Deloitte.

Europe’s turning point

Technical appendix

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Europe's turning point: Technical appendix

In 1990, the first Intergovernmental Panel on Climate Change (IPCC) report concluded that human-caused climate change would become apparent, but it could not confirm that it was currently happening.

Published in August of this year, the latest *IPCC sixth assessment report* provides the most up-to-date physical understanding of the climate system and climate change. In this assessment, the evidence is clear that the climate has changed since the preindustrial era and that human activities are the principal cause.

With more data and improved models, the assessment gives improved estimates and narrower ranges compared to the previous assessment. Global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered in the assessment. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in carbon dioxide (CO2) and other greenhouse gas (GHG) emissions occur in the coming decades. There is greater certainty that with every additional increment of global warming, changes in extremes will become larger – for example, every additional 0.5°C of global warming causes distinct increases in the intensity and frequency of hot extremes, including heatwaves, heavy precipitation as well as agricultural and ecological droughts in some regions.

Modelling the economic impacts of the physical risks from climate change and the economic impacts of mitigation and adaptation pathways can be fraught, but not insurmountable. The economics discipline has spent several decades debating the benefits and limitations of the established techniques to derive economic estimates. To this day, while there remain many uncertainties and technical limitations on what macroeconomic models can reasonably conclude, economic techniques have improved to integrate views of the physical climate and economies and provide important insights into the choices that can be made to drive prosperity.

The Deloitte Economics Institute strongly recognises the limitations of integrated assessment modelling (IAMs) – and determining relationships between GHG emissions, global surface temperature and economic impacts. But equally, we recognise that economics can provide useful insights for rapid decision-making today, and not discount the pragmatic in pursuit of the perfect.

In this context, the economic modelling conducted in this analysis for research purposes has several objectives and seeks to overcome limitations:

- The results indicate an order of magnitude impact on gross domestic product (GDP) and other economic variables over the next 50 years. These results should not be interpreted as predictions or 'most likely' estimates of climate change impacts. The modelling instead provides a consistent framework through which to understand the economic difference between possible future worlds – one with climate change impacts and one without. Establishing a long-term view of the impact – albeit narrowed down to precise scenario specifications – enables us to draw conclusions as to trade-offs and the direction of change in economies. This is true for both high emissions, high temperature increase pathways and low emissions, lower temperature increase pathways.
- In the absence of transformation, a pathway of higher emissions and higher global surface temperature is considered as our baseline outlook for the world. In this outlook, there will be economic damages from climate change. While there are several probable scenarios as to emissions profiles and corresponding temperature increases, all paths will result in some degree of climate change damage. In our work, we adopt a single, higher-emission and higher temperature future pathway (see section 2.1) that offers the basis for an integrated view of chronic physical damages becoming a trend.

This baseline outlook seeks to demonstrate that choosing a path of no change from current global emissions trends is not costless to the economy.[1] Economic growth does not, and will not, occur uninterrupted as and when the climate changes.

- In reference to this baseline outlook, a view to the costs and benefits of mitigation and adaptation can more reasonably be considered. To inform this, we model a single pathway of economic transformation that decouples emissions intensity from the system of economic production. This is a view to decarbonisation of economies that aligns to a near net-zero GHG emission profile – compared to preindustrial levels – and limits global surface temperature warming to as close to 1.5°C – well below 2°C – by 2050. This decarbonisation pathway has many variables attached to it. In our work, we do not prescribe probability or likelihood to this pathway, much like the baseline. Rather the focus is on the sequencing, pace and scale of economic actions and transformations that could support economies to decarbonise within a carbon budget that limits global surface temperature warming to well below 2°C by 2050.

The goal is in understanding the economic rationale for acting to avoid increases in global surface temperature and unmitigated climate change and costs associated with a choice to not act. To this end, economic analysis of climate change is important to reframe the debate and inform decision-making today, in full understanding of the limitations of both science and economics.

Governments, business and communities all need to accelerate decision-making to decarbonise, and this requires economic analysis that accounts for the climate. If we can't reframe the starting point – that inaction comes with significant economic costs – then any action on climate change will always appear as an unreasonable cost to society and economies.

Any economic change will have a cost attached to it – whether that is a change in the climate, or a change to decarbonise. It is about how we understand the potential magnitude of those costs, the options to minimise them and how the choices we all make today determine the extent of them. There is a narrow, and closing, window of time to create a new engine for sustainable economic prosperity while preventing the worst consequences of a warming world.

There is uncertainty in the economic impacts of climate change and decarbonisation. But there is high confidence we will regret looking up in 2050 to face a planet with warming and economic loss all because we did not try to understand the economic rationale to change.

IPCC sixth assessment and relationship to analysis

The IPCC has released the Working Group I contribution to the *Sixth assessment report* (AR6) as the most up-to-date physical understanding of the climate system and climate change. AR6 outlines improved knowledge of climate processes, paleoclimate evidence and the response of the climate system to increasing radiative forcing (driven by higher greenhouse gas concentrations). AR6 provides the best estimate of equilibrium climate sensitivity of 3°C, with a narrower range compared to the previous AR5. According to AR6, the global surface temperature will continue to increase until at least mid-century under all emissions scenarios considered. Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO2 and other greenhouse gas emissions occur in the coming decades.

The analysis using the D.CLIMATE model does not take a probabilistic approach to the baseline and net-zero scenarios. Rather, it models narrow economic impacts that relate to specific damage functions from the selected emission pathways, without assigning probability to the outcome. This approach is to inform a better framework for decision-making today, based on orders of magnitude of economic trade-offs over time.

① Definitions

1.1 Net zero

The Deloitte Economics Institute has modelled a scenario that reflects the world reaching net-zero GHG emissions by 2050. Of this, around 13.4Gt (or around 20 per cent) of CO2e is expected to be offset or captured via carbon sinks in 2050.[2]

The EU offset or captured emissions are benchmarked to feasible LULUCF, natural and man-made carbon sinks by 2050, noting that the likelihood of these becoming viable is enhanced by the modelled carbon price.

1.2 Close to 1.5°C world

This pathway to net zero for the world limits global average warming to well below 2°C and close to 1.5°C compared to preindustrial levels, in alignment with current Paris Agreement objectives. The precise warming in global average mean surface temperature used in modelling is 1.7°C above preindustrial levels by 2100.

The climatic and economic implications of this global temperature pathway are modelled as the comparison scenario to a world of climate inaction.

1.3 Around 3°C world

An economic scenario that relates to a pathway of climate inaction. The socioeconomic and emissions pathways underpinning this exercise are broadly consistent with the SSP2-6.0 scenario (see section 2.4.1).[3] The implied temperature change is 3°C above preindustrial levels by 2100.

