BYD	Build Your Dreams
CAAGR	Compound Average Annual Growth Rate
CCUS	Carbon capture, utilisation, and storage
CGE	Computable General Equilibrium
CH4	Methane
CHD	Coronary Heart Disease
CO_2	Carbon Dioxide
CS-N0W	Climate Services for a Net-Zero Resilient World
DESNZ	The UK Department for Energy Security & Net Zero
EAT	EAT-Lancet
ECRL	East Coast Rail Link
ENGAGE	Environmental Global Applied General Equilibrium
EU	European Union
EVs	Electric Vehicles
FAO	Food and Agriculture Organization
F-gases	Fluorinated gases
GAINS	Greenhouse gas-Air Pollution Interactions and Synergies
GBD	Global Burden of Disease
GDP	Gross Domestic Product
GEC	Global Energy and Climate
GHG	Greenhouse Gas
HFCs	Hydrofluorocarbons
HOV	High-Occupancy vehicle
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IIASA	International Institute for Applied Systems Analysis
IMHE	Institute for Health Metrics and Evaluation
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade

IPCC	Intergovernmental Panel on Climate Change
LRT	Light Rail Transit
MET	Metabolic Equivalent of Task
MR-BRT	Meta Regression-Bayesian, Regularized, trimmed
N_2O	Nitrous Oxide
NDCs	Nationally Determined Contributions
NH_3	Ammonia
NMVOC	Non-methane volatile organic compounds
NOx	Nitrogen Oxide
NZE	Net Zero Emissions
OPT	Optimistic Scenario
OSCE	Organization for Security and Co-operation in Europe
PES	Pessimistic Scenario
PFCs	Perfluorocarbons
PM	Particulate Matter
PM2.5	Fine particulate matter – particles that are 2.5 microns or less in diameter
PPM	Parts per million
SDGs	Sustainable Development Goals
SDS	Sustainable Development Scenario
SF_6	Sulphur hexafluoride
SO_2	Sulphur Dioxide
SSP	Shared Socioeconomic Pathways
STEPS	Stated Policies Scenario
T2DM	Type-2 Diabetes Mellitus
TEN-T	Trans-European Transport Network
UK	United Kingdom of Great Britain and Northern Ireland
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WHO	World Health Organisation
WPE1	Work Package E1

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1. Executive summary

This report on climate change mitigation and co-benefits globally comprises two parts. First, a *review of reviews* summarises the academic review literature that focused on co-impacts of mitigation actions that address greenhouse gas emissions. Second, a modelling exercise to quantify the co-impacts of mitigation actions proposed under three different pathways to 2050.

The evidence review highlights the positive and strong co-impacts in the health domain resulting from climate change mitigation measures. The evidence review shows that reduction of air pollution through cleaner energy generation, improved cooking stoves, and enhanced industrial energy efficiency have benefits to health. Increased physical activity and sustainable diets also contribute to improved cardiovascular health and reduced obesity and can be a direct impact of climate actions as discussed below. Positive economic co-impacts involve savings in fuel/material inputs, productivity improvements, and agricultural benefits from improved soil quality. However, employment effects vary depending on local circumstances, with both positive and negative impacts observed. Other benefits drawn from the review include that resource efficiency measures such as sustainable diets and improved manufacturing processes reduce land use and water demand. There are also opportunities for energy security to be enhanced through decentralized renewable generation, while food security can be improved through sustainable agricultural practices.

The co-benefit modelling was conducted to assess the economic and health co-impacts of climate change in more depth for different regions under different mitigation scenarios. The areas of modelling reflected key impact areas drawn from the *review of reviews*. The modelling focused on three key areas: reductions in particulate air pollution, improvements in diet, and increases in physical activity. The scenarios were based on the IEA Global Energy and Climate Model (GEC) and incorporated data from the International Institute for Applied Systems Analysis (IIASA) to estimate future concentrations of particulate matter and health impacts. The modelling considered three scenarios from the IEA: the Stated Policies Scenario (STEPS), the Announced Pledges Scenario (APS), and the Sustainable Development Scenario (SDS). The SDS is designed to achieve the goal of the Paris Agreement to limit global average temperature rise to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C. It reflects the trajectories of countries with more ambitious reduction pathways. The year 2050 was chosen as the principal year of analysis due to its alignment with national targets and efforts. For the economic modelling, because it includes economic data not directly included in the IEA scenarios, the STEPS corresponds to a ‘current policy’ approach, while the APS corresponds to an ‘enhanced policy’ approach. They are designed to be comparable in terms of their features.

The results of the co-benefit modelling demonstrated the potential health and economic impacts of climate actions. In terms of air quality, adopting the SDS had the largest gains, preventing deaths associated with particulate matter exposure. The APS scenario showed progress in energy access, but it failed to meet the Paris Goals. The SDS, however, achieved net-zero CO_2 emissions by 2070 and provided substantial health and economic benefits. Under an accelerated decarbonisation scenario, where a global economy achieves faster emissions reductions than shown in the SDS, differences in the modelled sectors would include further improvements in health due to additional earlier reductions in air pollution levels, and modest additional improvements in diet and transport health benefits.

In terms of diet-related risks, the modelling highlighted the benefits of reducing red meat consumption and increasing the consumption of fruits, vegetables, nuts, and seeds. A scenario designed to sustainably meet global nutritional needs while also maximising health (i.e. the EAT-Lancet scenario) offered the greatest mitigation co-benefits by reducing GHG emissions associated with red meat production. This was compared to a scenario which focuses on reducing the health risks associated with weight-related issues (the WHO scenario), as well as a benchmark dietary scenario.

The modelling also assessed the potential impacts of increasing active travel, such as walking and cycling, as a mitigation strategy. While increasing rates of active travel in the population lead to improved health outcomes, the scale of mortality reduction from increased active travel participation was lower compared to air pollution and diet-related mortality. The scale of mortality reduction is also dependent on current transport modes and infrastructure, as well as the scope for improving these in the future. The impact of road casualties is not considered. Overall, the impacts of decarbonisation actions are driven by a combination of exposure changes to the affected population, which comprise the majority of the impact, alongside smaller impacts due to change in risk to those exposures among the affected population, i.e. aging population.

The economic modelling analysed the economy-wide impacts of decarbonisation scenarios and the co-benefits of reduced heat stress. It showed that the costs of climate change mitigation were proportional to the level of decarbonisation, with stronger mitigation measures resulting in larger economic costs (when damage costs related to climate change impacts are not considered). Regional costs varied depending on factors such as current carbon intensity, primary energy production, and reliance on fossil fuels. Heat stress had varying impacts on labour productivity and GDP, particularly in developing regions with tropical weather.

The Sustainable Development Scenario (SDS) envisions a significant increase in renewable energy technology deployment, making renewable generation the largest source of energy in all regions except the Middle East and Eurasia. This scenario aims for all nations to achieve global net-zero CO_2 emissions by 2070, with China reaching this goal by 2060 and most other developing economies doing so by 2050. The scenario also reflects the net zero emission ambitions of a number of developed economies (e.g. Europe, UK) of reaching net-zero emissions by 2050. Under SDS, the global temperature rise is projected to reach 1.6°C in 2100, with a 50% chance of limiting it to this level. The temperature trajectory peaks in 2050 and then declines towards 2100. Energy efficiency improvements and the deployment of carbon capture, utilisation, and storage (CCUS) technologies play a crucial role in achieving the SDS objectives.

Key messages from the analysis work are:

1. **Air pollution:** The adoption of the Sustainable Development Scenario (SDS) offers significant gains in reducing air pollution-related deaths, particularly in East & South East Asia, South & Central Asia, and Latin America. In both East & South East Asia and South & Central Asia, adopting SDS prevents 55 deaths per 100,000 people compared to the Stated Policies Scenario (STEPS). The highest relative change is observed in Latin America, where SDS cuts mortality associated with PM2.5[1] exposure by approximately half compared to STEPS. SDS has the greatest impact on reducing PM2.5 mortality related to industrial sources, while the mortality impacts associated with agricultural emissions are largely unaffected by the adoption of SDS.

2. **Diets:** The EAT-Lancet diet presents the greatest potential for mitigating climate change through a reduction in red meat production, as red meat is associated with higher greenhouse gas emissions compared to other dietary protein sources. Adopting the EAT-Lancet diet can eliminate mortality related to red meat consumption and lead to substantial reductions in greenhouse gas emissions, particularly in Europe, Latin America, and North America. Additionally, both the EAT and WHO scenarios eliminate mortality associated with weight-related issues such as underweight, overweight, and obesity. While these improvements in metabolic dietary risks do not directly contribute to greenhouse gas mitigation, addressing obesity would likely require increased physical activity, which has the potential to reduce short car journeys and provide additional co-benefits. Further research is

[1] Fine particulate matter – particles that are 2.5 microns or less in diameter.

needed to explore the potential for mitigation policies that offer cross-domain co-benefits to population health.

3. **Transport:** The impact of increasing active travel on mortality reduction is likely lower compared to the benefits of reducing air pollution and improving diets. The effectiveness of promoting active travel depends on the existing transportation infrastructure and the ability of governments to regulate and make changes. Implementing active travel solutions, such as adding bike lanes, is more effective in densely populated areas compared to rural areas. In regions where mortality rates from low physical activity have improved over the past 30 years, such as the US, Canada, and much of Europe, efforts should focus on seeking further decreases in mortality. However, in regions like Asia, North Africa, and the Middle East, where mortality rates are high, efforts should be directed towards preventing future increases in mortality.

4. **Economics:** The costs of pure mitigation (without benefits of avoided damages) are directly related to the level of decarbonisation. It is crucial to recognise that decarbonising the economy aligns with a continuous trajectory of sustained economic growth over time. Enhanced policies (APS) can lead to a 62% reduction in global emissions by 2050, which is compatible with a 2.4% global GDP growth rate between 2020-2050. Achieving net-zero CO_2 emissions by 2050 would result in an average annual growth rate of 2.3%.
   Decarbonisation scenarios show that carbon emissions in the agriculture and food, electricity, and industry sectors are expected to decline by 2050 compared to 2020. However, emissions in the transport and building sectors increase under current policies (STEPS) but decline with stronger mitigation actions. This cross-sectoral transformation is influenced by many factors, including cost reductions, energy efficiency improvements, resource efficiency improvements and lifestyle changes.
   The impact of heat stress on labour productivity and associated economic losses can be mitigated with stronger measures. Without adequate mitigation, the global damage of heat stress as a share of 2020 GDP is around 1.7%, but under the net-zero CO_2 emissions scenario, the global damage is reduced to around 1.5%. Developing regions with tropical weather, such as Africa, Central and South America, India, the Middle East, and Other Developing Asia, are particularly vulnerable to heat stress, with GDP declines of 1% to 2% expected. Other damages from climate change, beyond heat stress, are not assessed within the economic model.

The review work and modelling analysis within this report shows the opportunities of prioritising health in climate change discourse and integrating co-benefits into climate policies. By reducing emissions, addressing air pollution, promoting healthy diets, and encouraging active travel, significant health improvements could be achieved. The economic analysis highlighted the potential costs and benefits of mitigation efforts, with regional variations and the need for transitioning away from fossil fuels. This report shows the potential implications of including co-impacts in climate change mitigation efforts to achieve a net-zero carbon economy while realizing broader benefits for human health and welfare.

2. Introduction

Climate change, driven by increasing global mean temperatures, presents one of the most pressing challenges of the coming decades, with far-reaching implications for all aspects of human society. Parties to the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Paris Agreement in 2015; a legally binding international treaty on climate change that aims to limit "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels". This goal will require rapid and deep cuts to net carbon emissions starting immediately and continuing in the coming decades through climate change mitigation actions. The secondary impacts of these mitigation efforts, described here as co-impacts of mitigation, are the central focus of the report.

In 2021, net annual greenhouse gas emissions stood at 53 billion tonnes of CO_2e (UNEP, 2022). As the magnitude of the efforts required to reduce these emissions has become apparent to the global community, so too have the direct impacts of global increases in temperature become apparent and the necessity of limiting them. However, what is less well generally understood is that in pursuing GHG mitigation efforts additional co-impacts and co-benefits may result. This report aims first to summarise the latest evidence on what these co-impacts are, and then to explicitly quantify the clearest co-benefits to health and economic impacts using established methods.

The health co-benefits associated with mitigation are assessed across three domains that have shown clear evidence of mitigation potential: air pollution, diets, and physical activity. By evaluating the effects of these sectors, we can better understand the broader implications of pursuing emissions reductions and develop strategies to optimise positive outcomes while minimising negative consequences. While this report does not directly assess the direct health impacts of climate change itself, such as deaths resulting from extreme temperatures, wildfires, or flooding, it recognises that mitigating climate change can indirectly contribute to reducing these direct impacts. Additionally, the role of mitigation in reducing the deaths directly caused by climate change is outside the scope of the study.

The health co-benefits and economic impacts are calculated through to 2050 across several macro regions globally. The central scenarios used to assess these impacts are based on the openly available data from the International Energy Agency (IEA), with additional data provided by the World Health Organization (WHO), the EAT-Lancet commission, the Global Burden of Disease (GBD) and International Institute for Applied Systems Analysis (IIASA).

This report represents the final report of work package E1 (WPE1) of the CS-N0W project. The project is divided into two subtasks as follows:

Subtask 1 of WPE1: Development of pathway model and impacts matrix, based on evidence, showing how different mitigation actions are linked to co-impacts, and in what contexts. This reporting was detailed in the Interim Report of 30th September 2022, but also summarised briefly herein.

Subtask 2 of WPE1: Sector and region-specific quantitative co-impacts modelling. The results of this analysis are the central focus of the present report.

2.1 Report outline

The remainder of the report is structured as follows. In the next section, the first portion of WPE1's outputs are summarised, namely the pathway model and co-impacts matrix which resulted from a comprehensive review of reviews into the impacts of climate mitigation actions.

An overview of the co-benefits modelling is given in section 4, with specific discussion of the key IEA scenarios used in this report. The results of this modelling are given in section 5, including the health co-benefits of mitigation across the three domains considered as well as economic impacts. Finally, the broad implications of these results are considered in the closing section. Methods and additional information are given in the appendices.

3. Co-impacts pathway model and co-impacts matrix

The first subtask of the WPE1, reported fully in the Interim Report, sought to comprehensively assess evidence of the co-impacts of climate change mitigation. It defined "climate change mitigation measures" as actions aimed at limiting or reducing greenhouse gas concentrations in the atmosphere. Other impacts that are distinct from greenhouse gas emissions are referred to as "co-impacts". Co-impacts may act to bolster or counter impetus to take mitigation action. While particular co-impacts may be plausible, the first subtask limited its scope to those specifically highlighted by the literature.

The method employed in this subtask followed a "review of reviews" approach. This is due to the substantial volume of research on climate change mitigation co-impacts, which suggested a comprehensive review process was necessary. This review proceeded in three stages:

1. A systematic search using pre-set search terms on a range of publication databases and relevant websites, designed to return review papers which assessed the co-impacts of climate change mitigation.

2. Screening against inclusion/exclusion criteria, first on title and abstract, and then on full text to remove irrelevant results

3. Extraction of relevant details and quality assurance of the review.

The results of this process were then synthesised through the pathway model and co-impacts framework. The pathway model visually illustrates the connections between climate change mitigation measures and co-impacts across various sectors, while the co-impacts matrix highlights these relationships in a structured format, with comments providing additional context as needed.

The pathway model is an interactive online tool designed to aid in identifying co-impacts related to the delivery of Sustainable Development Goals (SDGs) across sectors and regions. It allows for the exploration of co-impact pathways within specific sectors, assessment of the relevance of co-impacts based on contextual factors and national data, and access to the underlying evidence and its strength from the review. The online co-impacts matrix enables sorting and filtering to identify climate change mitigation measures associated with specific co-impacts, along with their associated evidence and relevance, by category/sector and vice versa. Ultimately, all this information can be used to develop, implement, and communicate policy.

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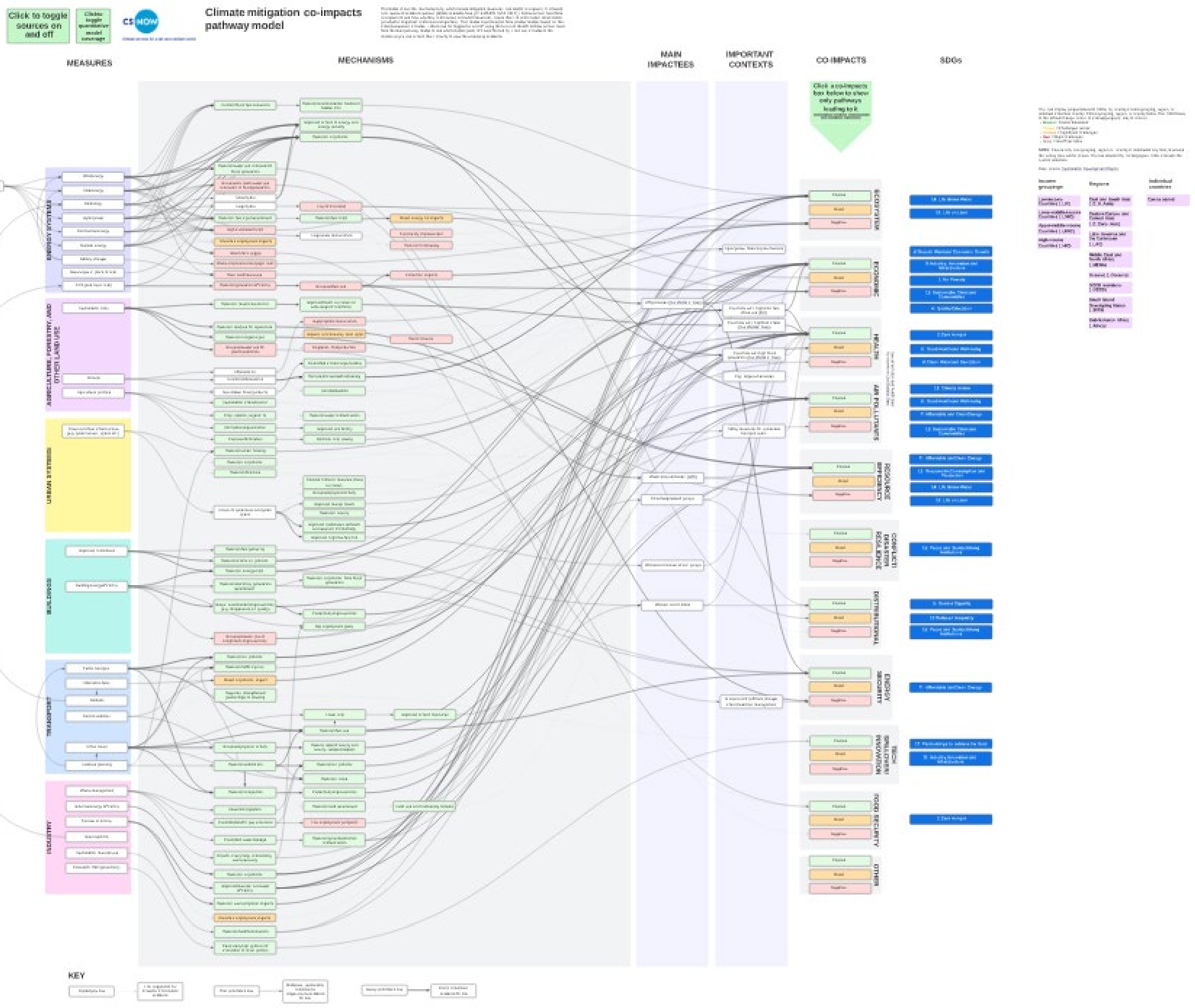