1.4 Turning point concept

Transitioning to a net-zero world and limiting warming to as close to 1.5°C requires an industrial and economic transformation that would typically occur over a century to take place in just three decades. The turning point concept highlights that choosing to rapidly accelerate will mean that, despite initial costs, countries and industries will see dividends to this investment. It is a climatic and economic turning point in the sense that the worst effects of climate change are avoided and the economic benefits of new industries and technologies offset the transitions from emissions-intensive production processes.

1.5 Deviations from baseline

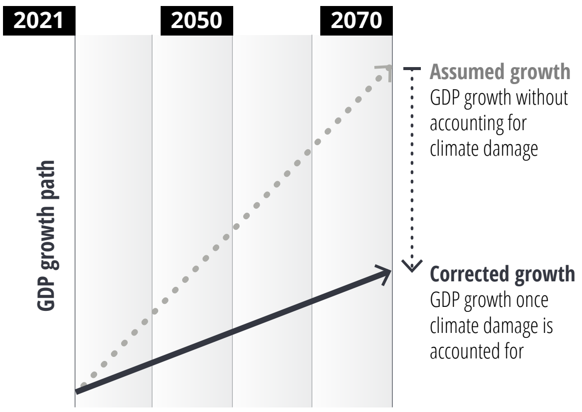
The turning point narrative is based on scenario analysis. The modelling does not provide a forecast of the future, but rather comparisons between possible future worlds. The discussion of modelling results will usually describe the state of the economy in reference to an alternative future – the deviation in a variable (like GDP) from one scenario (i.e. transition) to another (i.e. inaction).

1.5.1 Climate change impacts

When comparing two alternative futures, a **lower** GDP at the same point in time is not the same as having negative GDP growth. The example below demonstrates that comparing two GDP scenarios with and without the impacts of climate change shows that both scenarios reflect an economy that is still growing. The impact or 'loss' of GDP in 2022 due to climate change is the difference between the two GDP levels in figure 1 below.

FIGURE 1

Accounting for climate change impacts



Source: Deloitte Economics Institute.

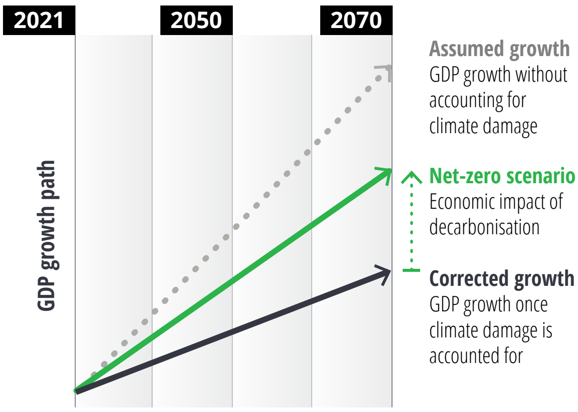
1.5.2 Deviations from a damaged baseline

Unlike most modelling exercises, though, the deviations presented in the net-zero scenario involve a two-step calculation to account for the combined impact of avoided damages alongside transition costs. This is done to reflect the idea that a more appropriate baseline for modelling and decision-making is one that accounts for climate impacts that arise from emissions-intensive economic growth.

In a simple example, a region might be expected to lose 3 per cent of output (figure 2) due to the damages associated with less ambitious domestic/global action on climate change. In a scenario where they and the rest of the world take more ambitious action, there might be a smaller loss due to damages, but there will be some cost associated with the policies enacted to reduce emissions. The results presented here show the combination of damages and transition costs, relative to the more severe damages from the baseline scenario.

FIGURE 2

Net-zero scenario impacts compared to a climate-damaged baseline



Source: Deloitte Economics Institute.

1.6 Decarbonisation

Decoupling emissions from growth in our context. Emissions intensities do not change by industry, but the industrial composition and production processes adapt to rely on less emissions-intensive activities.

1.7 Clean energy and electricity

Includes solar, wind, nuclear, hydropower and geothermal production technologies. Zero-emission hydrogen and bioenergy are included in clean energy (see section 2.3.3).

1.8 Conventional energy and electricity

Includes coal, oil and gas as fuels and energy production as well as their use in electricity production. Carbon capture, use and storage is not separately modelled.

② D.CLIMATE modelling

2.1 Overview

To date, most macroeconomic models and economic policy analysis are considered against a 'baseline' that assumes economic growth will occur unhindered by rising concentrations of GHGs in the world's atmosphere. The Deloitte Economics Institute believes that this viewpoint does not hold true in practice – particularly in the long run – and therefore economic analysis and climate policy are informed through a dated theoretical framework.

Climate change impacts should not be considered as a scenario 'relative to' a baseline of unconstrained emissions-intensive growth – because in the absence of fundamental societal and economic shifts, the impacts of unmitigated climate change *are* the baseline. By excluding the economic impacts of climate change from economic baselines, decision-making misses a fundamental point.

A shift to understand and incorporate this climate-affected baseline into decision-making is gaining momentum. The Network for Central Banks and Supervisors for Greening the Financial System, made up of 92 central banks, has been a prominent example, developing guidance and scenarios to assist the financial sector to better understand its climate risks.[4]

Understanding and accounting for the longer-term effects of climate change on productivity, potential output and economic growth are critical to understanding the likely future growth path of the global economy, as well as the distribution of disruptive climate impacts.

The Deloitte Economics Institute has invested in developing an extension of the in-house regional general equilibrium model (DAE-RGEM), giving it the functionality of a fully fledged integrated assessment model (IAM). Unlike many IAMs, this model has multiple economic damages that vary by sector and region, and unlike many regional computable general equilibrium (CGE) models, it has full integration with the global economy through the Global Trade Analysis Project (GTAP) database and a complete set of emissions accounts covering CO2 and non-CO2 gases.[5]

This work draws on, and contributes to, three key streams of research:

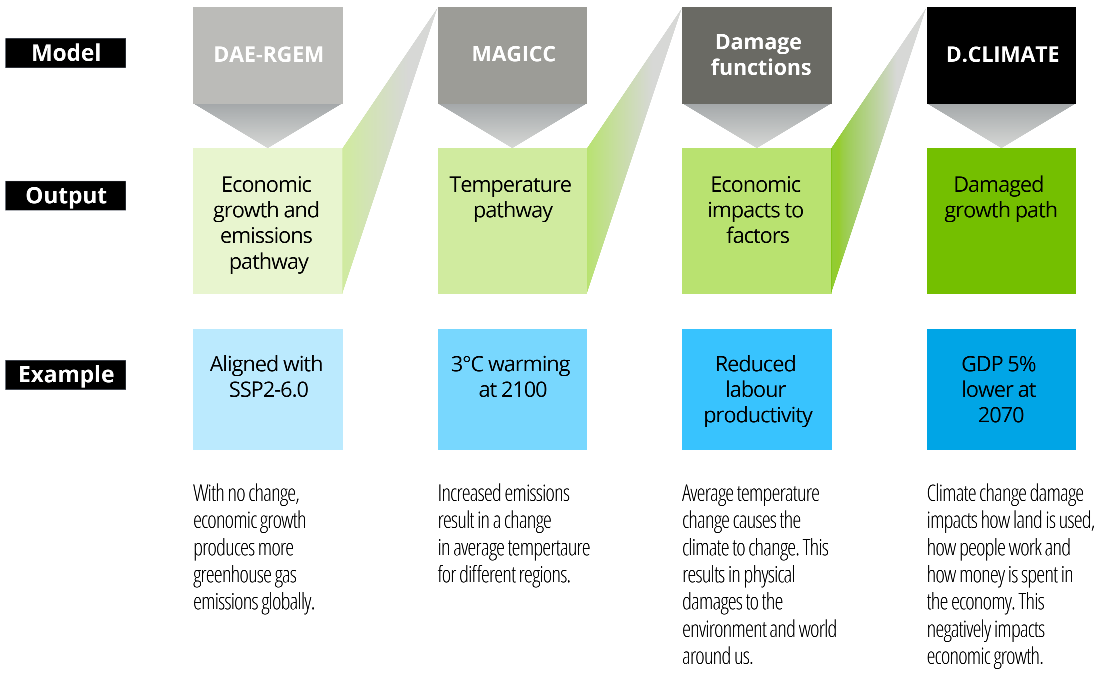
- The primary stream is that which has pioneered, refined and expanded CGE models, allowing for modelling of complex and dynamic policies, like those required to affect a transition to a low-carbon environment (see Adams and Parmenter, 2013).[6]
- Another stream is that which has followed the same process of pioneering, refinement and expansion, but for IAMs.[7] The IAM stream, in its initial phases, used a more aggregate representation of the economy that allowed for a stylised climate module.[8] These models sought to establish a link between the economic system potential damages associated with climate change to be incorporated to form an integrated (but simplified) framework for assessing the decisions facing policymakers when it came to emissions reduction targets (see Nordhaus, 2013).[9]
- The third and most recent stream is that which seeks to combine the two described above and provide the rich sectoral and policy detail inherent in modern CGE models, alongside climate feedback mechanisms that allow for integrated assessment (see Kompas, 2018).[10]

D.CLIMATE is an extension of a well-established modelling methodology and policy analysis technique that seeks to 'correct' the typical business-as-usual baseline assumed in most modelling.[11]

D.CLIMATE is built on an economic modelling framework that accounts for the economic impacts of climate change and establishes a reference case that can be modelled out to the year 2100 or beyond. The D.CLIMATE process and logic are as follows:

- The modelling produces a baseline economic growth path that draws on short- to medium-term global and regional forecasts in combination with a long-run assumption of contraction and convergence.
- The baseline economic growth path has an associated emissions growth path – derived from the established link between economic flows and emissions – and this corresponds to an evolution in atmospheric GHG concentration that rises in line with a Representative Concentrative Pathway (RCP).
- Rising atmospheric concentrations of GHGs causes global warming above preindustrial levels, as projected by a reduced complexity climate model (the Model for the Assessment of Greenhouse Gas Induced Climate Change, MAGGICC).[12]
- Warming causes shifts in global climate patterns and results in damages to the factors of production (capital, labour and land) and their productivities.
- Damages to factors of production are distributed across the economy, impacting GDP.
- These feedbacks are fed back into the model to determine the associated deviation in economic activity associated with a given level of warming (i.e., the damages).

FIGURE 3
D.CLIMATE framework



Note: The temperature pathway provided by MAGICC is global mean surface temperature. The damage functions estimate regional impacts based on this temperature pathway as well as other regional climate variables (e.g. precipitation), which are not provided by MAGICC.

Sources: Deloitte Economics Institute, Meinshausen et al. (2011, 2020), Nicholls et al. (2021).

Translating this concept into a modelling process involves three models that are linked through three key outputs. The Deloitte Economics Institute's approach extends methods adopted by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), the IPCC and other research organisations. The method is extended by necessity for practical public policy purposes and the modelling is regionalised – allowing results and insights to be produced at the regional level (such as countries or subnational regions).

The modelling process is summarised as follows:

1. Deloitte's in-house regional general equilibrium model (DAE-RGEM) is used to produce a projected path for economic output and emissions that align with a chosen SSP and RCP.
2. For each RCP scenario the associated climate data (global mean annual surface temperature increases and atmospheric concentrations) is sourced from a climate change model – MAGICC version 7 (MAGICC7). [13] Separately, regional average temperature, precipitation and relative humidity variables are sourced from a synthesis of models available from the Sixth Coupled Model Intercomparison Project (CMIP6).[14]
3. This climate data is then fed into damage functions to inform how shifts in temperature may play out in terms of impacts on the stocks and productivities of factors of production in each sector/region. Unlike most other models, we model a broad range of damages, including capital damages, sea-level rise (SLR) damages to land stock, heat stress damages on labour productivity, human health damages to labour productivity, agricultural damages from changes in crop yields and tourism damages to net inflow of foreign currency.

2.2 Baseline economic assumptions

In the baseline, a set of assumptions have been applied for macroeconomic growth rates and technological improvements over the period 2015 to 2070. These key variables have been calibrated drawing on historical and forecast time series from a range of reputable sources.

2.2.1 Macroeconomic variables

Macroeconomic variables including GDP, population and labour supply, and unemployment rate are calibrated for each year over the model period to 2070.

Growth rates for GDP are calibrated drawing on data from the International Monetary Fund's (IMF's) World Economic Outlook database that provides historical and forecast GDP growth over the period 1980 to 2025.[15] These growth rates are extrapolated using historical growth rates and assuming a degree of convergence over the long run.

Population growth rates are calibrated using the total population trajectories of the second socioeconomic pathway (SSP2) made available by the International Institute for Applied Systems Analysis (IIASA). A linear interpolation is applied to build yearly data.[16] Labour supply is calibrated employing a similar approach and is assumed to broadly reflect trends in population growth.

Unemployment rates are calibrated using short-term forecasts developed by the IMF[17] and extrapolated using a moving average. This approach implicitly assumes a steady state unemployment rate over the medium to long term.

2.2.2 Emissions, energy efficiency and productivity improvements

In the base year, once-off shocks are used to calibrate the energy mix for each region to ensure an accurate reflection of the current state of the energy mix between renewable and traditional sources. These shocks are calibrated drawing on data from Our World in Data.[18]

The emissions trajectory for the baseline is calibrated to align with the RCP6.0 emissions scenario, developed by the IPCC. RCP6.0 is chosen as an intermediate baseline scenario as it includes no specific or significant policy effort to mitigate, acting as an appropriate baseline for reference. Emissions are calibrated via uniform shocks to emissions efficiencies for all regions.[19]

In addition to these specific calibrations, a uniform energy efficiency improvement (0.5 per cent per annum) is applied across all regions, reflecting a continuation of the long-run improvement that has been observed to date.