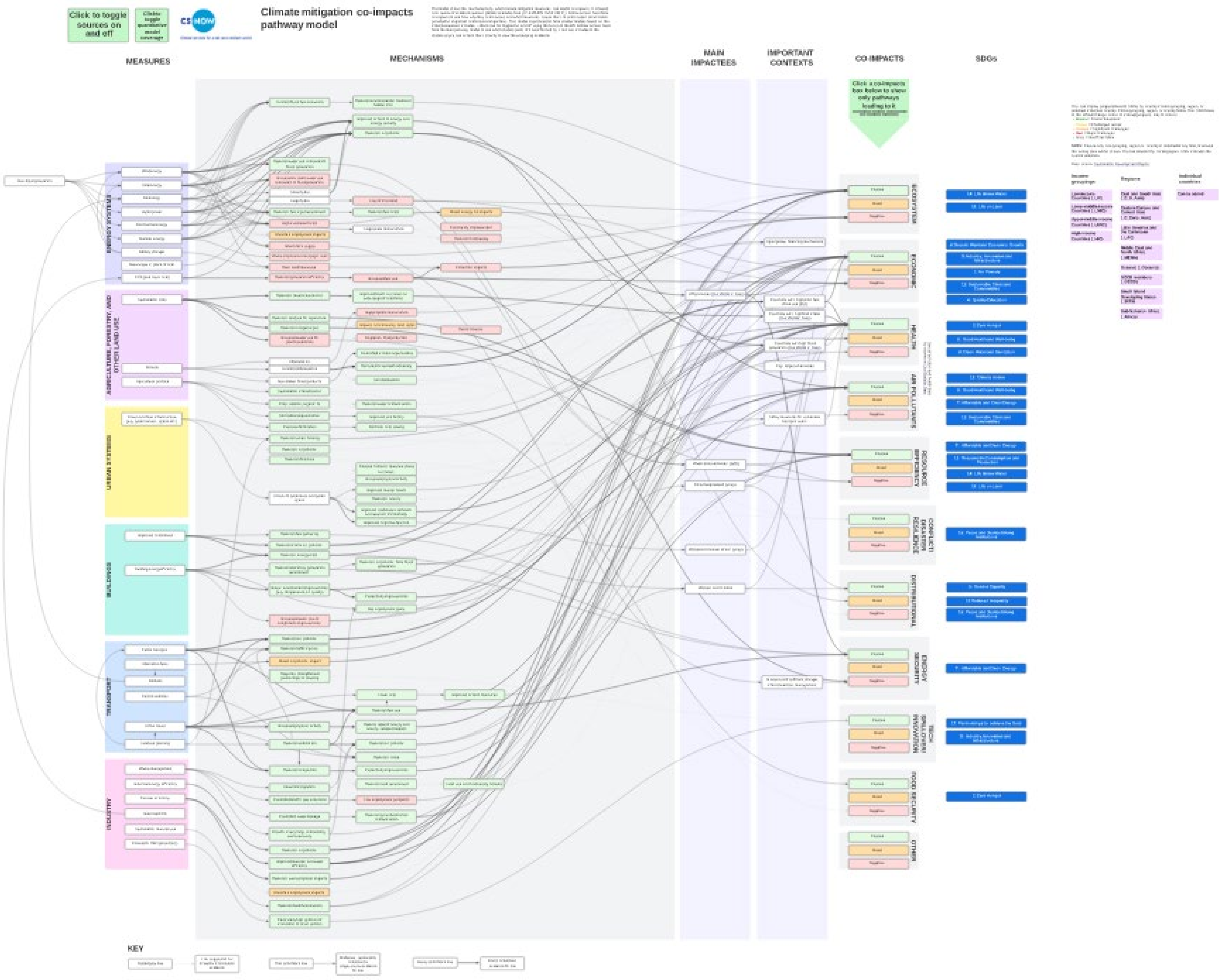


Figure 1 Summary image of the full co-impacts pathway model. Viewing the [interactive online version](#) is essential to see detail.

3.1.1 Review of reviews summary

The evidence review found that the most positive and strongest co-impacts have been identified in the health domain, which motivates the analysis given below. As drawn from the peer-reviewed literature, there is robust and consistent evidence indicating significant health benefits derived from the reduction of air pollution through the adoption of non-combustion-based electricity generation, cleaner cook stoves, and enhanced industrial energy efficiency. Air pollution exerts a diverse range of health impacts, encompassing short-term exacerbation of conditions such as asthma, as well as long-term effects including the development of lung cancer. Evidence also strongly supports the positive health impacts of increased physical activity and sustainable diets, as they contribute to reduced obesity and improved cardiovascular health.

These benefits are associated with climate change mitigation measures involving active transport, improved access to green spaces and infrastructure, and reduced consumption of animal products. Increasing active and public transport reduces traffic accidents, and green spaces and buildings reduce urban heating and improve mental health. There is also substantial evidence demonstrating the health benefits resulting from indoor environment improvements, particularly in relation to increased building energy efficiency, which can help avoid temperature extremes and indoor air pollution.

Substantial positive economic co-impacts were identified connected with fuel/material input savings and productivity improvements arising from climate change mitigation measures. Positive economic co-impacts include reduced spending on fuel/material inputs with improved energy and building efficiency, productivity improvements from active and public transport reducing traffic congestion, and agriculture-related economic benefits from improved soil quality, lower-cost fertiliser, and non-timber forest products. However, the net employment effects depend on local circumstances, with opportunities opening up in some sectors, particularly carbon-free energy plants, and negative impacts observed in fossil fuel extraction jobs. It should be noted that the scale and identity of low-carbon energy plants are instrumental in dictating job impact, for example large hydropower projects having less job opportunities and more negative community impacts than small renewable plants. Some mitigation strategies also reduce hard, unpaid labour, such as collecting firewood for cooking, and carbon capture and storage (CCS) can be viewed as reducing generation efficiency through a purely economic lens.

Co-impacts from protecting ecosystems and increasing resource efficiency are also covered. Resource efficiency is especially important in the context of resource scarcity; implementing sustainable diets, particularly by reducing meat consumption, can contribute to relative reductions in agricultural land use, complemented by sustainable agricultural practices, thus reducing nitrogen input requirements. Additionally, mitigation measures, including improvements in manufacturing processes and electricity generation technologies such as wind, solar, and geothermal power, can reduce water demand. On top of mitigation, evidence shows that increased recycling, composting, and waste recovery practices will also reduce the need for resource extraction. The main negative co-impact on resource efficiency is a possible increase in water demand from some plant-based diets and generation technologies, particularly nuclear, bioenergy and hydrogen production methods such as electrolysis. Ecological and some social impacts were also highlighted pertaining low carbon emissions technologies, particularly in relation to rare-earth mineral extraction for battery and renewables production, as well as the persistent negative impacts of nuclear waste.

The pathway model also demonstrates impacts from climate change mitigation measures from several other sectors where fewer co-impacts are apparent from the review. Energy security and security of access can be improved through decentralised renewable generation, especially in off-grid areas, improved energy efficiency, and various transport practices such as planning to reduce trip distances and greater reliance on active travel and public transport. This energy security can also be negatively impacted by decentralised generation where sufficient storage and interconnection is lacking, or technologies which reduce generation efficiency, such as carbon capture and storage (CCS).

Food security can be improved by sustainable agricultural practices improving soil fertility and enabling healthy intensification but can also be affected by measures such as afforestation which could reduce food agriculture. Furthermore, there is potential for disaster resilience benefits through soil stabilisation by forests and vegetation, reducing landslip risk, while better green infrastructure can mitigate urban water run-off and minimise flood risk.

The review features discussions of distributed co-impacts as well, including better access to basic services from more active travel opportunities and the risk of large-scale monocultures for bioenergy leading to food production and/or community displacement, though many distributional co-impacts are too nuanced for a high-level review. Many mitigation measures and their co-impacts can contribute to societal adaptation by reducing sensitivity and exposure to climate hazards, increasing adaptive capacity, and reducing vulnerabilities and risk, though the susceptibility of the mitigation measures themselves to these factors should be considered as well.

Overall, the strength of the evidence identified in the review of reviews, and summarised in the pathway model and co-impacts matrix, justifies the modelling section to follow, which reports the results of the explicit quantification of health co-benefits across the domains of air-pollutions, diets and increased physical activity, as well as the economic impacts of GHG mitigation strategies.

4. Co-benefit Modelling overview

4.1 Overview

This section reports the results of modelling designed to quantify the likely economic and health co-impacts of climate change mitigation, specifically surrounding reductions in particulate air pollution, improvements in diet, and increases in physical activity. The domains were chosen because they have a clear evidence base in the literature, as discussed in section 3, and modelling them is technically feasible globally.

The quantification of projected economic and health co-impacts in 2050 strikes a balance between allowing substantial societal changes to occur while minimising uncertainties related to climate change mitigation in the projections. The modelling scenarios are derived from the IEA Global Energy and Climate Model (GEC) (IEA, 2019), and soft-linked to domains which are not explicitly covered by this model, namely dietary intake and physical activity levels. The GEC incorporates assumptions about technological advancements, carbon pricing, and socioeconomic factors to generate data on potential future energy demands, emission levels, and required investments. The specific scenarios considered by the World Energy Model (WEM) are the subject of the section which follows this.

The International Institute for Applied Systems Analysis (IIASA) estimates exposure to and health impacts of concentrations of particulate matter less than 2.5 microns in diameter (PM2.5). These concentration levels are mapped to IEA GEC scenario outputs to estimate future concentrations of PM2.5 under these scenarios.

For diet related risks, GHG mitigation actions necessitate substantial reductions in the amount of red and processed meat consumed and increases in the share of fresh fruits and vegetables and other foods associated with good health. The production of red meat generates the highest carbon emissions among all food groups and consuming it is linked to a significant mortality burden.

The final health co-benefit pathway is assessed by considering possible future levels of physical activity. The mitigation pathway used here is that increased levels of active travel (walking and cycling), as promoted through increased public transport provision and active travel infrastructure, will offset car use in urban environments. This in turn reduces CO_2 emissions directly, or improves transport energy efficiency, by shifting journeys to communal forms of travel. This domain suffers from the lowest level of data coverage of the three health domains considered here (see supplementary methods on page 59), and therefore the highest level of implicit uncertainty in future projections.

The economic impacts of mitigation scenarios and heat stress impacts on labour productivity are assessed through Computable General Equilibrium (CGE) modelling, which quantifies economy-wide impacts of decarbonisation scenarios in terms of changes in macroeconomic variables such as GDP, welfare, employment, and prices. The model analyses economic impacts across sectors and countries, while also incorporating emissions of CO_2 to understand impacts and co-benefits of mitigation policies.

4.2 Scenario specification

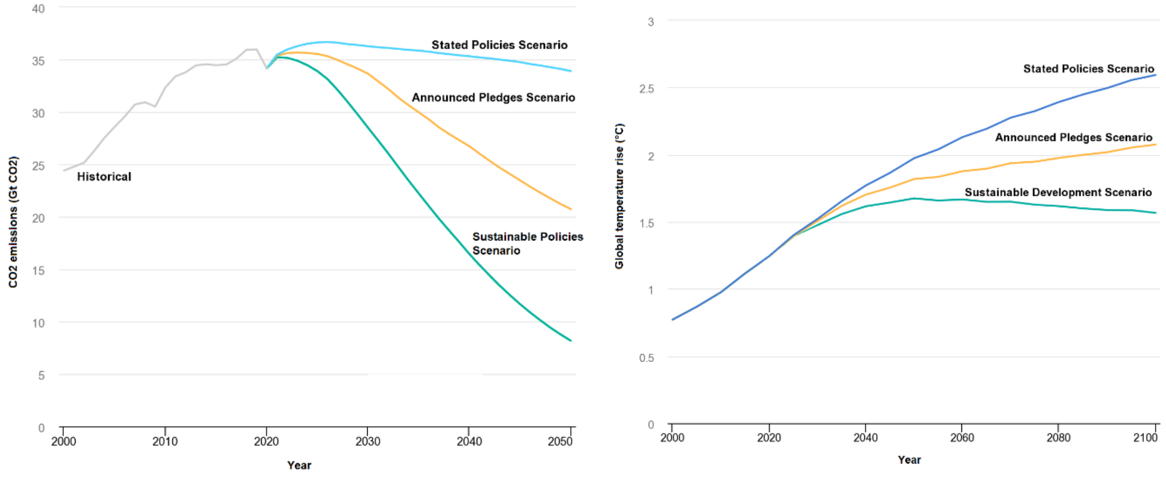


Figure 2 CO_2 emissions trajectories to 2050 and temperature rise in 2100 under three IEA scenarios used in this report (IEA, 2021).

The central basis for the energy system modelling used here is provided by the IEA. These provide the indicators of CO_2 emissions, temperature rises, and energy used by each sector. Furthermore, these data are used as inputs to the PM2.5 modelling and the economic modelling (see results on page 25). All IEA scenarios are built using the Global Energy and Climate Model (IEA, 2019), described in further detail in the models section below, and the subsequent appendix. Three central scenarios are assessed, namely Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS) and the Sustainable Development Scenario (SDS).

The year 2050 is chosen as the principal year of analysis, for two reasons. First, since projections of economic activity, population growth, dietary consumption habits and levels of physical activity are inherently uncertain, and increasingly so moving forward, 2050 represents a reasonable year balancing scope of possible change against uncertainty. Second, 2050 is emerging as a consensus year in national targets and modelling efforts as efforts are consolidated to limited global average temperature rise to 1.5˚C.

Stated Policies Scenario (STEPS)

This scenario is produced using a sector-by-sector and country assessment of existing and announced policies. It does not take into account pledges in government roadmaps such as Nationally Determined Contributions (NDCs). It provides a benchmark against which other scenarios may be measured (IEA, 2022). Median global temperature rises under STEPS are 2.0 (1.8 – 2.1) ˚C in 2050 and 2.6 (2.4 – 2.8) °C in 2100, where the 33% and 66% confidence intervals are given in parenthesis respectively.

Announced Pledges (APS)

This scenario takes as its basis the commitments to act on climate change that have been made by governments, including NDCs. Figure 2 shows that it is still associated with over 20 billion tons of CO_2 emissions per year in 2050, thus making it incompatible with the goal of keeping global temperature rise “well below 2°C” by the end of the century. Despite its failure to meet the Paris goal, it does make progress in terms of energy access – in 2030 around 300 million people lack electricity access under APS. This compares to STEPS, under which around 662 million people, 84% of whom reside in sub-Saharan Africa, still lack access to electricity in 2030 (IEA, 2022). Median global temperature rises under APS are 1.8 (1.7 – 2.0) °C in 2050 and 2.1 (1.9 - 2.3)°C in 2100.

Sustainable Development Scenario (SDS)

The IEA Sustainable Development Scenario (SDS) is built around the goal of reducing CO_2 emissions to keep global temperature rises “well below 2°C” by 2100. This provides further ambition on top of STEPS and APS (see Figure 2), with a view to limiting the most severe impacts of climate change. Major equity goals are also achieved under SDS, with 100% access to electricity and clean cooking occurring by 2030. Median global temperature rises under SDS are 1.5 (1.4 – 1.6)°C in 2050 and 1.6 (1.4 - 1.7)°C in 2100.

Diet scenarios

To assess the health co-benefits of dietary change and changes to physical activity levels, additional scenarios are required. For dietary change, three scenarios are considered as follows: First, the benchmark (BMK), which assumes current trajectories of consumption are maintained through to 2050, with no action on improving diets or reducing emissions associated with agriculture. Second, the WHO recommend diets (WHO), which principally works toward health benefits through actions on levels of overweight and obese adults in populations worldwide (WHO, 2020). Finally, the EAT-Lancet (EAT) scenario improves health outcomes by increasing portions of legumes, fruits and vegetables, nuts and seeds (see appendix 7.4.27.4.2) along with reducing red meat consumption (Willett, et al., 2019).

Active Travel scenarios

While the direct estimate of proportions of the population participating in active travel was not possible due to data limitations, levels of mortality attributable to low physical activity were projected through to 2050 under three scenarios. The active travel scenarios are defined fully in appendix 7.4.3. In summary, these are categorised as a benchmark (BMK) scenario, which assumes mortality rates associated with low physical activity remain constant through to 2050, an optimistic scenario in which these rates reduce (OPT) and a pessimistic scenario (PES) which increases rates.

4.3 Emissions & fuels

Global summary energy CO_2 emissions for the IEA scenarios considered here are given in Figure 3 and further detail on the energy mixes for the scenarios in

Figure 4.

Key Message 1

The Sustainable Development Scenario sees a surge in renewable energy technology deployment.

The APS and STEPS scenarios require significant increases in renewables' share of generation, but SDS requires that renewable generation become the largest source of energy in all regions apart from the Middle East and Eurasia. Under this scenario, all nations achieve net-zero CO_2 emissions by 2070 at the latest, with China achieving this goal by 2060 and the most development economics doing so by 2050.

Key Message 2

Global temperature rise reaches 1.6°C in 2100 under SDS.

Under SDS, there is a 50% chance of limiting global temperature rises to 1.6°C. This follows a temperature trajectory which peaks in 2050 and then declines towards 2100. Net negative emissions after 2070 have the potential to reduce the temperature rise to 1.5°C.

Key Message 3

Energy efficiency improvements and the deployment of carbon capture, utilisation, and storage (CCUS) play a major role in SDS.

Despite the global population projected to reach around 9.7 billion (see appendix section 7.5.1) in 2050, total primary energy demand is only marginally higher under SDS. This necessitates improvements in energy efficiency, achieved through the deployment of heat pumps and the electrification of transport. Net-Zero CO_2 emissions are achieved by 2070 under SDS. CCUS plays a substantial role in this scenario, accounting for an additional 15% of net CO_2 reductions compared to STEPS, amounting to 10.4 Gt of CO_2 of captured emissions in 2070. This is applied to abating remaining coal and natural gas use, but also through capturing bioenergy emissions leading to CO_2 drawdown.

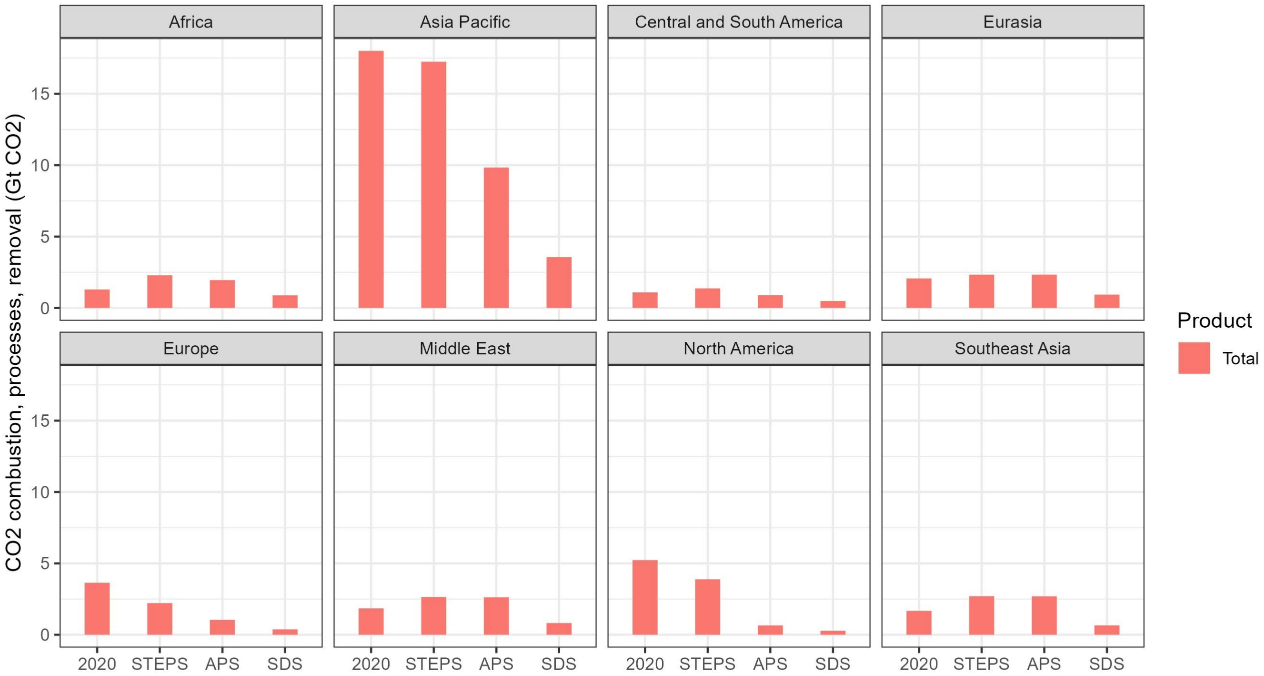


Figure 3 CO_2 emissions (Gt CO_2) in 2020, and by scenario in 2050

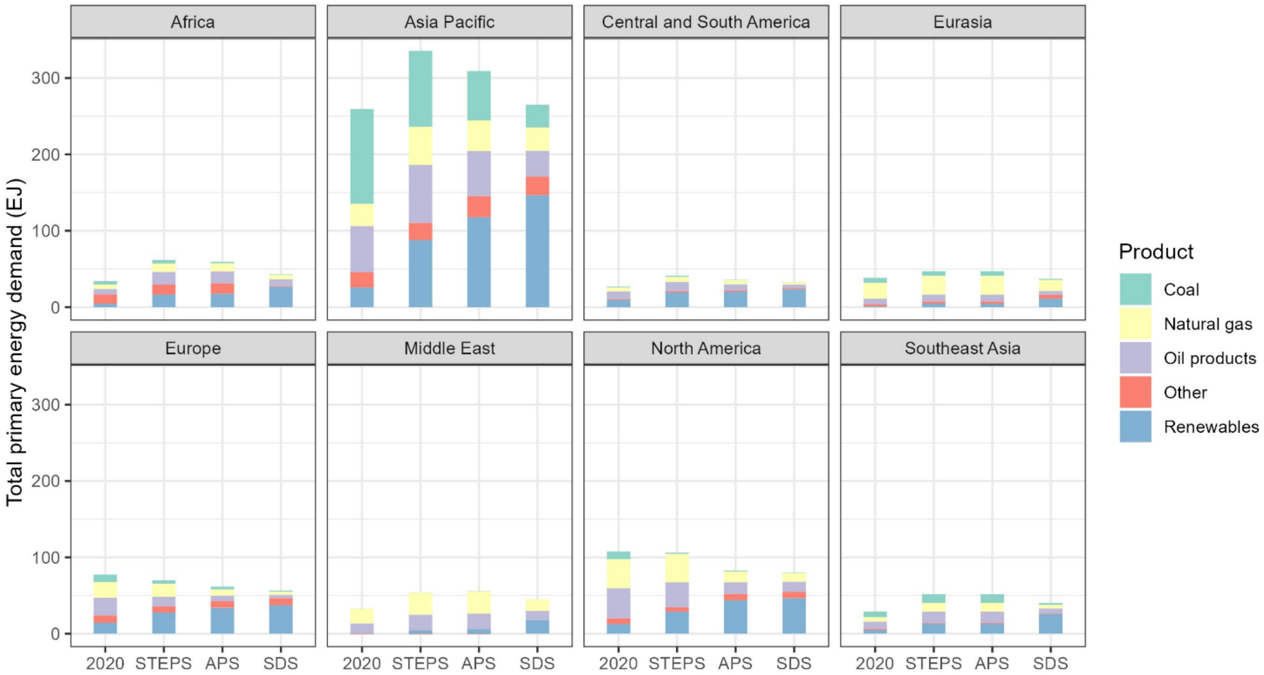


Figure 4 Total primary energy demand in 2020, and by scenario in 2050, by product and region (EJ).