2.3 Database: Regions and sectors

The core economic data underpinning DAE-RGEM – the social account matrix (SAM) – is sourced from the GTAP database (Walmsley et al., 2013).[20] This economic data is supplemented with specific data on electricity differentiated by power generation type (i.e. coal, gas, solar, etc.) from the GTAP satellite database GTAP-Power as well as CO2 and non-CO2 emissions data.[21] The behavioural parameters are also sourced from GTAP for the most part with some exceptions as discussed below.

This data is transformed in two key processes.

2.3.1 Regional aggregation

D.CLIMATE is a global model and can be tailored to a specified regional concordance in line with the GTAP database.[22] For this project, the European region was isolated in the model with several individual countries (the UK, France, Germany and Italy) and regional aggregations modelled within this geographical area. The regional concordances for this study are presented in figure 4.

FIGURE 4

Regional concordance

Subregion name ***Presented in Europe report***	Country or area	GTAP country code
United Kingdom of Great Britain and Northern Ireland	United Kingdom of Great Britain and Northern Ireland	GBR
France	France	FRA
Italy	Italy	ITA
Germany	Germany	DEU
Eastern Europe	Belarus	BLR
	Bulgaria	BGR
	Czechia	CZE
	Hungary	HUN
	Poland	POL
	Moldova	XEE
	Romania	ROU
	Russian Federation	RUS
	Slovakia	SVK
	Ukraine	UKR
Northern Europe	Åland Islands	FIN
	Guernsey	XER
	Jersey	XER
	Denmark	DNK
	Estonia	EST
	Faroe Islands	XER
	Finland	FIN
	Iceland	XEF
	Ireland	IRL
	Isle of Man	XER
	Latvia	LVA
	Lithuania	LTU
	Norway	NOR
	Svalbard and Jan Mayen Islands	NOR
	Sweden	SWE
Southern Europe	Albania	ALB
	Andorra	XER
	Bosnia and Herzegovina	XER
	Croatia	HRV
	Gibraltar	XER
	Greece	GRC

Subregion name ***Presented in Europe report***	Country or area	GTAP country code
	Holy See	XER
	Malta	MLT
	Montenegro	XER
	North Macedonia	XER
	Portugal	PRT
	San Marino	XER
	Serbia	XER
	Slovenia	SVN
	Spain	ESP
Western Europe	Austria	AUT
	Belgium	BEL
	Liechtenstein	XEF
	Luxembourg	LUX
	Monaco	XER
	Netherlands	NLD
	Switzerland	CHE

Source: Deloitte Economics Institute analysis of GTAP database.

2.3.2 Sectoral aggregation

D.CLIMATE can also be tailored to a specified sectoral concordance in line with the GTAP database.[23] For this project, a relatively high-level sectoral aggregation was chosen given the level of regional detail that was required for the European region. However, there was a specific effort made to distinguish two non-GTAP sectors (hydrogen and bioenergy) to aid in the representation of the transition to net zero.

The sectoral concordance for this study are presented in figure 5.

FIGURE 5
Sectoral concordance

Abbreviation	Sector name	GTAP sector(s)
AGRI	Agriculture, forestry, fishing	Paddy rice
		Wheat
		Cereal grains
		Vegetables, fruit, nuts
		Oil seeds
		Sugar cane, sugar beet
		Plant-based fibres
		Crops
		Bovine cattle, sheep and goats, horses
		Animal products
		Raw milk
		Wool, silk-worm cocoons
		Fishing
FORESTRY	Forestry	Forestry

Abbreviation	Sector name	GTAP sector(s)
COAL	Coal	Coal
OIL	Oil	Oil
GAS	Gas	Gas
OMIN	Other mining	Other mining
FOODMAN	Food manufacturing	Bovine meat products
		Meat products
		Vegetable oils, fats
		Dairy products
		Processed rice
		Sugar
		Food products
		Beverages, tobacco products
LIGHTMAN	Light manufacturing	Textiles
		Wearing apparel
		Leather products
		Wood products
		Paper products, publishing
HYD	Hydrogen	Petroleum, coal products*
BIO	Bioenergy (carbon-neutral)	Petroleum, coal products*
P_C	Petroleum, coal products	Petroleum, coal products
HEAVYMAN	Heavy manufacturing	Chemical products
		Basic pharmaceutical products
		Rubber and plastic products
		Mineral products
		Ferrous metals
		Metals
		Metal products
		Computer, electronic and optical products
		Electrical equipment
		Machinery, equipment
		Motor vehicles and parts
		Transport equipment
		Other manufactured goods (e.g. furniture)
ELYTND	Electricity transmission and distribution	Electricity transmission, distribution
ELYDIRTY	Fossil fuels	Coal base load
		Gas base load
		Oil base load
		Other base load
		Gas peak load
		Oil peak load
ELYCLEAN	New energy sector	Nuclear base load

Abbreviation	Sector name	GTAP sector(s)
		Wind base load
		Hydro base load
		Hydro peak load
		Solar peak load
GDT	Gas manufacture and distribution	Gas manufacture, distribution
WATER	Water	Water
CONS	Construction	Construction
TRADE	Retail trade and tourism	Trade
		Accommodation, food and service activities
TRANS	Transport	Transport
		Water transport
		Air transport
		Warehousing and support activities
OSERV	Other services	Communication
		Financial services
		Insurance
		Real estate activities
		Business services
		Recreational and other services
		Dwellings
GOVSERV	Government services	Public administration and defense
		Education
		Human health and social work activities

*The hydrogen and bioenergy sectors are not identified as individual sectors in the GTAP database but have instead been distinctly separated from the petroleum, coal products sector. An explanation of this process is provided in the following section.

Source: Deloitte Economics Institute analysis of GTAP database.

2.3.3 Commodity splits

In an effort to provide greater granularity in the representation of the transition to net zero, the hydrogen and bioenergy sectors were split from the parent sector: petroleum, coal products. This process was required as the GTAP database does not specifically identify either of these emerging energy sectors individually.

The petroleum, coal products sector was targeted as the parent sector due to the similarities in its sales structure to that of hydrogen and bioenergy. This transformation was informed by information gathered on the current size of the hydrogen, bioenergy and petroleum, coking sectors and the respective cost and sales structures of each individual sector. This research was gathered and the split executed so as to maintain the following high-level facts:

- The size of the hydrogen sector is approximately 2 per cent of the parent sector (petroleum, coal products). Its cost structure is different in that it draws more heavily on coal and P_C (i.e. the parent sector itself) although there is sufficient flexibility in its production function to allow for a shift towards production using zero-emission electricity and primary factors as the main inputs. The sales structure is the same as its parent.
- The size of the bioenergy sector is approximately 1.4 per cent of the parent sector (petroleum, coal products). It relies solely on the output of agriculture and waste as inputs to

production in conjunction with primary factors. The sales structure is the same as its parent. This is a subset of the broader bioenergy sector as it is exclusively carbon-neutral varieties.

- The remaining P_C sector is essentially the same as the original GTAP sector, but slightly smaller.

There is scope for further refinement of this process, drawing on more detailed data to help get a better picture of production, consumption and export, specifically at the detailed regional level.

2.4 Physical climate modelling for D.CLIMATE

The future of climate change is inherently uncertain. The rate at which CO2 and other pollutants accumulate in the earth's atmosphere could follow any number of trajectories, with each leading to a wide range of physical climate effects varying in both scope and scale. What is certain, however, is that the average global temperature has been rising and will likely continue to rise until a sustained and concerted effort is made to decarbonise globally.

In 2011, a set of four emissions and warming pathways were published to support consistent scenario analysis in the climate modelling community.[24] These so-called Representative Concentration Pathways (RCPs) were selected as plausible future GHG emissions and atmospheric concentration trajectories extending out to 2100. They are as follows:

- RCP2.6 (assumes stringent decarbonisation)
- RCP4.5 and RCP6.0 (two central scenarios)
- RCP8.5 (a high GHG emission scenario).

The IPCC's *Fifth assessment report* of 2014 adopted these RCPs as core scenarios for long-term projections and assessments.

In 2017, a concurrent research effort sought to develop a similar set of consistent future scenarios for human development, the five so-called Shared Socioeconomic Pathways (SSPs).[25] These include a range of societal factors such as demographics, human development (for example, health and education), economic growth, inequality, governance, technological change and policy orientations.[26] They are as follows:

- SSP1 – Sustainability
- SSP2 – Middle of the road
- SSP3 – Regional rivalry
- SSP4 – Inequality
- SSP5 – Fossil-fuelled development.

Neither RCPs nor SSPs are 'complete' without the other. RCPs generate climate projections that do not correspond to specific societal pathways. SSPs provide alternative societal futures, where climate change impacts and policies are not present. Thus, it is increasingly common to find research, including the IPCC's *Sixth assessment report*, adopting an integrated SSP-RCP scenario framework.[27]

Following this SSP-RCP framework, the baseline scenario for the modelling used in the present paper is broadly consistent with SSP2-6.0. It has been applied in over 150 studies between 2014 and 2019 and is one of the more commonly implemented scenarios that reflect continued emissions growth and temperature increase from today.[28]

Data consistent with the SSP2 narrative and RCP6.0 climate scenario was integrated in D.CLIMATE, representing the baseline state. RCP6.0 represents an economic future with a high rate of GHG emissions, where several technologies and strategies are implemented to reduce GHG emissions, and radiative forcing stabilises after 2100. The economic and emissions profile consistent with RCP6.0 has the potential to result in an increase to global average temperature in excess of 3°C.[29] The SSP2 narrative reflects a continuation of current social, economic and technological trends as well as slow global progress towards achieving sustainable development goals.[30]

2.4.1 Climate of global average temperature increase – MAGICC

Emissions produced by Deloitte's DAE-RGEM model are translated into global mean surface air temperature (GSAT) relative to the preindustrial (1750) period based on these emissions trajectories using a reduced complexity climate model. Specifically, the D.CLIMATE framework utilises outputs from the MAGICC as described in Meinshausen et al. (2011) and Meinshausen et al. (2020) and configured by Nicholls et al. (2021).[31] Global temperature increases are the main driver of climate impacts and are regionalised via the damage functions. MAGICC does not provide regional temperature outputs or regional climate impacts.

2.4.2 Other climate variables – CMIP6

Separately, regional average temperature, precipitation and wet bulb globe temperature (WBGT) have also been used. The data for each variable is the multimodel mean of 17 global climate models (GCMs) for the modelled SSP-RCP future pathways, which are available from the CMIP6.[32] The GCMs output was downloaded from the Earth System Grid Federation portal and then processed into monthly periods per geography/region across the modelled regions in Europe and the rest of the world from present day to 2100. [33]

Twenty-year averages of the GCM projections are used here to assess the key signals for future climate change across short- to long-term horizons. Each 20-year averaged period represents the climate of the mid-year. For example, the average temperature projection for the period 2011 to 2030 is assumed to represent the climate in the 2020 horizon.

2.4.3 Damage function overview

The fundamental 'driver' of economic damages is rising temperature. As rising temperature induces climate change, economic output (as measured by GDP) is impacted through the physical damages that affect productivity and/or the stock of production factors (figure 6).

This study includes six regionalised damages to Europe:

- heat stress damages to labour productivity
- human health damages to labour productivity
- SLR damages to land and capital stock
- chronic reductions in capital productivity
- agricultural damages from changes in crop yields
- tourism damages to net inflow of foreign currency.

The following section outlines each damage and how they impact the economy.

2.4.4 Heat stress damages on labour productivity

A working environment that is 'too hot' can negatively affect the health and safety of workers, as well as restrict their ability to perform tasks and limit their productive capacity.[34] For jobs where tasks are performed outdoors, it can be difficult for workers to moderate their heat exposure. The same can be true for indoor jobs where air-conditioning is not readily accessible.

Climate change is expected to see average global temperatures continue to rise, leading to shifts in the distribution of daily peak temperatures and relative humidity. Altogether, this means that heat waves are likely to become more frequent and increasingly extreme for many countries.

When workers exert energy to perform physical tasks, their bodies produce thermal energy and begin to heat up internally. For body temperature to be maintained at a healthy level, thermal energy needs to be transferred to a cooler external environment. If body temperature exceeds 39°C, an individual can suffer a heatstroke, and temperatures exceeding 40.6°C can be fatal. However, before these serious health effects occur at lower levels of heat exposure, workers can experience diminished 'work capacity' or mental task ability, and increased accident risk.

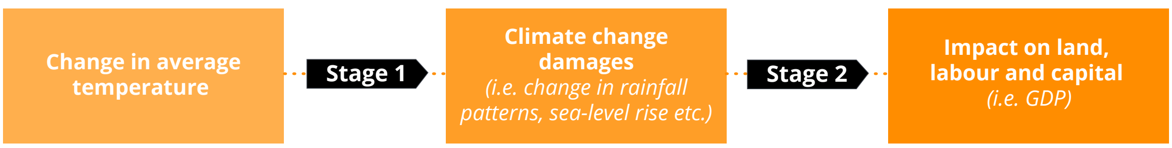
To continue functioning at elevated body temperatures, workers can take instinctive actions to reduce their work intensity or increase the frequency of short breaks. This 'slowing down' of activity (whether it occurs through self-instinct or occupational health management interventions) results in reduced 'work capacity' and lower labour productivity.[35]

This analysis estimates the effect of rising temperatures and changing relative humidity levels on labour productivity using WBGT as a measure of heat stress. Analysis is conducted at a geography or regional level. It is assumed that changes in labour productivity (an economic concept) are equal to changes in estimated work capacity (a physiological concept).