5. Co-benefit modelling results

5.1 Health

The health benefits derived from cleaner air, healthier diets, and active communities are apparent and applicable across various development and societal trajectories. However, these interactions are not yet fully integrated into climate policies, as there is limited reference to public health in current NDCs. Recognising and incorporating these co-benefits can strengthen the case for further ambition in meeting the climate change commitments of the Paris Agreement and create opportunities for collaboration among a range of stakeholders, including health professionals, policymakers, engineers, energy experts, transport and agriculture specialists, and economists. The following analysis highlights the potential health impacts, in terms of mortality, of climate actions that work towards mitigating GHG emissions across the domains of air pollution, dietary change and increased active travel.

Table 1 Avoided mortality per 100,000 population of adopting the most beneficial scenario for each domain compared to the least beneficial scenario by region in 2050[2].

Region	Air Pollution	Diet	Active travel
East & Southeast Asia	55	94	12
European Union	15	183	13
Latin America	15	142	5
North Africa & Middle East	18	141	14
Other Europe	28	268	7
South & Central Asia	55	103	9
Sub Saharan Africa	10	53	2
USA and Canada	9	154	7
World	34	92	7

5.1.1 Air quality

The global energy system along with sectors such as household and agriculture produce substantial qualities of fine particulate matter (PM2.5). Exposure to ambient particulate matter is a well-known contributor to mortality (see appendix 7.4.1). Here, concentrations of particulate matter were estimated, and the corresponding associated mortality calculated under each of the IEA scenarios described above, names STEPS, APS and SDS. The contribution of each sector of the economy is calculated for a series of global macro regions to quantify the mortality per 100,000 population in 2050 under each of the scenarios considered.

Key message 1

The largest gains for adopting SDS are to be found in East & South East Asia and South & Central Asia regions.

Adopting SDS prevents 55 deaths per 100,000 people versus STEPS in both the East & South East Asia and South & Central Asia regions. However, the highest relative change occurs in Latin America, where adopting SDS cuts mortality associated with PM2.5 exposure approximately by half, relative the STEPS scenario.

Key message 2

[2] The least beneficial and most beneficial scenarios for each domain are as follows, respectively. Air quality: [STEPS, SDS]. Diet: [benchmark (BMK), EAT-Lancet (EAT)]. Active travel: [Pessimistic, Optimistic].

Adopting SDS has the largest impacts for PM2.5 mortality associated with industrial sources. Mortality impacts associated with agricultural emissions remain largely unimpacted by the adoption of SDS.

While SDS provides substantial improvements in air quality in relation to industrial emissions, agriculture remains a key source of PM2.5 under this scenario. This suggests that substantive efforts beyond SDS should be considered, particularly in Europe and Asia, where large burdens associated with agriculture remain even after adopting SDS.

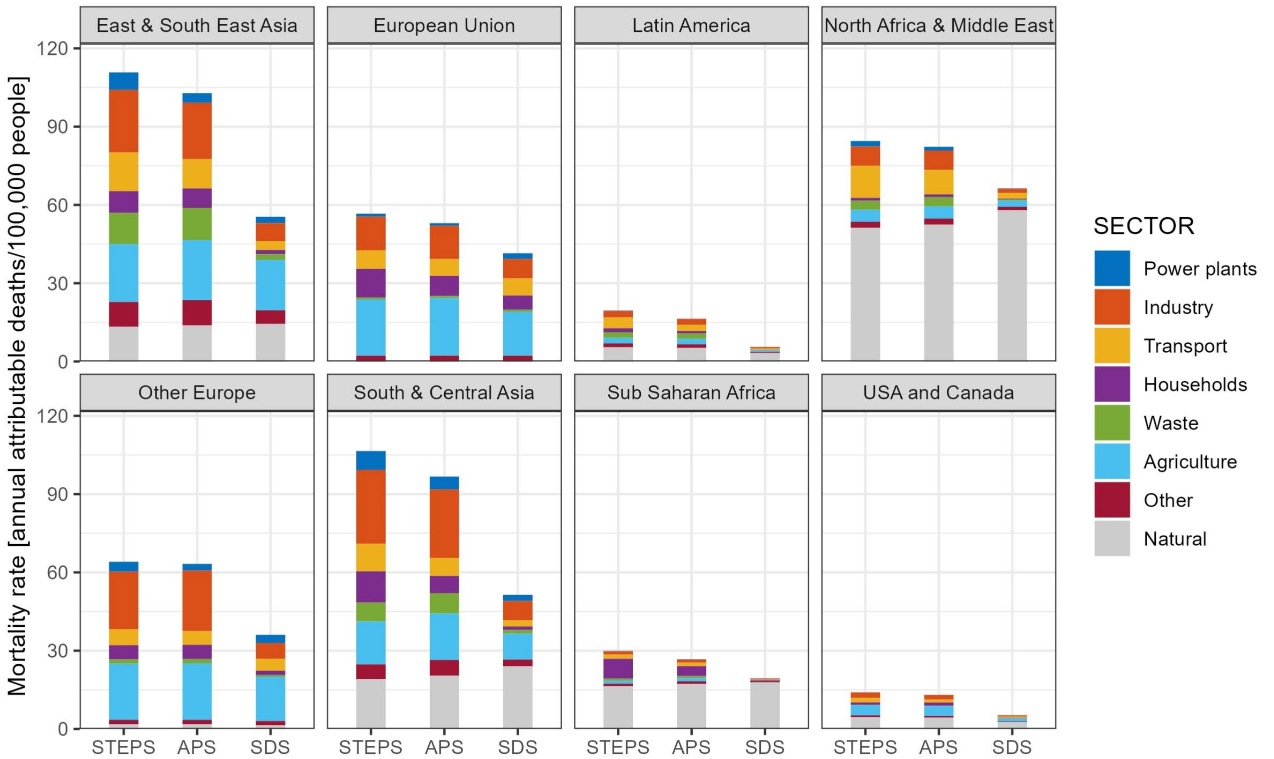


Figure 5 Mortality rate associated with ambient PM2.5 exposure by region, sector, and scenario in 2050

Table 2 Mortality by scenario and region in 2050 associated with PM2.5 pollution exposure.

Region	Population (thousands)	Stated Policy Scenario	Announced Pledges scenario	Sustainable Development Scenario
East & Southeast Asia	2,288	2,592,000	2,424,000	1,339,000
European Union	427	242,000	227,000	177,000
Latin America	779	162,000	140,000	47,000
North Africa & Middle East	637	539,000	524,000	423,000

Other Europe	387	248,000	245,000	140,000
South & Central Asia	2,419	2,577,000	2,340,000	1,243,000
Sub Saharan Africa	2,221	664,000	593,000	431,000
USA and Canada	435	61,000	57,000	23,000

5.1.2 Diet

The diet modelling exercise assessed mortality associated with dietary risks through to 2050 for each region under three scenarios, benchmark (BMK), World Health Organization recommendations (WHO, 2020) and the diet of the EAT-Lancet commission (Willett, et al., 2019). The dietary risks considered were overconsumption of red meat, and under consumption of fruits, vegetables, nuts and seeds, and legumes, as well as weight related risks of being underweight, overweight, or obese.

Key message 1

EAT-Lancet diet offers the greatest mitigation co-benefits through the reduction of red meat production.

Red meat production is associated with higher greenhouse gas emissions than other forms of dietary protein, therefore substantial GHG mitigation occurs by shifting consumption patterns away from high red meat diets. Mortality related to red meat consumption is eliminated under the EAT-Lancet diet, offering the potential for substantial reductions in GHGs associated with red meat production. The impacts are most evident in Europe, Latin America, and North America.

Key message 2

EAT and WHO scenarios eliminate weight-related (underweight, overweight, and obese) mortality.

The benchmark scenario shows that these deaths currently account for around half of diet-related deaths in all regions, meaning significant cultural and economic changes are required to achieve this reduction. Unlike the co-benefits associated with red meat reduction, improvements in metabolic dietary risks do not offer a direct mitigation pathway. However, it is likely that action on obesity would require increasing levels of physical activity (see section 5.1.3), which also has the potential to reduce short car journeys. These second-order cross-domain co-benefits are not considered in this report, opening a space for further research into mitigation policies which have virtuous cycle benefits to population health.

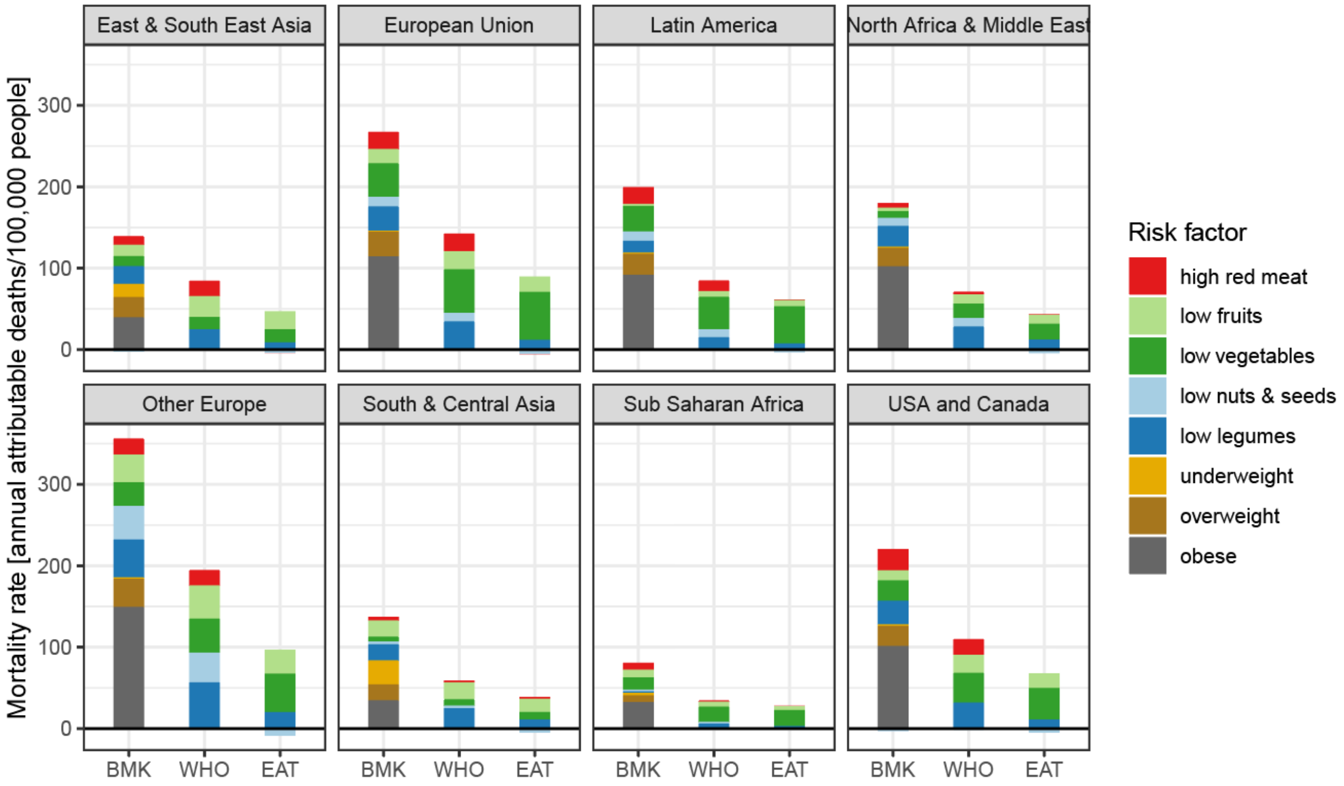


Figure 6 Mortality rate associated with diet by region, risk factor, and scenario in 2050

Table 3 Total attributable mortality by scenario in 2050 by scenario and region

Region	Population (millions)	Benchmark	WHO dietary recommendation	EAT-Lancet report
East & Southeast Asia	2119	2,899,000	1,785,000	911,000
European Union	416	1,111,000	592,000	350,000
Latin America	790	1,576,000	670,000	457,000
North Africa & Middle East	619	1,111,000	437,000	241,000
Other Europe	380	1,353,000	739,000	335,000
South & Central Asia	2144	2,937,000	1,262,000	723,000
Sub Saharan Africa	2091	1,686,000	717,000	569,000
USA and Canada	414	899,000	449,000	260,000

5.1.3 Active travel

The potential mitigation impacts of increasing active travel participation occur through shifting local journeys which are currently undertaken using carbon intensive mode towards cycling and walking, thus reducing CO_2 emissions. This is modelled by projecting possible changes in the prevalence of the number of people who have low physical activity. The approach taken here is to estimate optimistic and pessimistic future scenarios of the proportional of mortality attributable to low physical activity levels based on the trends of the last 30 years (see appendix section 7.4.3 for further detail). Data are based on global estimates made at the country level which are then aggregated to the regions shown.

The underlying drivers of these changes are difficult to specifically estimate, but any improvements to levels of active travel participation would likely be linked to improvements in infrastructure – not only through projects which build bike and walking paths, but also increased public transport investment, which encourages walking between stations and journey end points (for a survey of planned projects, see appendix section 8.1.)

Benchmark: attributable rates stay constant through to 2050.

Optimistic: In regions where the age standardised rate of mortality associated with low physical activity have been falling in the past 30 years, these gains continue. For regions that have been getting worse, the attributable rates stabilise.

Pessimistic: In regions where the age standardised rate of mortality associated with low physical activity have been falling in the past 30 years, these gains stall and rates remain the same through to 2050. For regions that have been getting worse, the rate of increase in attributable mortality doubles in the next 30 years.

Key message 1

The scale of possible mortality reduction due increasing active travel participation is likely lower than for both air pollution and diet related mortality.

Increasing active travel depends highly on current modes of transport and the governmental potential to regulate transport or change infrastructure in each region. The effectiveness of a given solution changes based on location and necessity; for example, adding bike lanes in a dense city would be much more effective than the same strategy implemented in a rural, isolated area. The density and relatively high-income of the EU make this region an ideal candidate for implementing active travel solutions.

Key message 2

Preventing growth in mortality in regions where the risk has been growing over time might be more impactful than further reductions in regions that have been improving.

Due to improvements in mortality rates over the last 30 years, the US, Canada, and much of Europe currently have death rates from low physical activity that are in line with pessimistic scenario in 2050. However, in other regions, particularly Asia, North Africa and the Middle East, efforts would be more effective when directed toward preventing increases in attributable mortality, which are closer to the optimum scenario and far from potential increases in the worst-case scenario.

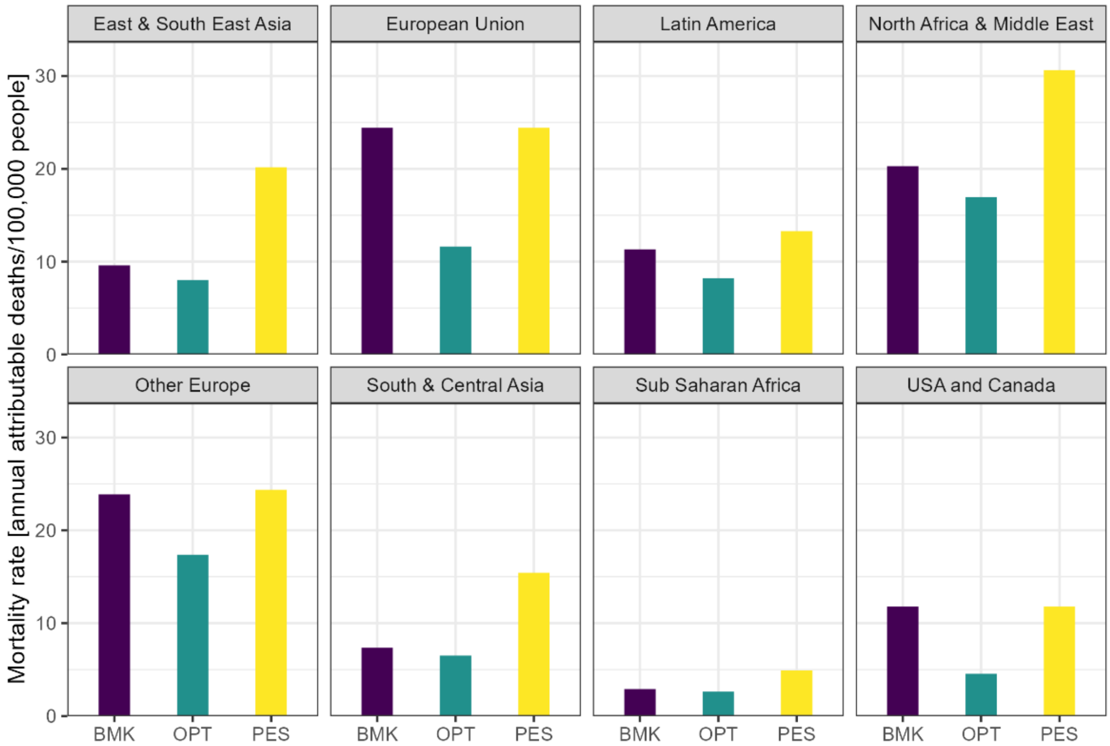


Figure 7 Mortality rate in 2050 attributable to low physical activity

Table 4 Mortality rate associated with low physical activity by region and scenario in 2050

Region	Population (thousand)	Benchmark	Optimistic	Pessimistic
East & South East Asia	2125	204,000	170,000	428,000
European Union	416	102,000	48,000	102,000
Latin America	790	90,000	65,000	105,000
North Africa & Middle East	619	125,000	105,000	189,000
Other Europe	380	91,000	66,000	93,000
South & Central Asia	2236	165,000	146,000	345,000
Sub Saharan Africa	2128	62,000	56,000	104,000
USA and Canada	414	49,000	19,000	49,000

5.2 Economics

The economic modelling has two main objectives. First, to assess the economy-wide impacts of alternative decarbonisation pathways to 2050. Second, to assess the co-benefits of reduced heat stress associated with those mitigation actions. The first objective aims to assess the pure mitigation costs to keep the average global temperature below 2ºC from pre-industrial level. The second objective, using as an example heat stress, aims to highlight the potential economic benefits from avoided climate damages. Other damages from climate change are not assessed within the economic model. An integrated assessment of the economic impacts of climate change should compare the cost of mitigation measures with the total cost of climate change damages. For instance, the IPCC Sixth Assessment Report highlights that the global economic benefit of limiting warming to 2˚C is expected to exceed the cost of mitigation (IPCC 2022, AR6 WGIII, Chapter 3, page 367).

Three decarbonisation pathways are evaluated: i) *STEPS*, which represents a business-as-usual scenario and provides a benchmark against which other scenarios are measured, ii) *APS*, which assumes that all commitments to act on climate change are fulfilled, and iii) *beyond SDS*, which goes beyond the SDS scenario described above and brings the global energy-related CO_2 emissions to net zero by 2050. Due to the absence of negative emission technologies in ENGAGE, emissions in the *beyond SDS* scenario are slightly positive in 2050. The economic modelling follows the narrative and representative global emissions reductions behind the IEAs' scenarios described above (see Section 4.3 and Appendix 7.5 for method and data).

Heat stress reduces the ability of workers to operate during the hottest hours. With rising temperatures caused by climate change, heat stress is expected to harm business and economic growth. Country estimates on the impact of heat stress on the productivity of labour in the agriculture, industry and services sectors are used to assess the economic impact in 2050 behind the three decarbonisation scenarios. Heat stress estimates are linked to the global mean temperature, so it does not consider extreme heat events. This section does not include the potential health benefits for the labour force that could be derived from cleaner air, healthier diets, and active communities, as discussed in section 5.

The UCL Environmental Global Applied General Equilibrium (ENGAGE) model is used to estimate the macro-economic impacts across sectors and across countries, considering the countries' economic characteristics and adjustment processes in domestic and international markets. ENGAGE uses a global carbon price as the main mechanism to reduce regional emissions per capita at the targeted level. The decarbonisation modelling also includes the development of renewable energy and the electrification of the economy. Future cost reductions in renewable technologies, based on the IEA and TIAM-UCL model, make renewables highly competitive at market conditions. A gradual increase in the elasticity of substitution between electricity and other energy inputs in the production of goods and services facilitates the industrial transformation necessary to decarbonise the entire economy. Energy demand changes are modelled via improvements in energy efficiency and lifestyle changes; the latter is achieved by gradually increasing the elasticity of substitution between electricity and other energy goods in the consumer's demand. All these changes are implemented alongside an autonomous improvement in resource efficiency. The more stringent the climate target the greater the speed of improvement and transformation of the economic system. Cost reductions, energy efficiency improvements, resource efficiency improvements, and elasticities of substitution are region and sector specific. Moreover, as capital is a scarce resource in the economy, the development of renewable technologies crowds-out investment in other parts of the economy.

Carbon dioxide removal (CDR) technologies have the potential to reduce net emissions in the short term, counterbalance residual emissions to achieve net-zero in the medium term, and achieve net-negative emissions in the long term. The deployment of CDR technologies is expected to be small in 2050, but they play a fundamental role in the long run. Results from nine integrated assessment models that explore the role of CO_2 removal technologies in scenarios with limited overshoot show that only around 13% of cumulative CDR required to keep the global temperature below 1.5°C is deployed by 2050 (Riahi et al 2021). As ENGAGE evaluates the economic impacts up to 2050, the limited representation of these technologies in ENGAGE has only a small influence on the overall results. However, it is worth noting that the economic cost of mitigation in 2050 might be overestimated, especially considering that some of these technologies (such as afforestation) are highly competitive. However, by omitting these technologies we avoid the risk and uncertainties of negative technologies and CCS not being available as part of a portfolio of mitigation options in the future.

Below we concentrate on discussing the economic impacts of pure mitigation and heat stress in 2050.

Key message 1

Climate change mitigation costs are directly related to the level of decarbonisation. It is crucial to recognise that decarbonising the economy aligns with a continuous trajectory of sustained economic growth over time. In *APS,* achieving a 62% reduction in global emissions by 2050 aligns with a 2.4% global GDP growth rate between 2020-2050 (Figure 8). Achieving net zero CO_2 emissions by 2050 (*beyond SDS* scenario) would result in an average annual growth rate of 2.3%. These results do not include economic benefits of mitigation from avoided climate change impacts.

Key message 2

Regional mitigation costs vary widely. The larger the emissions reduction, the wider the regional impact (Figure 9 and Figure 10). The individual outcome of the region depends on several factors, mainly on the size and pace of emissions reductions, the level of the carbon tax, the current energy mix and dependency of fossil fuels, the future development of renewable energy and its costs, the speed of the industrial decarbonisation and electrification, and the changes in competitiveness induced by climate and energy policies in other regions.

As observed in Figure 9, regional GDP continues to grow in all decarbonisation scenarios. The GDP growth rates in *APS* and *beyond SDS* are a few decimal percentage points lower for the period 2020-2050 compared to the pathway without mitigation (*STEPS*). The largest decline in a growth rate is 0.5 percentage points for the fuel exporting region Middle East in *beyond SDS*. However, the region is still growing at around 2.4% per year. Again, it is important to note that these figures do not include economic benefits of mitigation from avoided climate change impacts, neither the potential role of CDR in balancing climate goals and retaining competitiveness in the oil and gas sectors and energy-intensive industries.

The current carbon intensity of GDP explains around half of the slowdown in GDP growth rates (Figure 10). In fact, the higher the current carbon emissions per unit of GDP, the more costly the transition is expected to be. Furthermore, the current level of primary energy production per unit of GDP explains around 30% of the slowdown in GDP growth rates. Countries heavily reliant on fossil fuels will not only incur the costs of decarbonising their economies but also endure a decline in export revenues.

Key message 3

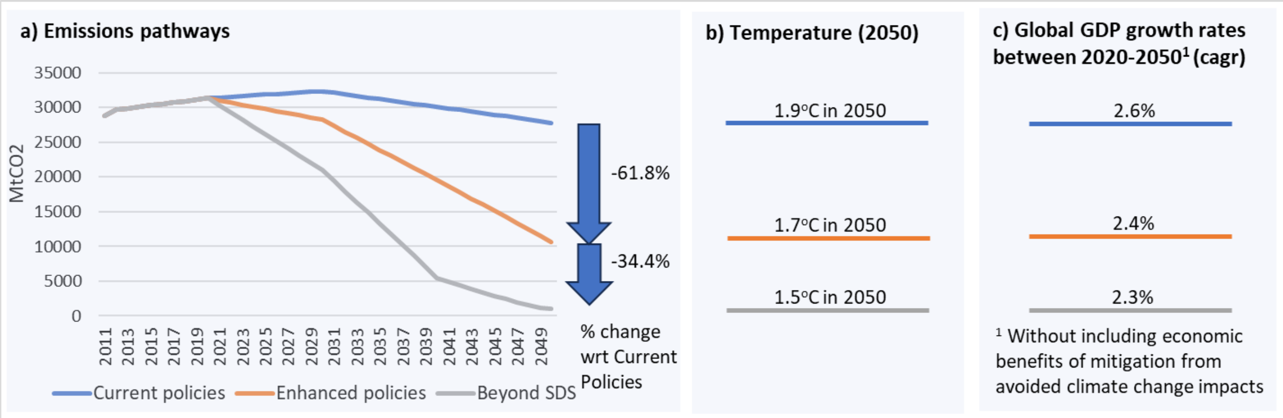
Compared to the 2020 level, carbon emissions in 2050 in the Agri&food, electricity and industry sectors are expected to decline under all decarbonisation scenarios (Figure 11). Implementing stronger mitigation measures leads to greater reductions in sectoral emissions. However, modelling results show that carbon emissions in 2050 in the transport and building sectors increase relative to 2020 under *STEPS*, but decline with stronger mitigation actions under *APS* and *beyond SDS*. This implies that current policy measures and efficiency gains are not enough to curb emissions in the transport and building sector.

Key message 4

The more stringent the mitigation measures, the lower the temperature, and consequently, the lesser the impact of heat stress on labour productivity and the associated economic losses. Without adequate mitigation measures (*STEPS* scenario) the global damage of heat stress as a share of 2020 GDP is around 1.7% (Figure 12). In contrast, the global damage caused by heat stress in the *beyond SDS* scenario is around 1.5%, as the expected increase in global temperature is limited at a lower level.

At the regional level, heat stress impacts more developing regions with tropical weather, such as Africa, Central and South America, India, the Middle East, and Other Developing Asia (Figure 12). In most of these regions, under the *STEPS* scenario, heat stress will decline 2050 GDP between 1% to 2%. The co-benefits of mitigation are evident in all these regions, especially for India and Other Developing Asia, where damages are reduced by around one third and half, respectively (when comparing the *beyond SDS* and *STEPS* scenarios).

The economic impacts of heat stress spread to all regions, even to those that are not physically affected by it. In fact, developed regions like the UK and the USA that are not impacted directly by heat stress experience economic losses as their decline in consumption and imports (due to the lower global economic activity) more than offsets their increase in exports (due to gains in comparative advantages).



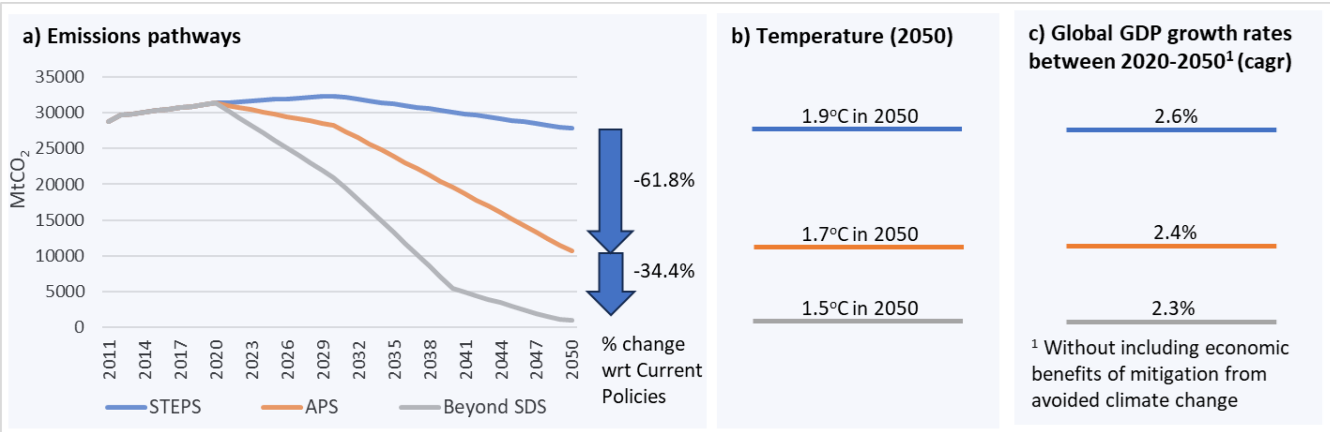
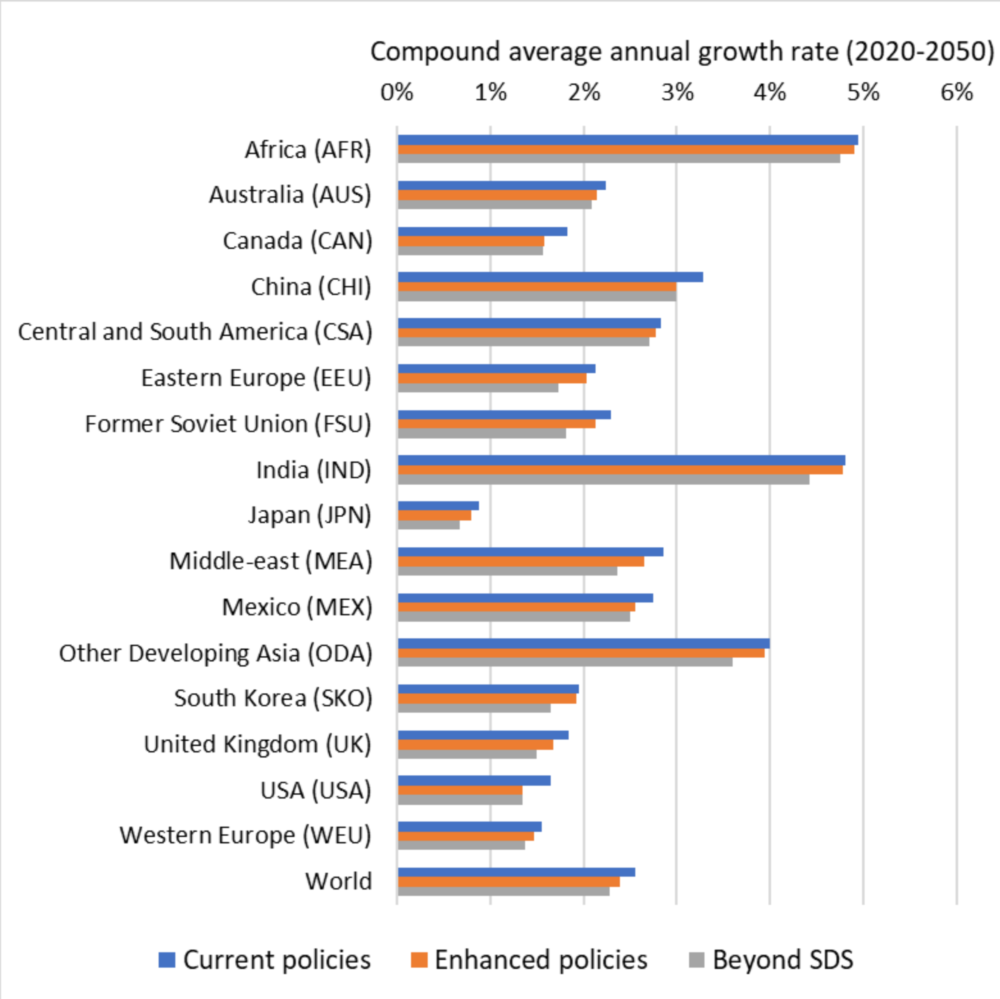


Figure 8 Global CO_2 emissions, temperature and economic impacts by decarbonisation scenario. (a) Global CO_2 emissions from energy only as ENGAGE does not account for process emissions. (b) The global temperature rise in 2050 in the decarbonisation scenarios are based on Figure 3.2 from the World Energy Outlook 2022 (IEA 2022). (c) The economic impacts are represented as changes in the GDP compound average annual growth rate (caagr) between 2020-2050, which do not include economic benefits of mitigation from avoided climate change impacts.


Compound average annual growth rate (2020-2050)
0%
1%
2%
3%
4%
5%
6%
Africa (AFR)
Australia (AUS)
Canada (CAN)
China (CHI)
Central and South America (CSA)
Eastern Europe (EEU)
Former Soviet Union (FSU)
India (IND)
Japan (JPN)
Middle-east (MEA)
Mexico (MEX)
Other Developing Asia (ODA)
South Korea (SKO)
United Kingdom (UK)
USA (USA)
Western Europe (WEU)
World
Current policies
Enhanced policies
Beyond SDS

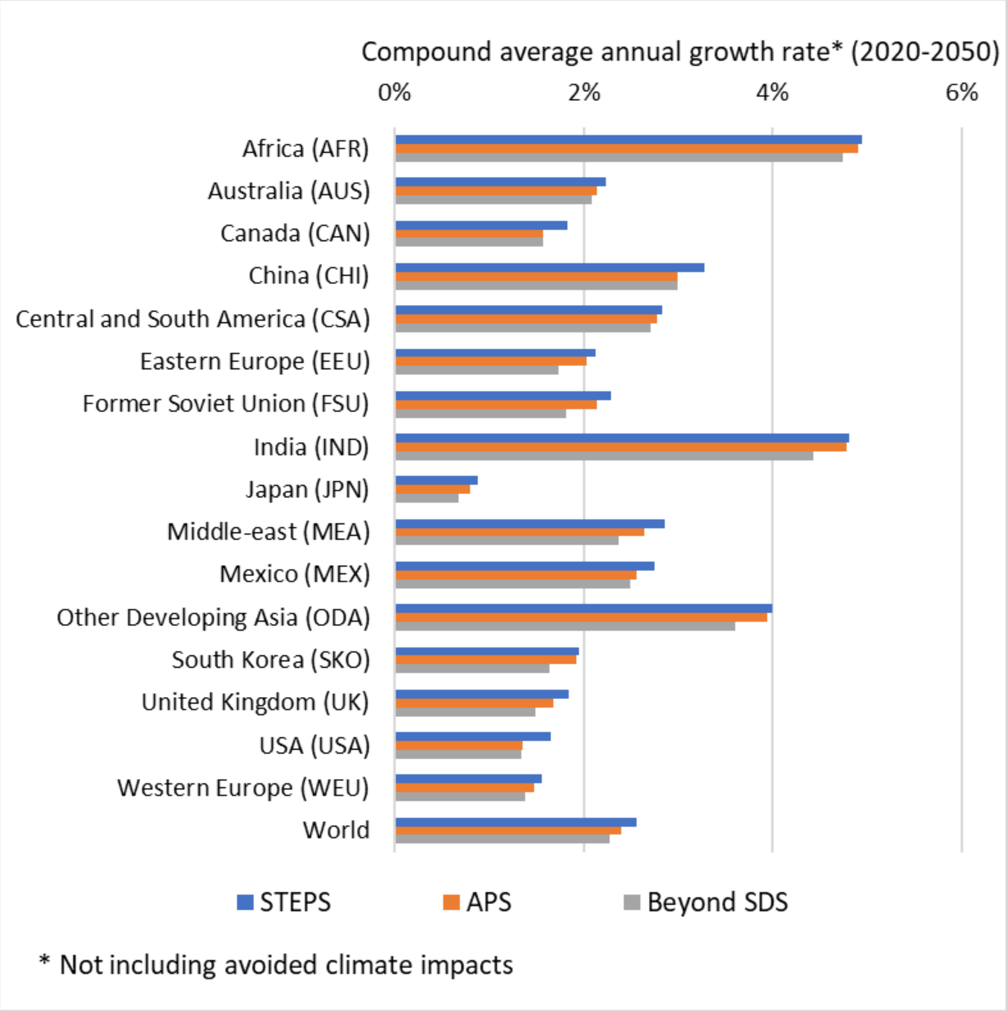


Figure 9 Regional GDP compound average annual growth rates between 2020-2050 by decarbonisation scenario. Mitigation only scenario, which do not include economic benefits of mitigation from avoided climate change impacts.