The methodology follows an approach proposed by Kjellstrom et al. (2017). This approach utilises a series of functions describing the relationship between WBGT and labour productivity across three different work intensities: 200W (equivalent to light manual labour, such as office work), 300W (equivalent to moderate manual labour, such as manufacturing) and 400W (equivalent to high-intensity manual labour, such as farming). Relationships have been determined by Kjellstom et al. (2017), based on a review of epidemiological datasets.

FIGURE 6

'Two-stage' economic damages relationship



Source: Deloitte Economics Institute.

Workers in each GTAP sector are assumed to perform tasks at one of the three work intensities specified above. GTAP sectors have been allocated to specific work intensities based on internal advice from Deloitte subject matter experts.

Consistent with the approach proposed by Kjellstrom et al. (2017), it is assumed that a geography or region's WBGT varies over three 4-hour intervals comprising the approximate 12 hours in a working day:

1. early morning and early evening – four hours at WBGT mean (calculated using average monthly temperature)
2. middle of the day – four hours at WBGT max (calculated using average monthly maximum temperature)
3. hours in between – four hours at WBGT half (calculated as the mid-point between WBGT mean and WBGT max).

These three variants of WBGT have been projected at monthly intervals using the simplified WBGT index – sWBGT – based on surface temperature and water vapour pressure (developed by the Australian Bureau of Meteorology).[36] Water vapour pressure was derived using estimates of relative humidity and the corresponding surface temperature.

Labour productivity is then estimated for each geography/region at monthly intervals, across each of the three 4-hour intervals assumed to comprise the working day. The mean of these three estimates is then taken to represent the average labour productivity for workers throughout the working day. Workers are assumed to maintain the same level of productivity for all days contained within each month. Monthly labour productivity estimates are then averaged to give an aggregate measure of labour productivity for each year in the modelling period.

2.4.5 Human health damages to labour productivity

The impacts of climate change on human health are many and complex.[37] Increasing temperatures can increase heat-related health problems, particularly for those with pre-established cardiovascular and respiratory disorders.[38] Increasing temperatures can also reduce cold-related health problems, again most prevalent in people with cardiovascular disorders.[39]

Climate change can impact the range, abundance and dispersion of species carrying diseases. Studies generally agree that the prevalence of malaria increases with increase in temperature. Other vector-borne diseases may increase or decrease.[40]

Climate change would allow diseases to invade immunologically naïve populations with unprepared medical systems and would affect food- and waterborne diseases, with cholera and diarrhoea being potentially most problematic.[41]

As extreme weather events become more severe and frequent, so too does the threat they present to human populations. Climate change can affect air quality, leading to greater incidence of diseases caused by air pollution – the 2020 summer of bushfires in Australia are a stark reminder of this. Climate change may also affect human health indirectly, through changes in food production, water resources, migration and economic development.[42]

Human health is therefore prominent in estimates of future climate change impacts. The welfare costs (or benefits) of health impacts contribute substantially to the total costs of climate change. Many estimates of economic damages rely on direct costs methodologies (i.e. price times quantity). With regard to human health, the price is typically equal to the value of a statistical life, based on estimates of willingness to pay to reduce the risk of death or diseases, or the willingness to accept compensation for increased risk.[43] However, these methods ignore the human health impacts on labour productivity and the demand for health services.

The approach adopted for this analysis is based on the work undertaken by Roson and Sartori (2015), which in turn is based on Bosello et al. (2006), by considering some vector-borne diseases (malaria, dengue, schistomiasis), heat- and cold-related diseases, and diarrhoea. It does not consider other diseases and impacts mentioned in the IPCC AR5 (2014), such as the effects of extreme events, heat exposure effects on labour productivity (separately considered), haemorrhagic fever with renal syndrome, plague, chikungunya fever, Japanese and tick-borne encephalitis, cholera and other (nondiarrhoea) enteric infections, air quality– and nutrition-related diseases, allergic diseases and mental health.[44]

The starting point of the analysis presented in Bosello et al. (2006) is a meta-analysis of the epidemiological, medical and interdisciplinary literature to achieve the best estimates for the additional number of extra cases of mortality and morbidity associated with a given increase in average temperature.[45] The information obtained in this research has been combined with data on the structure of the working population, to infer the number of lost working days. The changes in morbidity and mortality are interpreted as changes in labour productivity.

Roson and Sartori (2015) update the work of Bosello et al. (2006) to account for recent literature on health impacts and studies mentioned in IPCC (2014), scaling up or down the variations in labour productivity.

The results of these studies are expressed as changes in average labour productivity for a 1°C increase in temperature (implicitly assuming that the relationship is approximately linear). For the purposes of this analysis, and to understand the relationship between human health impacts, increase in average temperature and time, we regressed the variables to find an equation with a satisfactory fit for the relationship.

The analysis estimates the higher-order economic effects (or indirect costs) of human health impacts and variations in labour productivity. It is important to note that this methodology excludes induced demand for health care.

2.4.6 Sea-level rise damages to land and capital stock

As average global temperatures continue to rise, land-based glaciers are melting, and water bodies are experiencing thermal expansion. Together, these factors cause the phenomenon of SLR.

SLR can impact a geography's total stock of land (an economic factor of production) through a combination of erosion, inundation and salt intrusion along the coastline. As the global stock of land declines due to SLR, productive activity that would otherwise occur on that land is also foregone.

The extent of land lost to SLR will depend on several geography-specific characteristics, including (i) the composition of the shoreline (cliffs and rocky coasts are less subject to erosion than sandy coasts and wetlands), (ii) the total length of the coastline, (iii) the share of the coast that is suitable for productive purposes (i.e. in agriculture or urban land) and (iv) the VLM.[46]

This report estimates land area lost due to SLR using a methodology proposed by Roson and Sartori (2016), who estimated the mean SLR (in metres) associated with global mean surface temperature change from a series of regressions based on data within the latest IPCC AR5 Report, while also accounting for vertical land movement.

The proportion of agricultural land lost per metre of SLR is then estimated based on the findings of Roson and Sartori (2016), as well as World Bank data describing the extent of low-elevation coastal zones (LECZ) for each geography or region. The proportion of LECZ used for agricultural production in each geography is assumed to be equal to the proportion of total land area used for agriculture in that same geography.

This analysis extends the Roson and Sartori (2016) methodology to also capture urban land area lost due to SLR, again leveraging World Bank data describing the extent of urban area in LECZ. In low-lying and seacoast urban areas, residential and commercial properties may incur physical damages and economic activity that would otherwise occur in these urban areas will also need to transition to other geographies.