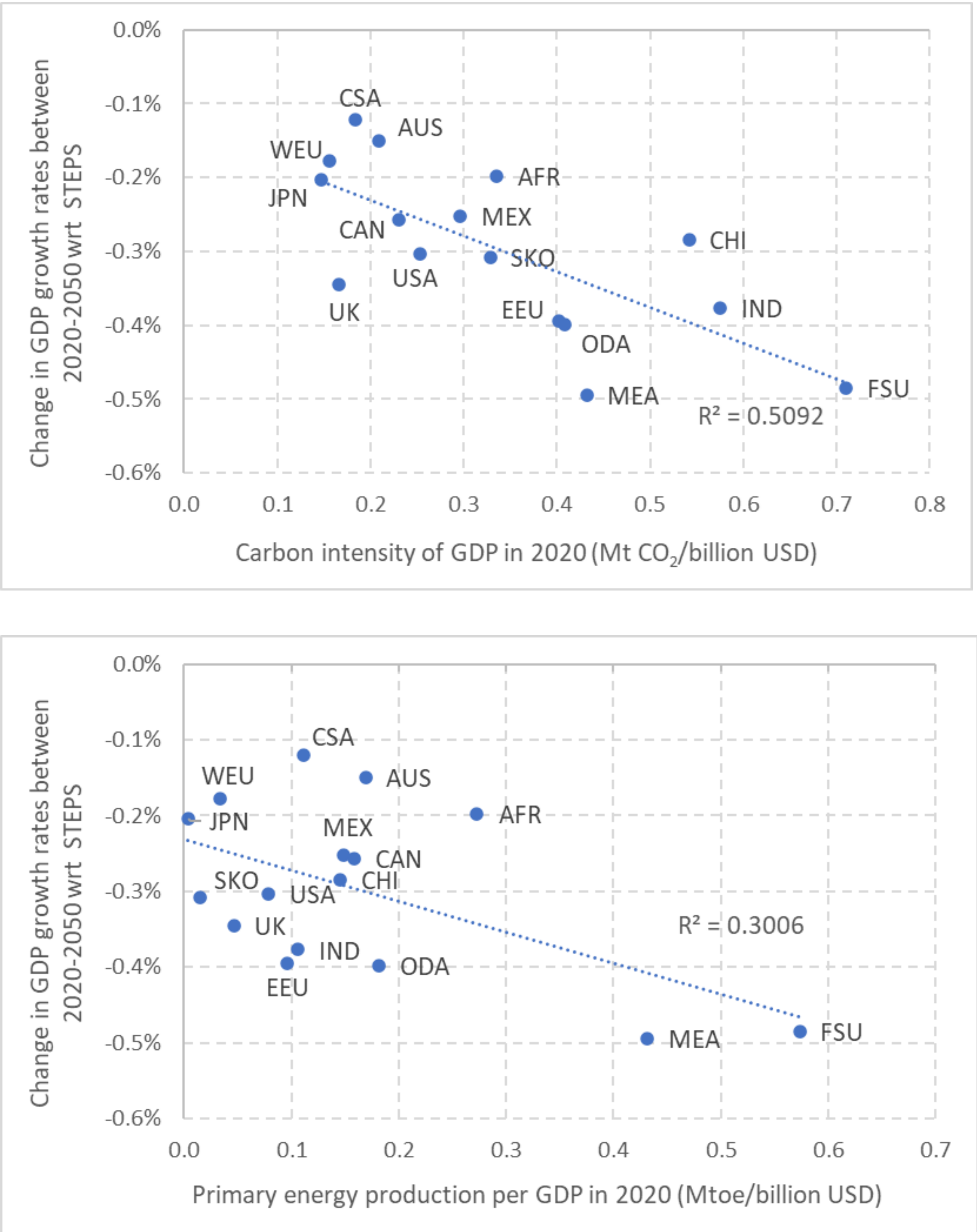


Figure 10 Changes in regional GDP growth rates between 2020-2050 compared to carbon intensity (top graph) and primary energy production (bottom graph) in 2020 under the *beyond SDS* scenario. Mitigation only scenario, which do not include economic benefits of mitigation from avoided climate change impacts. The growth rates are compound average annual growth rates. See appendix for regional description.

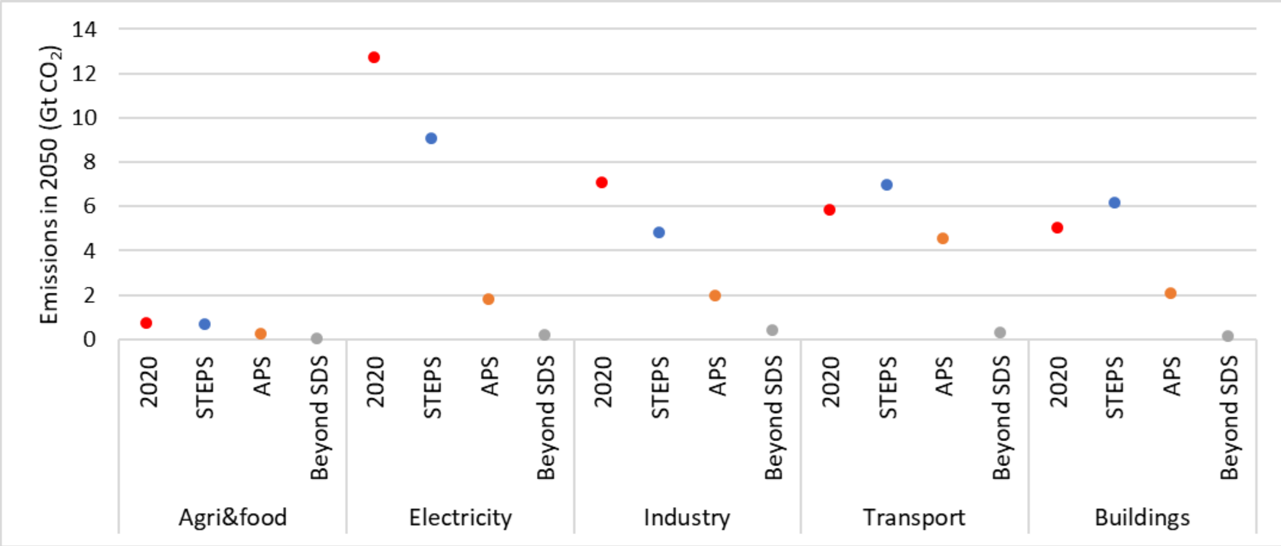


Figure 11 Global sectoral CO_2 emissions in 2050 by decarbonisation scenario. The graph shows only energy-related CO_2 emissions, process emissions and other GHG are not included. Mitigation only scenario. Household and government emissions are used as a proxy for emissions in the building sector.

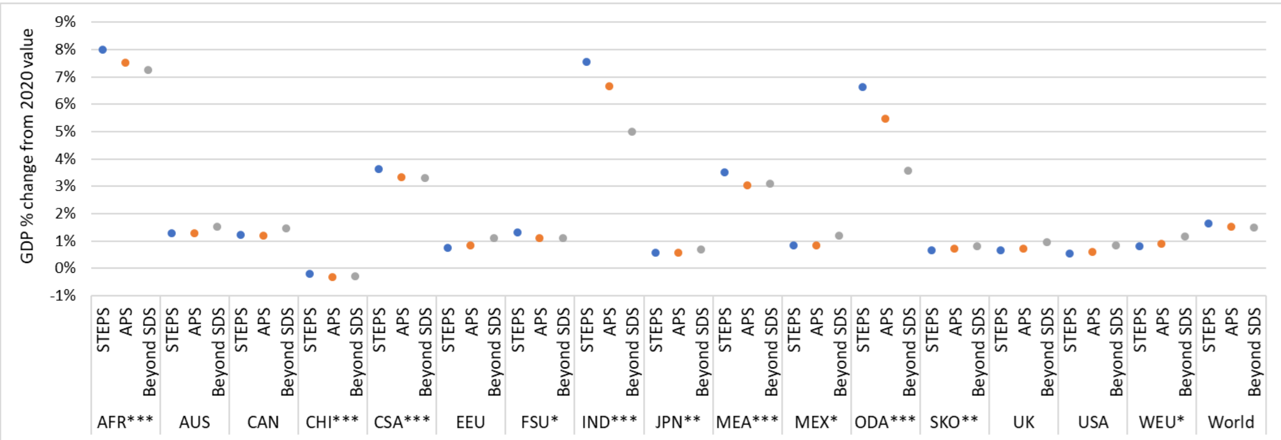


Figure 12 Regional economic costs of heat stress in 2050 by decarbonisation scenario. The 2050 costs are expressed as a percentage of GDP in 2020. The number of asterisks in a region's name indicate the number of sectors affected by heat stress: * agriculture, ** agriculture and industry, *** agriculture, industry and services. See appendix for regional description.

6. Policy implications and discussion

6.1 Impact of planned pathways on emissions, health and economy

Addressing climate change and achieving the temperature goal of the Paris Agreement require strengthened Nationally Determined Contributions (NDCs) to limit greenhouse gas (GHG) emissions and mitigate the risks of climate change. This not only has long-term health benefits but also offers substantial improvements to health in the present day. This analysis demonstrates that implementing mitigation actions, such as reducing emissions, tackling air pollution, promoting healthy diets, and encouraging active travel, across diverse countries with different geographic and development contexts, can lead to significant health improvements.

The consequences of failing to reach the Paris Agreement temperature goal could have substantial negative impacts on health, both because of direct impacts such as temperature increases and the unrealised co-benefits of mitigation. By embracing the broader objectives of the Paris Agreement and the Sustainable Development Goals (SDGs), substantial health gains can be achieved through increased access to clean energy, reduced household and outdoor air pollution, improved diets with reduced waste, and greater participation in active travel.

While acknowledging the existence of political, practical, institutional, and cultural barriers, it is crucial to emphasise the significance of prioritising health in the climate change discourse for the protection of population health. Poor air quality poses a significant burden on health, particularly among vulnerable communities worldwide. The health effects which result from air pollution are heavily dependent on national policy implementation. These have the potential to drive both reductions in emissions from fuel switching and pollution controls that align with the efforts required for meeting the Paris Agreement and addressing the SDGs. By reducing pollution from various sources such as electricity generation, household cooking, food and agriculture, industrial processes, and road transport, we can mitigate death and disease, especially among women and children. Among interventions reviewed from the literature and shown in the pathway diagram, the overall effect and the directionality (e.g. positive or negative) of the interventions are shown as broadly consistent across countries and present an opportunity for policy action to address harms and realize benefits. It may be the case that individual studies can show different impact outcomes, e.g. limited effect of cookstoves on indoor air pollution due to households use preferences, but these do not comprise the majority of the literature on the reviewed interventions and the pathways reflect this current evidence base.

Achieving high rates of walking and cycling while reducing car use necessitates urban planning that ensures sufficient population density, diverse land use, and the provision of safe and high-quality walking and cycling infrastructure, along with accessible public transport. It is crucial to avoid embedding sedentary lifestyles in travel practices, while also recognising the complexity of socioeconomic conditions and built environments across different countries and cities.

Likewise, improving health outcomes related to diets requires policymakers to address not only food-related factors but also the cultural, economic, and behavioural influences that shape dietary patterns. The challenge of food quality and availability, particularly among different populations and within complex food systems, poses a significant barrier to improving diets. National dietary patterns often conceal variations in caloric intake among individuals, particularly in low-income settings where inadequate nutrition and low food availability prevail. Consequently, achieving dietary changes at the population level necessitates substantial transformations in food systems.

From an economic and welfare perspective, the cost of climate change mitigation is directly related to the level of decarbonisation. It is crucial to recognise that decarbonising the economy aligns with a continuous trajectory of sustained economic growth over time. The Announced Policy Scenario (APS) results in a 62% reduction in global emissions compared to the Stated Policies Scenario (STEPS) by 2050, alongside an average annual GDP growth rate of 2.4% - even without including economic benefits of mitigation from avoided climate change impacts. Achieving emissions reductions in line with the Sustainable Development Scenario (SDS) results in an average annual growth rate of 2.3%. Regional mitigation costs vary greatly, with larger emissions reductions leading to wider regional impacts. The specific outcomes for each region depend on factors such as the pace of emissions reductions, carbon tax levels, energy mix, reliance on fossil fuels, development of renewable energy, industrial decarbonisation and electrification, and competitiveness changes induced by climate and energy policies in other regions. The current carbon intensity of GDP and primary energy production per unit of GDP significantly contribute to the projected impacts on GDP in 2050. Countries heavily reliant on fossil fuels not only face the costs of decarbonisation but also potential declines in export revenues.

Stronger mitigation measures help reduce the impact of heat stress on labour productivity and associated economic losses. Without adequate mitigation measures (STEPS), the global damage of heat stress as a share of 2020 GDP is around 1.7%, while the global damage in SDS is around 1.5% due to the limited increase in global temperature. Developing regions with tropical weather, such as Africa, Central and South America, India, the Middle East, and Other Developing Asia, are particularly vulnerable to the impacts of heat stress, with projected declines in GDP ranging from 1.5% to 2%.

Stronger mitigation actions may also have a direct impact on carbon emissions in the agriculture and food, electricity, and industry sectors, which are expected to decline by 2050 under all scenarios, while emissions in the transport and building sectors increase under STEPS but decline with stronger mitigation actions under APS and SDS.

6.2 Caveats

Several limitations should be considered in interpreting the study findings, and these limitations have further implications for understanding the potential impact of the research. The modelling conducted in our analysis is based on projections of potential resources, CO_2 emissions, and health effects based on plausible and policy relevant future scenarios. However, it is crucial to acknowledge the numerous uncertainties associated with such complex and multifactorial modelling – significant challenges exist in capturing these uncertainties using standard confidence estimates. Nevertheless, consideration of these uncertainties is given in the modelling appendices on page 65.

It is important to note that the models used here do not consider the interactions between each other. For example, the link between changing dietary risks and changing physical activity levels is not captured – and such a link could multiply both the climate and health increasing activity and eating healthier diets. Similarly, the interaction between increased activity levels and air pollution was not considered in these models. It is worth noting that as air pollution concentrations decrease, the benefits of active travel would increase. Equivalently, failing to act on air pollution might offset some of the benefits of increasing active travel. Therefore, the health impacts assessed here are non-additive. Further impacts, such as those resulting for differences in demographics within countries, such as gender or income levels, were also not considered. It is likely that optimal mitigation policy strategies would necessitate consideration of these differential impacts.

Additionally, it was not possible to harmonise the regional breakdown of the health modelling and economic modelling. Any effort to produce a bottom-up model across the domains considered here would require resources beyond those that were available for this activity.

Scenario feasibility is also an important source of uncertainty. The models used here do not assess the likelihood of achieving the necessary CO_2 reductions for each scenario provided by the IEA, for example. Accepted until otherwise proven wrong, the scenario outcomes which offer the highest benefits are potentially the most challenging to achieve. This is especially true when considering the magnitude of emissions reductions required by 2050 to meet the goal of the Paris Agreement.

As stated above, modelling of economic co-impacts of climate change mitigation does not take into account economic benefits of mitigation from avoided climate change impacts.

Finally, the scenarios assessed here do not include so called black swan events, which act to up-end the central features of the development pathway used as the basis of the modelling. The key example of this are events like the COVID-19 pandemic, which led to significant shifts in societal practice and impacted aggregate energy demand in a profound way. These impacts are still on-going, and may prove to be time limited, but it is likely that permanent shifts in working practices have resulted. Assessing the likelihood of further low-likelihood high impact events is outside the scope of this report.

6.3 Inclusion of co-impacts in climate change mitigation

The health and economic benefits derived from cleaner air, healthier diets, and active communities are apparent and applicable across various development and societal trajectories. However, these interactions are not yet fully integrated into climate policies, as there is limited reference to public health in current NDCs. Recognising and incorporating these co-benefits not only strengthens the case for further ambition in meeting the climate change commitments of the Paris Agreement but also creates opportunities for collaboration among health professionals, policymakers, engineers, energy experts, transport and agriculture specialists, and economists. Such collaborations ensure that human health becomes the fundamental consideration in all climate change policies. Adopting a health and welfare centred approach offers the opportunity to realise a range of co-benefits from climate actions, that can help build coalitions to support the transition to a net-zero carbon economy by creating benefits for a broader range of stakeholders.

Appendices

7. Appendix A: Methods

7.1 Model introduction

The overall structure of the modelling efforts is given in Figure 13. Subsequent sections of this appendix give details of the modelling approaches in each domain of health modelling, and of the approach taken to model economic co-impacts.

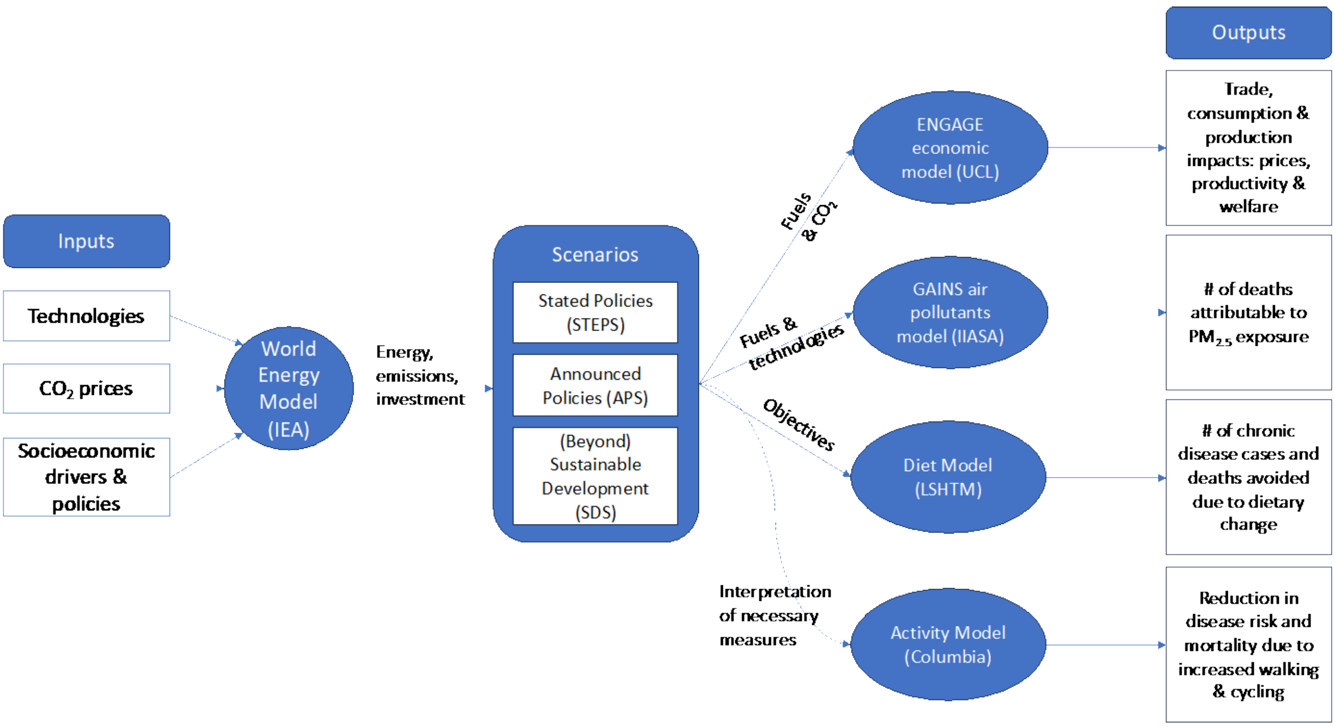


Figure 13 Schematic representation of model interrelations

7.2 Energy and CO_2 Emissions

The GEC Model is a comprehensive model that analyses the global energy uses several data input pathways to project future scenarios. To accurately represent energy supply, transformation, demand, and energy prices, the model utilizes data from the IEA's in-house databases of energy and economic data. In addition, it incorporates data from various external sources, often specific to particular sectors, to establish the historical size and energy-consuming stocks.

Every year, the model is recalibrated with the latest available data. While the formal base year is currently set as 2020, which provides a complete overview of energy demand and production, more recent data is incorporated where possible. This includes estimates for energy production and demand in 2021 and 2022. These estimates are based on updates from the Global Energy Review reports, which rely on a variety of sources such as the IEA Energy Data Centre's monthly data submissions, statistical releases from national administrations, and recent market data from the IEA Market Report Series covering coal, oil, natural gas, renewables, and electricity. UN population projections (2019) are used as a basis for understanding future populations in GEC model regions. Other input data which vary by scenario include fossil fuel prices, CO_2 prices where applicable, capital costs for technology development, and remaining recoverable fossil fuel stocks.