The process for estimating both components is as follows:

- The percentage of effective land area lost per metre of SLR is calculated by multiplying the following factors – the percentage loss in coastal wetland (a proxy for loss of land due to SLR, estimated using the HadCM3 climate model under the A1b SRES scenario),[47] the LECZ area, the percentage of erodible coast and relevant coastline.
- Considering which proportion of total coast is suitable for agricultural (productive)/urban purposes, the percentage of effective land change is adjusted by agricultural land area/ urban land area.
- The percentage change in agricultural and urban land stock is computed by multiplying the percentage of effective land change by metre of SLR and the estimated SLR.

Notably, there are a number of limitations involved with this methodology of measuring SLR. One is the assumption that the area of LECZ in each region is used for agricultural or urban purposes. This will not be true of all regions, some of which have large areas of unproductive coastal areas.

Further, the method used focuses primarily on the loss of total land stock. The method does not explicitly consider damage to labour productivity due to forced displacement, and SLR damage to infrastructure, which is generally established to be higher than damage to land stock.[48] However, it is widely assumed that submergence by SLR does not lead to damages to capital, because it is a slow process and by the time SLR arrives the capital stock will have fully depreciated and property markets will have adjusted.[49]

Further, as average rising increases (a gradual process), the impact of extreme or acute SLR (e.g. king tides and storm surges) will cause damage that may not be fully reflected in this function.[50] Financial and asset value shocks of SLR to coastal property will also not be captured through this damage, but may represent a significant economic risk if warming continues.[51]

2.4.7 Capital damages

This study captures climate-induced capital damages as a function of global mean average surface temperature.

Capital damages in this context are 'measured as a reduction in the capital productivity across sectors', that is, the output produced per unit of capital input. Reducing the productivity of capital as a result of climate change represents a need for firms to spend more on capital to achieve the same amount of output in every period. This effectively acts as a depreciation rate and diverts investment from otherwise productive applications.

Accounting for capital damages in this way represents a departure from existing economic impact modelling and integrated assessments of climate change. In some cases, capital damages are included but at a highly aggregated level that limits regional analysis. Often, reports discuss the exposure or risk of geographies to capital damages but do not attempt to monetise an impact.

The relationship between global mean average temperature and capital productivity is parameterised using projected data estimated by Forzieri et al. (2018).[52] This data provides projections of estimated annual damages (€ millions)[53] to capital that would occur due to a climate change – induced increase in intensity and frequency of natural hazards occurring in Europe.[54]

The specific natural hazards captured in this study include heat and cold waves, riverine and coastal flooding, wildfires, subsidence and high wind speeds (excluding cyclones). The capital that is damaged by these natural hazards in this study is described as 'critical infrastructure' including existing transport systems, renewable and nonrenewable energy generation plants, industries, water supply networks, roads, railways and education and health infrastructures. The projections are available up to 2080 and are provided at country and hazard levels.

The relationship between temperature increase and estimated annual damage in the analysis by Forzieri et al. (2018) is used as a proxy for the annual change in capital productivity in the D.CLIMATE model, by country and region. This effectively smooths a stochastic process of natural disaster impacts over time into an average annual damage estimate captured by a reduction in capital productivity.

This damage estimate does not measure the direct impact of any particular natural disaster to a particular location at a particular time in future modelled periods. Nevertheless, the implied relationship between temperature change and capital damage in Forzieri et al. (2018) indirectly and implicitly reflects the fact that, as global temperatures continue to increase above preindustrial levels, the frequency and intensity of natural hazards will rise in aggregate, and the productivity of capital will fall on average.

2.4.8 Agricultural damages from changes in crop yields

Climate change will see rising temperatures, higher concentrations of CO2 in the atmosphere and different regional patterns of precipitation.[55] These factors all affect crop yields and agricultural productivity.

The effects of climate change on agricultural productivity are one of the most studied areas of climate change impacts. Yet, despite the many existing studies and the extensive empirical evidence, it is still difficult to identify some sort of 'consensus' for the impacts of climate change on agricultural productivity. There are many factors at play, including the role of adaptation behaviour by farmers, firms and organisations, including variety selection, crop rotation, sowing times, the amount of fertilization due to higher CO2 concentration and the actual level of water available for irrigation and irrigation techniques.[56]

Modelling the economic consequences of yield changes to understand the consequences of climate change impacts on agriculture is important for two main reasons. Firstly, varying levels of agronomic and economic adaptation exist in the agricultural sector; farmers can adjust how they grow a particular crop, the location and timing of crop growth will shift in response to climate change impacts; trade in agricultural commodities will adjust; and consumers will be able to substitute goods as prices adjust.[57] Each of these adaptive responses will mediate the impacts of yield changes. Secondly, climate change impacts will vary by crop and by region, changing the comparative advantage of countries, and creating winners and losers in global agricultural markets.[58]

The approach undertaken in this analysis provides an estimate of productivity changes for the whole agricultural sector across the modelled regions. The methodology is based on Mendelsohn and Schlesinger (1999) and Cline (2007), where the variation in output per hectare is expressed as a function of temperature, precipitation and CO2 concentration.[59]

One disadvantage of this approach is that adaptation is not incorporated within the function. Studies that include an agronomic adaptation do, on average, report higher yields than those that do not; however, recent research has noted that the effects of agronomic, on-farm, within-crop adaptations (principally changes in crop variety and planting date) are small and statistically insignificant.[60] Additional economic adaptations such as crop switching, increasing production intensity, substituting consumption or adjusting trade relationships are captured within the CGE model.

A further constraint of this approach to note is that the methodology is not as thorough as Agricultural Model Inter-Comparison Project (AgMIP). AgMIP has used both partial and general equilibrium models to examine the economic implications of climate-induced yield shocks, determined using a number of process-based crop models (Nelson et al., 2014). Modelling based on AgMIP explicitly accounts for regional variation resulting from soil type, irrigation, baseline temperature and nutrient limitations.

2.4.9 Tourism damages to net inflow of foreign currency

Climate-induced economic tourism damages are driven by changes in net visitor flows and expenditure. In D.CLIMATE, changes to net visitor flows and expenditure are fundamentally driven by the exposure of each region to climate change. However, the impacts can be varied. Countries with lower current temperatures can experience a beneficial net inflow of foreign currency as temperatures rise and tourism increases in the region. Conversely, for countries with high current temperatures, further temperature rises mean the economy could experience a net outflow of foreign currency as tourism spending is reallocated to other regions.[61]

The functional relationship of the tourism damages means that in a region, there is a point where rising temperatures reach a threshold and the relationship between temperature and net flow of foreign currency switches from a net inflow to a net outflow.