7.3 IEA scenarios (all data from IEA WEO 2021 under CC BY-NC-SA 3.0 IGO))

Table 5 Global energy supply for Stated Policy Scenario (STEPS)

	Stated Policies Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total energy supply	**544.7**	**613.0**	**589.1**	**671.0**	**714.8**	**743.9**	**100**	**100**	**100**	**1.3**	**0.8**
Renewables	47.7	65.8	68.5	109.0	153.0	192.5	12	16	26	4.8	3.5
Solar	0.8	4.0	4.7	15.9	30.0	43.5	1	2	6	13	7.7
Wind	1.2	5.1	5.7	14.4	23.5	31.3	1	2	4	9.6	5.8
Hydro	12.4	15.2	15.6	18.3	21.1	24.3	3	3	3	1.6	1.5
Modern solid bioenergy	27.3	31.1	31.8	41.6	49.3	54.7	5	6	7	2.7	1.8
Modern liquid bioenergy	2.4	4.1	3.8	7.1	9.7	11.9	1	1	2	6.5	3.9
Modern gaseous bioenergy	1.0	2.1	2.2	3.8	6.1	9.4	0	1	1	5.6	4.9
Other renewables	2.6	4.2	4.5	7.9	13.3	17.6	1	1	2	5.8	4.7
Traditional use of biomass	26.2	24.2	24.1	21.0	19.1	17.2	4	3	2	-1.3	-1.1
Nuclear	30.1	30.5	29.4	34.0	38.4	40.5	5	5	5	1.5	1.1
Unabated natural gas	115.1	141.4	138.7	155.9	168.0	174.0	24	23	23	1.2	0.8
Natural gas with CCUS	0.1	0.4	0.4	1.0	1.3	1.5	0	0	0	8.3	4.2
Oil	172.1	187.9	171.4	198.5	199.6	198.3	29	30	27	1.5	0.5
of which non-energy use	23.6	28.5	28.5	34.6	37.5	38.2	5	5	5	1.9	1.0
Unabated coal	153.0	162.2	155.8	150.2	132.9	116.8	26	22	16	-0.4	-1.0
Coal with CCUS	0.0	0.0	0.0	0.2	0.8	1.0	0	0	0	35	18
Electricity and heat sectors	**199.8**	**233.5**	**230.5**	**253.5**	**280.0**	**301.9**	**100**	**100**	**100**	**1.0**	**0.9**
Renewables	21.2	35.7	38.1	66.9	100.4	131.3	17	26	43	5.8	4.2
Solar PV	0.1	2.5	3.0	12.6	24.1	34.8	1	5	12	15	8.5
Wind	1.2	5.1	5.7	14.4	23.5	31.3	2	6	10	9.6	5.8
Hydro	12.4	15.2	15.6	18.3	21.1	24.3	7	7	8	1.6	1.5
Bioenergy	5.1	9.5	10.1	15.0	19.2	23.2	4	6	8	4.1	2.8
Other renewables	2.4	3.4	3.6	6.7	12.6	17.7	2	3	6	6.4	5.5
Hydrogen	0.0	0.0	0.0	0.0	0.1	0.1	0	0	0	n.a.	n.a.
Ammonia	0.0	0.0	0.0	0.0	0.2	0.3	0	0	0	n.a.	n.a.
Nuclear	30.1	30.5	29.4	34.0	38.4	40.5	13	13	13	1.5	1.1
Unabated natural gas	46.7	55.7	55.1	57.3	60.8	63.3	24	23	21	0.4	0.5
Natural gas with CCUS	0.0	0.0	0.0	0.1	0.1	0.1	0	0	0	n.a.	n.a.
Oil	10.9	8.2	7.9	5.4	4.3	3.4	3	2	1	-3.7	-2.8
Unabated coal	91.0	103.3	100.0	89.6	75.1	62.0	43	35	21	-1.1	-1.6
Coal with CCUS	0.0	0.0	0.0	0.1	0.7	1.0	0	0	0	36	19
Other energy sector	**54.2**	**59.1**	**58.1**	**66.9**	**72.4**	**76.7**	**100**	**100**	**100**	**1.4**	**0.9**
Hydrogen production	0.0	0.0	0.0	0.4	1.3	2.2	0	1	3	n.a.	n.a.
Biofuels production	2.6	4.1	4.5	11.6	16.8	20.0	8	17	26	9.9	5.1

Table 6 Global energy supply for Announced Pledges Scenario (APS)

	Announced Pledges Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total energy supply	**544.7**	**613.0**	**589.1**	**651.1**	**670.4**	**674.4**	**100**	**100**	**100**	**1.0**	**0.5**
Renewables	47.7	65.8	68.5	120.6	194.4	248.4	12	19	37	5.8	4.4
Solar	0.8	4.0	4.7	19.1	42.3	64.2	1	3	10	15	9.1
Wind	1.2	5.1	5.7	18.0	37.4	51.4	1	3	8	12	7.6
Hydro	12.4	15.2	15.6	18.3	21.5	24.7	3	3	4	1.6	1.5
Modern solid bioenergy	27.3	31.1	31.8	42.4	57.4	62.0	5	7	9	2.9	2.2
Modern liquid bioenergy	2.4	4.1	3.8	9.9	12.9	14.8	1	2	2	10	4.6
Modern gaseous bioenergy	1.0	2.1	2.2	4.4	8.3	11.9	0	1	2	7.2	5.8
Other renewables	2.6	4.2	4.5	8.5	14.5	19.5	1	1	3	6.6	5.0
Traditional use of biomass	26.2	24.2	24.1	20.7	18.8	17.1	4	3	3	-1.5	-1.1
Nuclear	30.1	30.5	29.4	35.8	44.1	48.5	5	5	7	2.0	1.7
Unabated natural gas	115.1	141.4	138.7	143.6	127.4	119.1	24	22	18	0.3	-0.5
Natural gas with CCUS	0.1	0.4	0.4	2.9	8.7	14.1	0	0	2	20	12
Oil	172.1	187.9	171.4	185.1	162.4	147.6	29	28	22	0.8	-0.5
of which non-energy use	23.6	28.5	28.5	33.7	34.3	33.9	5	5	5	1.7	0.6
Unabated coal	153.0	162.2	155.8	140.9	101.5	62.7	26	22	9	-1.0	-3.0
Coal with CCUS	0.0	0.0	0.0	0.6	12.0	15.6	0	0	2	55	29
Electricity and heat sectors	**199.8**	**233.5**	**230.5**	**252.6**	**295.7**	**323.6**	**100**	**100**	**100**	**0.9**	**1.1**
Renewables	21.2	35.7	38.1	75.1	131.0	177.7	17	30	55	7.0	5.3
Solar PV	0.1	2.5	3.0	15.1	33.3	51.1	1	6	16	18	9.9
Wind	1.2	5.1	5.7	18.0	37.4	51.4	2	7	16	12	7.6
Hydro	12.4	15.2	15.6	18.3	21.5	24.7	7	7	8	1.6	1.5
Bioenergy	5.1	9.5	10.1	16.2	23.5	29.0	4	6	9	4.9	3.6
Other renewables	2.4	3.4	3.6	7.5	15.1	21.5	2	3	7	7.6	6.1
Hydrogen	0.0	0.0	0.0	0.6	2.3	3.1	0	0	1	n.a.	n.a.
Ammonia	0.0	0.0	0.0	0.0	0.2	0.5	0	0	0	n.a.	n.a.
Nuclear	30.1	30.5	29.4	35.8	44.1	48.5	13	14	15	2.0	1.7
Unabated natural gas	46.7	55.7	55.1	52.9	44.8	44.5	24	21	14	-0.4	-0.7
Natural gas with CCUS	0.0	0.0	0.0	0.6	2.4	4.2	0	0	1	n.a.	n.a.
Oil	10.9	8.2	7.9	4.9	3.9	3.1	3	2	1	-4.6	-3.0
Unabated coal	91.0	103.3	100.0	82.2	58.2	29.9	43	33	9	-1.9	-3.9
Coal with CCUS	0.0	0.0	0.0	0.5	8.8	12.1	0	0	4	57	30
Other energy sector	**54.2**	**59.1**	**58.1**	**65.9**	**75.1**	**79.1**	**100**	**100**	**100**	**1.3**	**1.0**
Hydrogen production	0.0	0.0	0.0	2.5	13.7	22.7	0	4	29	n.a.	n.a.
Biofuels production	2.6	4.1	4.5	10.6	16.1	21.6	8	16	27	8.9	5.3

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Table 7 Global energy supply for Sustainable Development Scenario (SDS)

	Sustainable Development Scenario (EJ)						Shares (%)			CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2020	2030	2050	2030	2050
Total energy supply	**544.7**	**613.0**	**589.1**	**599.2**	**580.5**	**577.9**	**100**	**100**	**100**	**0.2**	**-0.1**
Renewables	47.7	65.8	68.5	142.7	238.6	316.4	12	24	55	7.6	5.2
Solar	0.8	4.0	4.7	23.8	55.2	86.3	1	4	15	17	10
Wind	1.2	5.1	5.7	21.6	45.7	62.9	1	4	11	14	8.3
Hydro	12.4	15.2	15.6	19.4	23.8	28.5	3	3	5	2.2	2.0
Modern solid bioenergy	27.3	31.1	31.8	48.8	66.5	74.4	5	8	13	4.4	2.9
Modern liquid bioenergy	2.4	4.1	3.8	12.3	16.3	18.7	1	2	3	12	5.5
Modern gaseous bioenergy	1.0	2.1	2.2	4.9	9.1	13.5	0	1	2	8.2	6.2
Other renewables	2.6	4.2	4.5	12.0	22.0	32.1	1	2	6	10	6.8
Traditional use of biomass	26.2	24.2	24.1	0.0	0.0	0.0	4	0	0	n.a.	n.a.
Nuclear	30.1	30.5	29.4	37.0	46.8	51.4	5	6	9	2.3	1.9
Unabated natural gas	115.1	141.4	138.7	134.6	93.2	59.4	24	22	10	-0.3	-2.8
Natural gas with CCUS	0.1	0.4	0.4	4.7	14.7	25.8	0	1	4	27	14
Oil	172.1	187.9	171.4	168.3	124.8	89.4	29	28	15	-0.2	-2.1
of which non-energy use	23.6	28.5	28.5	32.7	32.6	31.0	5	5	5	1.4	0.3
Unabated coal	153.0	162.2	155.8	107.6	46.6	16.9	26	18	3	-3.6	-7.1
Coal with CCUS	0.0	0.0	0.0	3.4	15.0	17.9	0	1	3	84	29
Electricity and heat sectors	**199.8**	**233.5**	**230.5**	**242.4**	**277.1**	**327.6**	**100**	**100**	**100**	**0.5**	**1.2**
Renewables	21.2	35.7	38.1	88.1	165.0	234.1	17	36	71	8.8	6.2
Solar PV	0.1	2.5	3.0	18.0	40.6	62.8	1	7	19	20	11
Wind	1.2	5.1	5.7	21.6	45.7	62.9	2	9	19	14	8.3
Hydro	12.4	15.2	15.6	19.4	23.8	28.5	7	8	9	2.2	2.0
Bioenergy	5.1	9.5	10.1	18.0	29.2	38.7	4	7	12	6.0	4.6
Other renewables	2.4	3.4	3.6	11.2	25.7	41.2	2	5	13	12	8.5
Hydrogen	0.0	0.0	0.0	0.6	2.4	3.3	0	0	1	n.a.	n.a.
Ammonia	0.0	0.0	0.0	0.0	0.3	3.2	0	0	1	n.a.	n.a.
Nuclear	30.1	30.5	29.4	37.0	46.8	51.4	13	15	16	2.3	1.9
Unabated natural gas	46.7	55.7	55.1	51.3	29.9	17.1	24	21	5	-0.7	-3.8
Natural gas with CCUS	0.0	0.0	0.0	0.7	3.2	5.1	0	0	2	n.a.	n.a.
Oil	10.9	8.2	7.9	3.8	2.2	1.6	3	2	0	-7.1	-5.2
Unabated coal	91.0	103.3	100.0	58.3	16.5	0.7	43	24	0	-5.3	-15
Coal with CCUS	0.0	0.0	0.0	2.5	10.9	11.1	0	1	3	86	29
Other energy sector	**54.2**	**59.1**	**58.1**	**61.6**	**69.2**	**77.5**	**100**	**100**	**100**	**0.6**	**1.0**
Hydrogen production	0.0	0.0	0.0	4.0	17.3	34.6	0	7	45	n.a.	n.a.
Biofuels production	2.6	4.1	4.5	10.3	16.0	19.9	8	17	26	8.6	5.1

Table 8 Global CO_2 emissions Stated Policies Scenario (STEPS)

	Stated Policies Scenario (Mt CO_2)						CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2030	2050
Total CO_2*	**32 345**	**35 966**	**34 156**	**36 267**	**35 312**	**33 903**	**0.6**	**-0.0**
Combustion activities (+)	**30 447**	**33 464**	**31 617**	**33 353**	**32 305**	**30 940**	**0.5**	**-0.1**
Coal	13 828	14 768	14 240	13 487	11 857	10 277	-0.5	-1.1
Oil	10 530	11 344	10 123	11 693	11 590	11 468	1.5	0.4
Natural gas	6 040	7 270	7 165	8 091	8 779	9 123	1.2	0.8
Bioenergy and waste	49	82	89	83	79	72	-0.7	-0.7
Industry removals (-)	**0**	**0**	**1**	**1**	**1**	**1**	**0.0**	**0.0**
Biofuels production	0	0	1	1	1	1	0.0	0.0
Direct air capture	0	0	0	0	0	0	n.a.	n.a.
Electricity and heat sectors	**12 380**	**13 933**	**13 530**	**12 425**	**11 116**	**9 915**	**-0.8**	**-1.0**
Coal	8 933	10 171	9 832	8 791	7 373	6 100	-1.1	-1.6
Oil	826	626	601	412	325	256	-3.7	-2.8
Natural gas	2 621	3 136	3 097	3 222	3 418	3 559	0.4	0.5
Bioenergy and waste	0	0	0	0	0	0	n.a.	n.a.
Other energy sector*	**1 434**	**1 565**	**1 435**	**1 725**	**1 770**	**1 786**	**1.9**	**0.7**
Final consumption*	**18 530**	**20 467**	**19 191**	**22 118**	**22 425**	**22 202**	**1.4**	**0.5**
Coal	4 692	4 464	4 288	4 563	4 358	4 058	0.6	-0.2
Oil	9 075	10 106	8 967	10 700	10 719	10 718	1.8	0.6
Natural gas	2 836	3 395	3 380	3 993	4 422	4 568	1.7	1.0
Bioenergy and waste	48	82	89	83	80	72	-0.7	-0.7
Industry*	8 191	8 876	8 736	10 078	10 309	10 068	1.4	0.5
Iron and steel	1 989	2 500	2 591	2 945	2 861	2 743	1.3	0.2
Chemicals	1 143	1 182	1 160	1 382	1 456	1 428	1.8	0.7
Cement	1 921	2 455	2 534	2 774	2 771	2 630	0.9	0.1
Transport	7 010	8 211	7 102	8 886	9 082	9 229	2.3	0.9
Road	5 217	6 043	5 419	6 391	6 311	6 194	1.7	0.4
Passenger cars	2 615	3 192	2 788	3 003	2 862	2 688	0.7	-0.1
Heavy-duty trucks	1 420	1 673	1 532	2 190	2 415	2 638	3.6	1.8
Aviation	751	1 027	606	1 242	1 463	1 631	7.4	3.4
Shipping	796	866	811	999	1 063	1 171	2.1	1.2
Buildings	2 891	2 941	2 917	2 706	2 596	2 494	-0.7	-0.5
Residential	1 963	2 023	1 958	1 760	1 625	1 557	-1.1	-0.8
Services	928	918	960	946	971	937	-0.1	-0.1
Total CO_2 removals	**0**	**0**	**1**	**1**	**1**	**1**	**1.8**	**1.6**
Total CO_2 captured	**4**	**40**	**40**	**89**	**176**	**228**	**8.3**	**6.0**

Table 9 Global CO_2 emissions for Announced Pledges Scenario (APS)

	Announced Pledges Scenario (Mt CO_2)						CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2030	2050
Total CO_2*	**32 345**	**35 966**	**34 156**	**33 640**	**26 722**	**20 726**	**-0.2**	**-1.7**
Combustion activities (+)	**30 447**	**33 464**	**31 617**	**30 822**	**24 634**	**19 471**	**-0.3**	**-1.6**
Coal	13 828	14 768	14 240	12 614	9 235	5 713	-1.2	-3.0
Oil	10 530	11 344	10 123	10 754	9 041	7 988	0.6	-0.8
Natural gas	6 040	7 270	7 165	7 415	6 521	6 087	0.3	-0.5
Bioenergy and waste	49	82	89	40	- 164	- 317	-7.8	n.a.
Industry removals (-)	**0**	**0**	**1**	**35**	**193**	**518**	**46**	**24**
Biofuels production	0	0	1	33	142	361	45	23
Direct air capture	0	0	0	2	50	157	n.a.	n.a.
Electricity and heat sectors	**12 380**	**13 933**	**13 530**	**11 375**	**8 424**	**5 506**	**-1.7**	**-3.0**
Coal	8 933	10 171	9 832	8 056	5 787	3 045	-2.0	-3.8
Oil	826	626	601	374	298	238	-4.6	-3.0
Natural gas	2 621	3 136	3 097	2 976	2 531	2 524	-0.4	-0.7
Bioenergy and waste	0	0	0	- 32	- 193	- 301	n.a.	n.a.
Other energy sector*	**1 434**	**1 565**	**1 435**	**1 570**	**1 160**	**726**	**0.9**	**-2.2**
Final consumption*	**18 530**	**20 467**	**19 191**	**20 696**	**17 188**	**14 650**	**0.8**	**-0.9**
Coal	4 692	4 464	4 288	4 436	3 362	2 635	0.3	-1.6
Oil	9 075	10 106	8 967	9 865	8 357	7 451	1.0	-0.6
Natural gas	2 836	3 395	3 380	3 598	3 219	2 807	0.6	-0.6
Bioenergy and waste	48	82	89	72	29	- 16	-2.2	n.a.
Industry*	8 191	8 876	8 736	9 661	7 958	6 483	1.0	-1.0
Iron and steel	1 989	2 500	2 591	2 871	2 325	1 964	1.0	-0.9
Chemicals	1 143	1 182	1 160	1 301	1 009	755	1.1	-1.4
Cement	1 921	2 455	2 534	2 707	2 175	1 642	0.7	-1.4
Transport	7 010	8 211	7 102	8 149	7 012	6 339	1.4	-0.4
Road	5 217	6 043	5 419	5 889	4 855	4 338	0.8	-0.7
Passenger cars	2 615	3 192	2 788	2 725	2 135	1 889	-0.2	-1.3
Heavy-duty trucks	1 420	1 673	1 532	2 040	1 865	1 734	2.9	0.4
Aviation	751	1 027	606	1 147	1 205	1 145	6.6	2.1
Shipping	796	866	811	909	781	702	1.1	-0.5
Buildings	2 891	2 941	2 917	2 476	1 902	1 589	-1.6	-2.0
Residential	1 963	2 023	1 958	1 670	1 235	1 027	-1.6	-2.1
Services	928	918	960	806	667	562	-1.7	-1.8
Total CO_2 removals	**0**	**0**	**1**	**67**	**409**	**885**	**54**	**26**
Total CO_2 captured	**4**	**40**	**40**	**350**	**2 501**	**3 813**	**24**	**16**

Table 10 Global CO_2 for Sustainable Development Scenario (SDS)

	Sustainable Development Scenario (Mt CO_2)						CAAGR (%) 2020 to:	
	2010	2019	2020	2030	2040	2050	2030	2050
Total CO_2*	**32 345**	**35 966**	**34 156**	**28 487**	**16 441**	**8 170**	**-1.8**	**-4.7**
Combustion activities (+)	**30 447**	**33 464**	**31 617**	**26 049**	**14 924**	**7 807**	**-1.9**	**-4.6**
Coal	13 828	14 768	14 240	9 493	4 034	1 395	-4.0	-7.5
Oil	10 530	11 344	10 123	9 571	6 413	3 986	-0.6	-3.1
Natural gas	6 040	7 270	7 165	6 931	4 645	2 799	-0.3	-3.1
Bioenergy and waste	49	82	89	54	- 168	- 373	-5.0	n.a.
Industry removals (-)	**0**	**0**	**1**	**73**	**234**	**643**	**57**	**25**
Biofuels production	0	0	1	64	181	419	55	23
Direct air capture	0	0	0	10	53	224	n.a.	n.a.
Electricity and heat sectors	**12 380**	**13 933**	**13 530**	**8 891**	**3 376**	**887**	**-4.1**	**-8.7**
Coal	8 933	10 171	9 832	5 741	1 733	179	-5.2	-12
Oil	826	626	601	290	168	121	-7.0	-5.2
Natural gas	2 621	3 136	3 097	2 888	1 698	990	-0.7	-3.7
Bioenergy and waste	0	0	0	- 28	- 223	- 403	n.a.	n.a.
Other energy sector*	**1 434**	**1 565**	**1 435**	**1 296**	**681**	**101**	**-1.0**	**-8.5**
Final consumption*	**18 530**	**20 467**	**19 191**	**18 311**	**12 437**	**7 406**	**-0.5**	**-3.1**
Coal	4 692	4 464	4 288	3 637	2 226	1 190	-1.6	-4.2
Oil	9 075	10 106	8 967	8 850	5 996	3 719	-0.1	-2.9
Natural gas	2 836	3 395	3 380	3 345	2 461	1 462	-0.1	-2.8
Bioenergy and waste	48	82	89	82	56	30	-0.8	-3.5
Industry*	8 191	8 876	8 736	8 377	5 874	3 447	-0.4	-3.1
Iron and steel	1 989	2 500	2 591	2 574	1 745	1 027	-0.1	-3.0
Chemicals	1 143	1 182	1 160	1 169	873	440	0.1	-3.2
Cement	1 921	2 455	2 534	2 552	1 635	755	0.1	-4.0
Transport	7 010	8 211	7 102	7 348	5 112	3 239	0.3	-2.6
Road	5 217	6 043	5 419	5 343	3 468	1 996	-0.1	-3.3
Passenger cars	2 615	3 192	2 788	2 425	1 356	617	-1.4	-4.9
Heavy-duty trucks	1 420	1 673	1 532	1 866	1 457	1 076	2.0	-1.2
Aviation	751	1 027	606	1 028	968	797	5.4	0.9
Shipping	796	866	811	809	564	372	-0.0	-2.6
Buildings	2 891	2 941	2 917	2 249	1 238	599	-2.6	-5.1
Residential	1 963	2 023	1 958	1 582	891	419	-2.1	-5.0
Services	928	918	960	667	347	180	-3.6	-5.4
Total CO_2 removals	**0**	**0**	**1**	**103**	**466**	**1 076**	**60**	**27**
Total CO_2 captured	**4**	**40**	**40**	**892**	**3 461**	**5 404**	**36**	**18**

7.4 Health modelling

The modelling of attributable mortality relating to air pollution, dietary risks, and active travel derive aspects of their core methodology from the Global Burden of Disease (GBD). While the specifics of this process differ in their detail, as described in the following sections, the relative impact on global populations of these three domains over the last 30 years are summarised in Figure 14. This shows that of the three domains, dietary risks have the largest associated burden, followed by air pollution. Low physical activity, as modelled by the GBD, has the lowest relative summary exposure value.

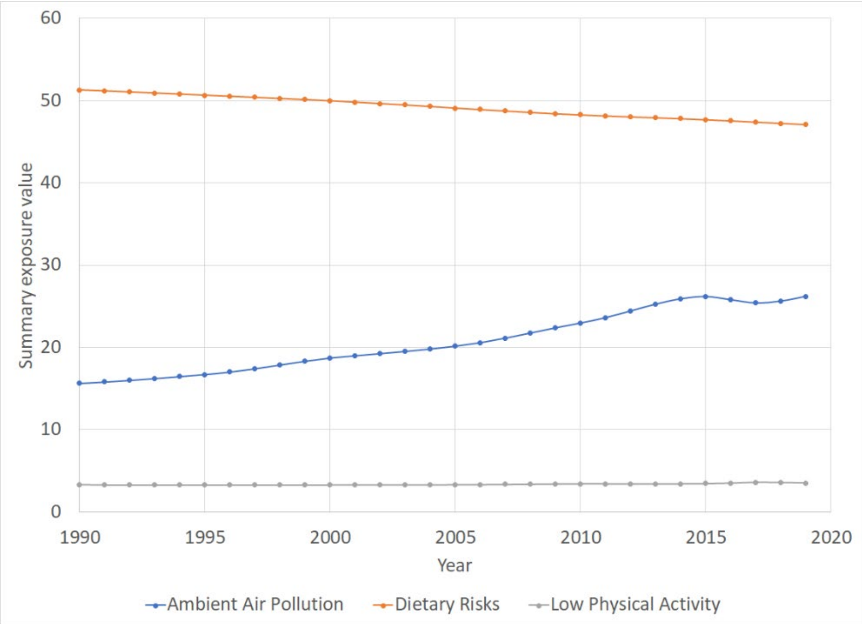

Figure 14 Historic rate of change of age-adjusted summary exposure values for low physical activity, ambient air pollution and dietary risks (Institute for Health Metrics and Evaluation, 2023)

7.4.1 Air pollution

The GAINS (Greenhouse gas-Air Pollution Interactions and Synergies) model is designed to investigate efficient and economical strategies for controlling multiple pollutants while achieving environmental goals related to air quality impacts on human health and ecosystems, as well as greenhouse gas emissions. Developed by the International Institute for Applied Systems Analysis (IIASA), GAINS integrates various data sets, including information on economic development, emission sources' characteristics, control capabilities, and costs, as well as the formation, dispersion, and environmental consequences of pollutants in the atmosphere. By incorporating these factors, the model facilitates a comprehensive assessment of pollution's environmental effects.

In its broadest instance, GAINS can analyse various air pollution impacts on human health, including those stemming from fine particulate matter (this report) and ground-level ozone. It has also been utilized to assess vegetation damage caused by ground-level ozone, the acidification of terrestrial and aquatic ecosystems, excess nitrogen deposition to soils, and the mitigation of greenhouse gas emissions. The model effectively captures the interdependencies among these different effects and the pollutants (SO_2, NOx, PM, NMVOC, NH_3, CO_2, CH_4, N_2O, F-gases) responsible for generating them at a regional level.

For this study, the global version of the GAINS model is employed, featuring a spatially disaggregated representation of 180 source regions worldwide. These regions encompass countries, provinces, or sub-national aggregates. Specifically, China is depicted at the provincial level with 35 provinces, India is represented by 23 aggregates of states/union territories, the USA encompasses the mainland and Alaska, while all other countries are treated as individual entities.

The GEC model provided by the IEA supplies activity projections within its respective native regions, sectors, and fuel breakdown (IEA, World Energy model, 2019).These projections are then translated into the GAINS model's region, sector, and fuel classification using the proportional downscaling algorithm outlined in the work of Rafaj et al. (Rafaj, Schöpp, Russ, Heyes, & Amann, 2013) (Rafaj, et al., 2018).The output of the IEA's GEC model under the scenarios considered here generates the future trajectory of the energy system, taking into account diverse climate and energy policies across subsectors such as power generation, fuel extraction and conversion, industry, transport, and buildings. It is important to note that the GEC model encompasses not only combustion-related activities but also includes projections for industrial processes like iron and steel production, cement manufacturing, and aluminium production. In cases where specific emission sources are not explicitly represented in the GEC model, they are estimated based on socio-economic factors such as population growth, economic trends, and sector-specific value added. Examples of emitting sectors in the GAINS model that are not explicitly covered by the GEC model include livestock populations, burning of agricultural residues, waste generation, brick production, and other industrial process activities.

The GEC projection's energy consumption data is distributed among GAINS sub-regions (countries, states, provinces) using shares derived from international and national energy and industrial statistics (Amann, et al., 2017) (Bhanarkar, et al., 2018) (Cofala, et al., 2015) (Purohit, et al., 2010).The downscaling procedure also assigns energy consumption to detailed subsectors and fuel types in GAINS, including various transport sub-categories, industrial demand activities (such as furnaces/boilers), and fuel processing and conversion.

The spatial patterns of PM (particulate matter) and its precursors emissions for each key source sector are estimated at a resolution of $0.5^0 \times 0.5^0$ longitude-latitude. These estimates are based on relevant proxy variables (updated from (Klimont, et al., 2017)) and rely on the most recent updates of data on population distribution, road networks, plant locations, open biomass burning, and other related factors that were initially developed within the Global Energy Assessment project (GEA, 2012). Additionally, for the residential sector, a more detailed emission distribution map has been created at a resolution of 0.1^0, which combines fine-grained gridded population data with urban-rural classification and estimates of the prevalence of different fuel use in urban and rural areas.

For detailed discussion of the specific treatment of CO_2 see Amann, M., et al., 2008 (Amann, Bertok, Borken-Kleefeld, & Cofala, 2008). Additional GHGs (CH_4, N_2O, HFCs,PFCs,SF_6) are considered via internally consistent analyses of technical mitigation potentials for global non-CO_2 GHGs to 2050 (Höglund-Isaksson, Gómez-Sanabria, Klimont, Rafaj, & Schöpp, 2020) (Purohit & Isaksson, 2017) (Winiwarter, Höglund-Isaksson, Klimont, Schöpp, & Amann, 2018).

Ambient PM2.5 and health impact calculations

The use of GAINS to model ambient PM2.5 concentrations is outlined in Amann et al. (Amann, et al., 2011). The history of the development of the GAINS modelling approach means that there are slight differences between the way it is implemented for European regions compared to the rest of the world, as described below. Nevertheless, all versions use perturbation simulations of atmospheric chemistry transport models. Emissions from a specific region and pollutant are reduced from the base case, and the resulting change in ambient concentration levels is used to calculate a linear transfer coefficient. Source pollutants for PM2.5 formation include primary PM2.5 (parts per million – PPM), SO_2, NOx, NH_3, and VOC. PPM transfer coefficients are divided into low-level emissions from traffic and residential combustion, and emissions from other sources, to take account of varying dispersion characteristics at different injection heights. The calculations for ambient PM2.5 concentrations in Europe are described by papers by Kiesewetter et al. (Kiesewetter, Schoepp, Heyes, & Amann, 2015) (Kiesewetter, et al., 2015). Calculations outside Europe are described Amann et al. (Amann, et al., 2017).

The Global Burden of Disease studies provide the methodology for calculating deaths from total ambient PM2.5 for regions other than Europe. Meta-regression—Bayesian, regularised, trimmed (MR-BRT) curves were used to calculate relative risk for six diseases associated with particulate exposure: Chronic Obstructive Pulmonary Disease, Ischemic Heart disease, stroke, lung cancer, type 2 diabetes, and acute lower respiratory infection. Exposure levels below the theoretical minimum exposure level were given RR=1.

The GBD results database (Institute for Health Metrics and Evaluation, 2023) provided disease and age specific baseline mortality rates. Future populations were based on UN World Population Prospects (2017 update). For Europe the method differs slightly, concentration-response relationships follow 2021 WHO Air Quality Guidelines (WHO, 2021) and exposure-response relationships are used for all-cause non-accidental mortality among the total population over 30 years of age.

7.4.2 Sustainable diets

The core approach to estimate dietary risks is based on the approach published by Springmann and colleagues (Springmann, et al., 2018) (Springmann, Wiebe, Mason-D'Croz, Sulser, & Mike Rayner, 2018). Baseline food consumption was approximated by utilizing FAO's food balance sheets to estimate food availability, which was then adjusted to account for food wastage during consumption. This estimation of food consumption was further broken down by age and sex, using age and sex-specific trends observed in dietary surveys. The food waste methodology is based on that developed by the FAO (FAO, 2011).

Baseline and projected food intake were estimated by adapting food demand projections from the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) themselves derived from a harmonised dataset of country-specific food availability data. These were further adjusted for household food waste (Robinson, et al., 2015) (Gustavsson, Cederberg, & Sonesson, 2011). These projections provide the basis for the benchmark BMK scenario.

Comparative risk analysis was based on publicly available data. Mortality and population data were adopted from the Global Burden of Disease project, with projections through to 2050 parameterized under the SSP2 development pathway (Wang, et al., 2020). Weight distributions for the baseline were adopted from a pooled analysis of population-based measurements undertaken by the NCD Risk Factor Collaboration (N. C. D. Risk Factor Collaboration., 2013). The prevalence of obese, overweight and underweight in each population was estimated by fitting a log-normal distribution to WHO estimates of mean BMI (Springmann, et al., 2016) with projects based on correlations between BMI and food availability.

Health analysis

A comparative risk assessment across framework nine risk factors and five disease endpoints was employed to analyse the implications of future dietary change that were constructed (Murray, 2001). The risk factors included are:

- high consumption of red meat

- low consumption of fruits,
- low consumption of vegetables,
- low consumption of nuts and seeds
- low consumption of legumes
- being underweight (BMI<18.5)
- being overweight (25<BMI<30)
- being obese (BMI>30)

The disease endpoints included coronary heart disease (CHD), stroke, type-2 diabetes mellitus (T2DM), cancer (in aggregate and as colon and rectum cancers), and respiratory disease (which is associated with changes in weight).

The formulae employed in these projections are outlined in equivalent analysis for recent years in the Lancet Countdown (Romanello, et al., 2022). An overview of the relative-risk parameters used the analysis is given in Table 11. Relative risk estimates that link risk factors to disease prevalence were derived from meta-analyses of a comprehensive pool of prospective cohort studies (Afshin, Micha, Khatibzadeh, & Mozaffarian, 2014) (Aune, et al., 2016) (Aune, Giovannucci, Boffetta, Fadnes, & Keum, 2016) (Bechthold, Boeing, Schwedhelm, Hoffmann, & Knüppel, 2019) (Schwingshackl, et al., 2017) (Zheng, et al., 2012) (Global BMI Mortality Collaboration, 2016). These meta-analyses suggest a non-linear dose-response relationships for nuts and seeds, and fruits and vegetables, and use a linear dose-response relationships for the remaining risk factors by assumption. Adults ages over 20 years of age are used, since chronic diseases are the main endpoint of dietary risk factors. Relative-risk estimates were adjusted for attenuation with age based on a pooled analysis of cohort studies focussed on metabolic risk factors (Singh, et al., 2013) in line with other assessments (GBD 2013 Risk Factors Collaborators, 2015) (Micha, et al., 2017).

Table 11 Relative risk parameters (mean and low and high values of 95% confidence intervals) for dietary risks and weight-related risks.

Food group	Endpoint	Unit	RR mean	RR low	RR high	Reference
Processed meat	CHD	50 g/d	1.27	1.09	1.49	Bechthold et al (2019)
	Stroke	50 g/d	1.17	1.02	1.34	Bechthold et al (2019)
	Colorectal cancer	50 g/d	1.17	1.10	1.23	Schwingshackl et al (2018)
	Type 2 diabetes	50 g/d	1.37	1.22	1.55	Schwingshackl et al (2017)
Red meat	CHD	100 g/d	1.15	1.08	1.23	Bechthold et al (2019)
	Stroke	100 g/d	1.12	1.06	1.17	Bechthold et al (2019)
	Colorectal cancer	100 g/d	1.12	1.06	1.19	Schwingshackl et al (2018)
	Type 2 diabetes	100 g/d	1.17	1.08	1.26	Schwingshackl et al (2017)
Fruits	CHD	100 g/d	0.95	0.92	0.99	Aune et al (2017)
	Stroke	100 g/d	0.77	0.70	0.84	Aune et al (2017)
	Cancer	100 g/d	0.94	0.91	0.97	Aune et al (2017)
Vegetables	CHD	100 g/d	0.84	0.80	0.88	Aune et al (2017)
	Cancer	100 g/d	0.93	0.91	0.95	Aune et al (2017)
Legumes	CHD	57 g/d	0.86	0.78	0.94	Afshin et al (2014)
Nuts	CHD	28 g/d	0.71	0.63	0.80	Aune et al (2016)
Whole grains	CHD	30 g/d	0.87	0.85	0.90	Aune et al (2016b)
	Cancer	30 g/d	0.95	0.93	0.97	Aune et al (2016b)
	Type 2 diabetes	30 g/d	0.65	0.61	0.70	Aune et al (2016b)
Underweight	CHD	15<BMI<18.5	1.17	1.09	1.24	Global BMI Collab (2016)
	Stroke	15<BMI<18.5	1.37	1.23	1.53	Global BMI Collab (2016)
	Cancer	15<BMI<18.5	1.10	1.05	1.16	Global BMI Collab (2016)
	Respiratory disease	15<BMI<18.5	2.73	2.31	3.23	Global BMI Collab (2016)
Overweight	CHD	25<BMI<30	1.34	1.32	1.35	Global BMI Collab (2016)
	Stroke	25<BMI<30	1.11	1.09	1.14	Global BMI Collab (2016)
	Cancer	25<BMI<30	1.10	1.09	1.12	Global BMI Collab (2016)
	Respiratory disease	25<BMI<30	0.90	0.87	0.94	Global BMI Collab (2016)
	Type 2 diabetes	25<BMI<30	1.88	1.56	2.11	Prosp Studies Collab (2009)
Obesity (grade 1)	CHD	30<BMI<35	2.02	1.91	2.13	Global BMI Collab (2016)
	Stroke	30<BMI<35	1.46	1.39	1.54	Global BMI Collab (2016)
	Cancer	30<BMI<35	1.31	1.28	1.34	Global BMI Collab (2016)
	Respiratory disease	30<BMI<35	1.16	1.08	1.24	Global BMI Collab (2016)
	Type 2 diabetes	30<BMI<35	3.53	2.43	4.45	Prosp Studies Collab (2009)
Obesity (grade 2)	CHD	30<BMI<35	2.81	2.63	3.01	Global BMI Collab (2016)
	Stroke	30<BMI<35	2.11	1.93	2.30	Global BMI Collab (2016)
	Cancer	30<BMI<35	1.57	1.50	1.63	Global BMI Collab (2016)
	Respiratory disease	30<BMI<35	1.79	1.60	1.99	Global BMI Collab (2016)
	Type 2 diabetes	30<BMI<35	6.64	3.80	9.39	Prosp Studies Collab (2009)
Obesity (grade 3)	CHD	30<BMI<35	3.81	3.47	4.17	Global BMI Collab (2016)
	Stroke	30<BMI<35	2.33	2.05	2.65	Global BMI Collab (2016)
	Cancer	30<BMI<35	1.96	1.83	2.09	Global BMI Collab (2016)
	Respiratory disease	30<BMI<35	2.85	2.43	3.34	Global BMI Collab (2016)
	Type 2 diabetes	30<BMI<35	12.49	5.92	19.82	Prosp Studies Collab (2009)

Projections of future food demand are income dependent and follow the SSP2 shared socio-economic pathway. Development projections and uncertainties are described in Samir and Lutz (2017).

7.4.3 Active travel

Modelling for levels of active travel in future populations is challenging. Fundamentally, any assessment of population health impacts requires a baseline level of activity data and a method of projecting this data under different scenarios. Previous work undertook a rapid review of available survey to determine levels of the population who regularly walked or cycled (Hamilton, et al., 2021). However, this review was limited to nine countries, and further searches revealed little additional survey data to increase the number of countries under consideration. Since the present study is global in scope, a global data source was required. For this, the Global Burden of Disease provides an estimate of mortality attributable to low physical activity. This provides estimates of the total burden of five disease endpoints associated with total physical activity between 1990 and 2018 worldwide.

However, the use of this global data may serve to provide inherently conservative estimates of total potential intervention that might be possible with respect to active travel. As Garcia et al. (2023) note, these estimates include occupational activity levels. Despite being poorly measured, work-related activity levels are often estimated to be far larger than non-occupational activity levels. Furthermore, work related activity levels are typically long duration and low intensity in terms of gross metabolic equivalent of task (MET) hour/week. The result is impact of non-occupational activity, those activities typically associated with active travel, may be underestimated. It is therefore important to view the estimates as potentially inherently modest. However, their use allows comparison of different regions worldwide, with a view to assessing the potential scope of shifts towards activity travel with a view to reducing CO_2 emissions associated with transport.

These considerations notwithstanding, the following approach is taken to understand the broad changes that might occur in the coming 30 years. These are designed to be an envelope of possible ways in which the age standardised deaths rates associated with low physical activity could evolve, and not a specific prediction regarding increases in percentages of active inhabitants in a region. However, it is important to note that where improvements do occur, these will likely be coupled with significant investment in public transport and active travel infrastructure. A rapid scoping review of current plans in these respects are given in appendix section 8.

Benchmark: attributable rates stay constant through to 2050.

Optimistic: In regions where the age standardised rate of mortality associated with low physical activity have been falling in the past 30 years, these gains continue. For regions that have been getting worse, the attributable rates stabilise.

Pessimistic: In regions where the age standardised rate of mortality associated with low physical activity have been falling in the past 30 years, these gains stall and rates remain the same through to 2050. For regions that have been getting worse, the rate of increase in attributable mortality doubles in the next 30 years.

As has been noted elsewhere, interactions between the models are not estimated. For example, encouraging active travel may have second order impacts on reducing air pollution from car use. There is also a potential effect that increasing active travel in areas of high air pollution could adversely impact cardio-vascular health due to the increased exposure to air pollution, offsetting or reversing any benefit from increased activity. This effect is not well understood at present but is examined in further detail in Kim et al. (2021).

7.5 Economic impacts

Model Description

ENGAGE (ENvironmental Global Applied General Equilibrium) is a multi-region, multi-sector dynamic Computable General Equilibrium (CGE) model developed at UCL for the analysis of energy, environmental, resource and economic policies (Calzadilla & Carr, 2020) (Winning, Calzadilla, Bleischwitz, & Nechifor, 2017) (Nechifor, et al., 2020). ENGAGE is based on the GTAP9-Power database (Peters, 2016) and represents the global economy in 2011. ENGAGE not only includes a detailed representation of different power technologies and energy related industries, it also represents other sectors of the economy (i.e. agriculture, industry and service sectors), allowing in this way the assessment of the economy-wide impacts of energy related policies and shocks. ENGAGE models 27 economic activities, 16 regions and 4 factors of production (Table 12).

Table 12 Regions, sectors, and factors of production in ENGAGE.

16 Regions		27 Sectors	
AFR	Africa	PDR	Paddy rice
AUS	Australia	WHT	Wheat
CAN	Canada	GRO	Cereal grains
CSA	Central and South America	OCR	Other crops
CHI	China	A_F	Agriculture and food
EEU	Eastern Europe	MIN	Minerals
FSU	Former Soviet Union	PPP	Paper
IND	India	CRP	Chemical
JAP	Japan	NMM	Non-metalic minerals
MEA	Middle-east	I_S	Iron and steel
MEX	Mexico	MPR	Metal products
ODA	Other Developing Asia	IND	Other industry
SKO	South Korea	COA	Coal
UK	United Kingdom	OIL	Crude oil
USA	USA	GAS	Gas
WEU	Western Europe	P_C	Petroleum & Coke
		NUP	Nuclear power
4 Factors of production		CFP	Coal-fired power
LND	Land	GFP	Gas-fired power
LAB	Labour	WIP	Wind power
CAP	Capital	HYP	Hydroelectric power
RES	Natural resources	OFP	Oil-fired power
		OTP	Other power
		SOP	Solar power
		TnD	Transmission and distribution
		SER	Services
		TRN	Transport

Inputs, assumptions and process

ENGAGE uses openly available data from the International Energy Agency (IEA 2022) to model three decarbonisation scenarios: *STEPS*, *APS* and *beyond SDS*, which mimic the global decarbonisation pathways set out by the IEA (IEA, 2022). Due to the lack of information regarding country specific decarbonisation pathways, we apply the IEA's regional rates of decarbonisation to the different countries/regions in ENGAGE. Except for Australia, Mexico and South Korea, where we used the rates of North America, Central and South America, and Japan, respectively. All other information regarding regional energy mix and cost reductions in renewable technologies are based on the TIAM-UCL model (Pye et al. 2020). Therefore, besides the global CO_2 emissions reduction, the three scenarios represented here are not directly comparable to those from the IEA, but are broadly aligned.

ENGAGE uses the SSP2 regional population and GDP growth assumptions to calibrate the *STEPS* scenario (adjusting the total factor productivity), leaving GDP endogenous in all other scenarios. A global carbon price in a future of global climate cooperation is the mechanism used to reduce regional emissions per capita to match the targeted emissions trajectories in ENGAGE. The decarbonisation modelling also includes the development of renewable energy and the electrification of the economy. Cost reductions in renewables technologies (based on the IEA and TIAM-UCL model) and a gradual increase in the elasticity of substitution between electricity and other energy inputs help to achieve these outcomes. Energy-demand changes are modelled via improvements in energy efficiency and lifestyle changes, which is achieved by gradually increasing the elasticity of substitution between energy goods in the consumer demand. All these changes are implemented alongside an autonomous improvement in resource efficiency. The more stringent the climate target the greater the speed of improvement and transformation of the economic system. Cost reductions, energy efficiency improvements, resource efficiency improvements, and elasticities of substitution are region and sector specific. Moreover, as capital is a scarce resource in the economy, the development of renewable technologies crowds-out investment in other parts of the economy. ENGAGE assumes full employment of resources. Damages from climate change are not included in this version of ENGAGE, apart from heat stress impacts on labour productivity. An integrated assessment of the economic impacts of climate change should compare the cost of mitigation measures with the total cost of climate change damages.

The impact of heat stress on labour productivity is based on the World Bank Policy Research Working Paper “Estimation of climate change damage functions for 140 regions in the GTAP9 database” (Roson & Sartori, 2016). The authors estimate heat damage functions for three sectors: agriculture, manufacturing and services for a given increase in global temperature. They compute the average monthly “wet bulb globe temperature” (to define the percentage of a typical working hour that a person can work assuming the remaining time is rest) using average temperature and relative humidity. Based on Figure 3.2 from the World Energy Outlook 2022 (IEA 2022), we deduced that the global temperature in 2050 could reach 1.9ºC, 1.7ºC and 1.5ºC under the decarbonisation scenarios behind the IEA scenarios (see Figure 7). The heat stress impact on labour productivity behind those temperatures is calculated by using above damage functions and then they are introduced in ENGAGE as a decline in the productivity of labour.

Results within the literature context

Based on eight[3] state-of-the-art climate-energy-economy models (three of them CGEs), Vrontisi et al. (2018) find that the pace of economic growth is affected by climate change mitigation action only to a limited degree. The global annual GDP growth rates in the period 2020–2030 in the 1.5ºC scenario are around 0.21 to 0.48 percentage points lower compared to the reference scenario. Moreover, Vrontisi et al. (2018) highlight that this decline is much lower than the uncertainty of the pace of economic growth reported in the different models. A recent study by Akin-Olçum et al. (2023), that uses seven[4] global CGE models to assess the costs of mitigation in 2030 in the 1.5ºC scenario shows similar results in terms of regional GDP changes compared to a reference scenario. The uncertainty among models is highlighted in both publications.

Vrontisi et al. (2018) do not use the same targeted emissions across models. Therefore, global emissions decline around 36% to 64% with respect to the reference scenario. Akin-Olçum et al. (2023) use the same targeted emission across models—global emissions for the 1.5ºC scenario are 33% below 2011 emissions.

The GDP costs presented in this report consider emissions reductions in 2050 of around 62% in the *APS* scenario and around 96% in the *beyond SDS* scenario, compared to the *STEPS* scenario. The anticipated GDP growth rates in the *APS* and *beyond SDS* scenarios in this report are slightly lower than the above publications but it considers much more stringent emissions reduction targets in 2050.

The difference in GDP impacts is mainly driven by the assumptions behind the level of the reference scenario (determining the level of emissions reductions in mitigation pathways) and key parameters such as cost reductions in low-emission power technologies, improvements in energy efficiency, improvements in material productivity, and behavioural changes captured by the elasticities of substitution.

Resource efficiency and material productivity are generally the most sensitive parameters, as they enable greater production with less resources and, most importantly, they are costless in most of these models. For example, the annual change in global primary energy intensity (a measure of energy efficiency) under the IEA's 'net-zero' scenario is around 4% for the 2021-2030 period.

[3] The list of models in this study are: IAM/CGE, GEM-E3-ICCS, IMACLIM, IMAGE, MESSAGE-GLOBIOM, POLES, REMIND and WITCH. The first three are CGE models.
[4] The list of models in this study are: EC-MSMR, EDF-GEPA, ICES, DART, C-GEM, TU-Berlin and PACE. All of them are CGE models.

However, the largest change observed in recent years was around 2% for the 2011-2015 period (IEA's Energy Efficiency 2022).

Moreover, the global material productivity under the UNEP's 'Towards Sustainability' scenario, which is compatible with 1.5ºC, is 43% higher in 2060 than historical trends (Global resources outlook 2019). However, the same report shows that global material productivity started to decline around 2000 and has stagnated in recent years.

The numbers used in ENGAGE for future levels of energy efficiency and material productivity are more conservative. As ENGAGE does not include negative emission technologies and CCUS, the economic costs of mitigation in the long run might be overestimated. This is discussed further in the caveats section, below.

Caveats

There is a large uncertainty in the regional and global costs of mitigation, which depends on the type of model and the model's specification and assumptions. Results from a model intercomparison analysis using 7 CGE models shows that regional GDP changes in 2030 under an NDC 1.5ºC scenario range between -15.3% to 1.8% (Akin-Olçum, et al., 2023).

Regional mitigation costs are not only dependent on the current energy mix and dependency level of fossil fuels, but also on the modeller's assumptions regarding the future development and costs of advanced technologies like direct air capture and carbon capture, utilisation and storage (CCUS), as well as on regional and sectoral resource efficiency improvements and elasticities of substitution. Since the dynamic assumptions of these parameters are drawn from external sources, considerations, such as the dynamic effects of learning, are implicit on the assumptions provided by the sources.

ENGAGE does not represent negative emission technologies or CCUS. Therefore, the economic cost of mitigation in the long run might be overestimated as these technologies play a key role on decarbonising the power and industrial sectors. In addition, there is not an explicit representation of commercial and residential buildings. Energy consumption and emissions of the household and government sector are used as a proxy to assess decarbonisation in buildings.

Roson and Sartori (2016) provide estimates of the potential impacts of heat on labour productivity across various sectors and regions, considering different levels of global warming. However, the results derived from their methodology and data sources inherently carry a degree of uncertainty. To address this uncertainty and enhance the robustness of the economic analysis, it would be beneficial to incorporate additional estimates, potentially derived from a variety of methodologies and diverse data sources.

It is assumed that the global temperature increase in 2050 is the same across all regions. This is inaccurate as local temperatures vary widely for a given global temperature level.

As most global economic models, the ENGAGE model includes very aggregated sectors and regions. This is a limitation of the model that average out local effects.

7.5.1 Population Modelling Uncertainty

In addition to the uncertainties outlined in previous appendix sections, uncertainties with respect to input population parameters are summarised here. Two sources of population projections are used in the models employed here, namely UN Department of Economic and Social Affairs World Population Prospects (United Nations, 2019), 2017 and 2019 versions, IMHE reference population forecasts (Institute for Health Metrics and Evaluation, 2020) and the IEA's modifications to UN projections (see table 2.1 of IEA (2022)). Population normalised mortality estimates are used to minimise the impact of differences in population estimates. As is clear from Table 13, central global population estimates are remarkably similar, but the greatest differences lie at the country level.

Table 13 Population estimates for 2050 by variant

Source	UN Medium variant 2022	UN Medium variant 2019	UN Medium variant 2017	UN Medium variant 2000 (for 2049)	IHME Reference	IEA GEC Climate Model
Global 2050 population (billions)	9.709	9.735	9.771	9.281	9.550	9.692

8. APPENDIX B: PUBLIC TRANSPORT EXPANSION APPRAISAL

The following appendix provides a narrative summary of planned travel infrastructure projects that might contribute to increases of physical activity for the local population. It is not intended to provide a comprehensive global overview of planned projects, but is included as a basis of follow-up work.

8.1 North America

Phoenix: Phoenix's Transportation 2050 Plan intends to expand the existing light-rail system by 42 miles to cover south, north, and west Phoenix neighbourhoods. They also plan to enhance 780 bus stops with lighting or shade structures and transition to carbon-neutral buses by 2040. Additional bus services will be introduced on major streets, with expanded hours of operation. Moreover, the plan includes the construction of 135 miles of sidewalks, installation of 2,000 streetlights, creation of 1,100 miles of bike lanes (some protected from car traffic), and the implementation of a virtual fare system.

Philadelphia: The Vision for 2045 in Philadelphia focuses on modernising the trolley system and transforming regional rail into a frequent transit service, with trains arriving every 15 minutes throughout the day. The plan also includes the expansion of high-capacity transit options.

Houston: Houston's MetroNEXT plan has secured $7.5 billion in funding and aims to introduce significant improvements to the city's transportation infrastructure. This includes the construction of 110 miles of Regional Express Network featuring two-way HOV lanes, the establishment of 21 new park and ride lots and transport centres, and the extension of the light rail system to the airport. Additionally, a 75-mile rapid bus service similar to light rail will be implemented, and the existing bus service will cover 290 additional miles.

San Francisco: The San Francisco 2050 Transportation Plan outlines various enhancements, such as repaving, maintaining, and upgrading streets, sidewalks, signs, signals, and bike lanes. The plan also focuses on implementing 200 miles of pedestrian and bike improvements, which will contribute to a 15% increase in transit speeds and reduce average commute times by approximately seven hours annually. The expected revenue for these initiatives through 2050 amounts to $80 billion.

8.2 Sub Saharan Africa

The World Bank has been involved in several Bus Rapid Transit (BRT) projects across Africa, aiming to address chronic traffic congestion and inadequate public transport capacity. In cities such as Dar es Salaam, Lagos, Cape Town, George, Johannesburg, and Pretoria, BRT corridors are already operational, while ten additional projects are being planned or constructed throughout Africa. The World Bank is providing financial or technical assistance to eight of these projects, including those in Abidjan, Dakar, Dar es Salaam (phases 3 & 4), Douala, Kampala, Kumasi, Maputo, and Ouagadougou.

In Dakar, an 18.3-km BRT corridor with 23 stations is currently under construction, with plans to begin passenger service in June 2023. This corridor is expected to carry approximately 300,000 passengers daily, reduce travel times from Guédiawaye to central Dakar from 90 to 45 minutes, and create 120,000 jobs. Feeder buses will connect more distant neighbourhoods to the BRT stations, and the system will be closely integrated with other modes of transportation, offering discounted transfers to local buses and commuter train services. The BRT operator is committed to hiring at least 25% female workers, with a long-term goal of increasing that figure to 50%. Safety measures, such as adequate lighting, security cameras, alert systems, and station agents, will be implemented to ensure a safe travel experience, particularly for women.

The C40 Dar es Salaam BRT system, currently in operation, covers 130 km and serves 90% of the population. It features large trunk buses and feeder buses, replacing the existing daladalas (privately owned buses) that were responsible for up to 60% of daily trips. The BRT line has exclusive lanes and elevated terminals, transporting about 200,000 passengers daily.

Addis Ababa's Light Rail system, launched 10 months prior, has a capacity of transporting up to 60,000 individuals per hour and operates using predominantly renewable energy sources. The introduction of this efficient transportation mode is expected to stimulate the local economy, attract investments, and serve as a model for growth in the region. The project was a collaborative effort involving the Ethiopian government, foreign banks, and the Chinese government. The LRT has significantly improved average transport speeds in the city and created over 1,100 jobs.

In Nairobi, the African electric mobility company ROAM secured funding and partnered with Uber to deploy electric motorcycles and the ROAM Rapid electric bus. The bus, designed to address the unique demands of public transportation in Nairobi, has a range of 360 km, a 90-person capacity, and features prioritised seating for the elderly and individuals with limited mobility.

The International Finance Corporation has partnered with the Lagos state government to upgrade bus transport corridors in Lagos, aiming to reduce commute times for 150,000 people per day. The initiative is part of Lagos's State Bus Reform Initiative and aims to address the high vehicle density in the city.

Furthermore, in Maputo, Mozambique, a BRT expansion project is underway to improve transportation access in rapidly expanding neighbourhoods and suburbs. The project involves revamping roads, paving and weather-proofing streets, and adding drainage systems and lighting to enhance safety and reduce accidents. The World Bank has granted $250 million to finance these improvements, and existing informal minibuses, known as chapas, will be integrated into the new transport system.

These various initiatives reflect a concerted effort to improve public transportation infrastructure, enhance mobility, reduce congestion, and promote sustainable modes of transportation across African cities.

8.3 Asia

The government of Kazakhstan has allocated substantial investments for the modernisation of railway projects, depot and rail carriage renovation, and overhaul of rail locomotives. Additionally, a new terminal is being developed at Almaty International Airport with funding from the International Finance Corporation and the European Bank for Reconstruction and Development. Air Astana, the national airline, plans to purchase two freighters in 2024 to establish Kazakhstan as an air cargo hub between China and Europe.

Kazakhstan is actively involved in the Belt and Road Initiative, with 51 mega projects worth $35 billion, including investments in the Khorgos dry port. A declaration was signed by Kazakhstan, Turkey, Georgia, and Azerbaijan to integrate into the international transport system through the Middle Corridor. Development work is ongoing at Aktau and Kuryk ports to increase capacity and construct essential infrastructure. Under the Nurly Zhol national project, Kazakhstan aims to build, repair, and reconstruct 27,000 kilometres of roads by 2025.

At the China-Central Asia Summit, China and Tajikistan announced plans to promote the construction of the China-Tajikistan-Northern Afghanistan Economic and Transportation Corridor. Efforts will be made to ensure the smooth operation of the Karasu-Kulma Pass throughout the year. The proposed China-Kyrgyzstan-Uzbekistan railway, which has been under consideration for 26 years, also gained attention at the summit, with China and Kyrgyzstan expressing satisfaction with the completion of the railway project's feasibility study and a commitment to continued collaboration on construction. The Organization for Security and Co-operation in Europe (OSCE) conducted a study on the Belt and Road Initiative in Central Asia in 2019, analysing its impact and potential in the region.

8.4 Southeast Asia

In Southeast Asia, several countries are embracing electric vehicles (EVs) for public transport. Bangkok plans to switch its entire fleet of public buses to electric vehicles, introducing 3,200 electric buses by 2025. Jakarta's Transjakarta public bus system in Indonesia will introduce 1,000 EVs by the end of 2023, with plans to expand to 3,000 by 2025. The Thai government aims to increase the proportion of EVs among new cars by 2030 and has introduced tax incentives for EV and battery manufacturers. Vietnam's VinFast, affiliated with Vingroup, secured funding to manufacture electric buses and charging equipment. Malaysia aims to increase the share of public transportation in urban areas to 50% by 2040.

In terms of infrastructure projects, Laos is constructing the Boten Vientiane Railway, a 414-kilometer electrified railway connecting Vientiane to Boten, neighbouring China, as part of the Trans-Asia railways. Malaysia's East Coast Rail Link (ECRL) will connect the east coast economic region to the peninsula's west coast, spanning 640 kilometres. Thailand is developing the Northeastern High-Speed Railway, which will increase passenger rail capacity and connect Bangkok to the northeastern part of Thailand. Bangkok is also expanding its Mass Rapid Transit system with the construction of the Yellow, Pink, and Orange lines, extending the network by approximately 87 kilometres.

8.5 Europe

The European Commission is focused on expanding the high-speed rail network through the Trans-European Transport Network (TEN-T). By 2040, new high-speed rail connections will be constructed, reducing travel times on routes such as Budapest to Bucharest, Vigo to Porto, and Hamburg to Copenhagen. The Commission aims for a minimum speed of 160 km/h for passenger trains and 100 km/h for freight. Efforts will be made to exempt tickets from sales taxes and simplify the booking process for international journeys.

The Commission is providing $5.4 billion in EU grants for 135 projects under the TEN-T. These projects contribute to the completion of the TEN-T core network by 2030 and the comprehensive network by 2050. Some selected projects include the Fehmarn Belt tunnel linking Denmark and Germany, upgrading rail-road transhipment terminals in Slovakia, creating a cross-border waterway connection between France and Belgium, and implementing intelligent transport systems for road safety and secure parking infrastructure.

In Wales, the government has allocated funding to develop active travel schemes through the Active Travel Fund Programme. The funding has significantly increased from £10 million in 2018/19 to approximately £60 million in 2021/22. Initiatives focus on improving conditions for walking, cycling, and scooting, including safe routes to schools and lowering speed limits. The government plans to increase cycle parking spaces at stations, enhance capacity for carrying cycles on trains and bus services, and provide dedicated carriages for walkers and cyclists where demand exists. Bus services in Wales are also supported through the Bus Services Support Grant, which aids local authorities and operators in providing various services.

8.6 Latin America

In Latin America, there is a growing shift towards electric buses in major cities. Celsia, a Colombian energy company, won a tender in 2019 to provide 120 BYD buses to the SITP in Bogota. With an equity investment of approximately $30 million, Celsia will now rent these buses to operators and has plans to expand to other markets.

Santiago, Chile, is also making progress in adopting electric buses. Enel X and Metbus have invested around $40 million in 102 BYD buses, 100 chargers, and the construction of an electro-terminal. Additionally, Engie has partnered with two operators, STP Santiago and Buses Vule, to invest in 100 Yutong electric buses. NEoT Capital, a French investment platform, has recently invested in 25 King Long e-buses through RedBusUrbano.

In Bogota, Colombia, there are currently 483 electric buses in operation, and further expansion is planned. In Mexico City, there are plans to procure e-buses, with 500 new trolley buses in the pipeline. Medellin, another city in Colombia, has already purchased 64 e-buses.

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