To estimate tourism damages in D.CLIMATE, functions that relate visitor arrivals and departures to average temperature are employed. These functions are consistent with those employed by Roson and Satori and are derived from econometric models expressed in terms of land area, average temperature, length of coastline, per capita income and the number of countries with shared land borders.[62] Existing inflows and outflows of tourism expenditure for each country are based on data collected from the World Bank, the Statistical Office of the European Union, the OECD Tourism Statistics and local national government sources.[63] Tourism data is based on 2019 levels (or prior years if data was absent) as 2020 was considered a short-term anomaly in tourism flows as a result of the pandemic. Forecast average temperatures are used as inputs to these functions to determine a resulting net flow of foreign currency.

The magnitude and persistence of tourism damages are also a function of the economic structure of each region's economy. Regions with more diverse economic structures are less likely to experience persistent economic damages as industries are less reliant on tourism and more malleable/adaptable.

2.4.10 Benchmarking climate change impacts

There is a wide range of estimates around the relationship between climate change and economic outcomes, although consensus has formed around a negative relationship between global GDP and over 2°C of warming.[64] Around this global estimate there will be significant regional variation in climate impacts.[65]

For Europe, the overall effect of the impact channels described in section 2.4 can be situated within a literature of similar estimates for a sense of 'reasonableness' (figure 7).[66] There are a range of damage function specifications and impact channels adopted within the literature as well as other scenario (emissions, temperature and time horizon) and methodological differences,[67] so the numbers in figure 7 are not necessarily like-for-like comparisons.

Further spatial disaggregation of climate impacts, from continent to country level, increases the uncertainty around individual estimates. There are fewer studies, furthermore, that model these impacts at a country level, limiting available comparisons. The geographic patterns observed in other studies, that northern European countries (e.g. the UK and Germany) are likely to be less economically impacted by warming than southern European countries (e.g. France and Italy), are consistent with these modelling results.[68]

FIGURE 7

Select damage estimates from comparable studies, Europe

Source	GDP deviation from baseline	Scenario (°C)	Year
Deloitte (2021)	-1.5%	3	2070
Kompas (2018)	-0.5%	3	2100
McKibbin (2021)	-1.2%	3	2070
SwisseRE (2021)	-0.8%	2.6	2050
Network for Greening the Financial System (2021)	-1.8%	2.5	2070
IMF (Kahn et al.) (2019)	-2.8%*	RCP 8.5	2070
European Commission (2021)	-1.5%**	3	N/A
European Central Bank (2021)	-8%***	At least 3	2070

Note: *Measured in GDP per capita. Estimated by linear interpolation between 2050 and 2100 reported in the paper. **European Commission does not use IAM modelling, instead opting for 'static analysis' (see Peseta IV, 2021). ***This deviation likely reflects a 90th percentile warming outcome that result from a 'Hot house world' emissions pathway (NGFS, 2020), while other scenarios in this table adopt the median. The geographical definition of Europe varies in the sources above, ranging from the EU–27 to the European continent as defined in this report.
Source: Deloitte Economics Institute.

NGFS climate scenarios

The Network for Greening the Financial System (NGFS) released a range of climate scenarios for central banks and supervisors in July 2021. Their inaction scenario, known as 'Current Policies', reaches a global mean temperature rise of just above 3°C by 2100. Under this warming outcome, their central estimate of global GDP impact is –4.4 per cent in 2070 and –7 per cent in 2100, relative to their baseline.

Given the uncertainty around the temperature response to the 'Current Policies' emissions pathway, the NGFS also provides global GDP impacts for warming as high as 5°C by 2100, leading to as much as –7.5 per cent in 2070 and –13 per cent in 2100.

The same scenario for the EU (28 member countries) reached –1.8 per cent by 2070 relative to baseline (figure 7). This damage estimate is generated by the REMIND-MAgPIE IAM model, using a median temperature outcome given the 'Current Policies' emissions pathway.

These results and scenarios were published as the second of a series of 'vintages' by the NGFS within a program of developing and improving the relevance of this work for economic and financial analysis.

③ Policy scenario

3.1 Emission-abatement drivers: Scenario inputs and assumptions

A number of high-level emission-abatement drivers are included to reflect a possible path to global net zero by 2050. To summarise and distinguish from the baseline/inaction scenario, see figure 8. It is worth noting that the policy scenario does not model in detail the current policies of jurisdictions in Europe, but a set of drivers that enable Europe and the world to rapidly reach net zero by 2050.

FIGURE 8

Summary of emissions pathways and drivers in both scenarios

Scenario	Drivers
Baseline (3°C world)	• RCP 6.0 emissions pathway, reflecting global inaction on climate change mitigation • 3°C of warming and a range of climate damages by region and industry
Policy (1.5°C world)	• RCP 2.6 emissions pathway, reflecting significant global climate action • 1.5°C of warming and 'locked-in' climate damages • Global economy is net-zero emissions at 2050 • Improved learning rates in switching between fuel and electricity generation technologies • Productivity improvements to clean electricity driven by cost reductions to renewable energy • Transition assistance by governments to support industries and regions that face higher transition costs

Source: Deloitte Economics Institute.

There are four steps implemented in the policy scenario: an emissions constraint, 'locked-in' climate damages in a close to 1.5°C world, clean electricity productivity improvements and transition assistance.

3.1.1 Emissions constraint

The transition to a low-carbon economy has been modelled as one in which policymakers set clear and ambitious targets. These are implemented as constraints on the total level of emissions in each region such that global and regional emissions are reduced at a rapid rate over the next 30 years in line with the budget prescribed in the RCP2.6 scenario.

As a first step, the emissions constraint forms a shadow price on carbon such that processes that have associated emissions – like the combustion of coal to produce electricity – become more expensive. Those processes that don't have associated emissions – like the generation of electricity from renewables – don't face this price increase. Relative price changes such as these lead to changes in behaviour – like the switching from fossil fuel–based electricity generation to renewables. As these changes aren't seamless, their combined effect is to impose an aggregate cost on each economy, which is known as the shadow price of carbon. This isn't the same as a legislated carbon tax, or a traded emissions price, but it is analogous in that it represents the projected price at which a given reduction in emissions can be achieved.

Reductions in fugitive and industrial process emissions, which cannot be achieved via switching to alternative fuel sources, are modelled using emissions response parameters (ERPs), which allow for the gradual adoption of low-emission processes or technological alternatives, as they become more viable over time, relative to a growing shadow price on carbon.

3.1.2 Locked-in climate damages under a close to 1.5°C world

The combined effect of warming driven by historical emissions already in the atmosphere and the amount that will be emitted under the emissions path described in section 3.1.2 means that some amount of climate damage is unavoidable. This is incorporated into the 1.5°C world scenario.

One component of the benefits of climate action in the close to 1.5°C world scenario is the avoided damage – the difference between damages under a 3°C and close to 1.5°C world.

3.1.3 Clean electricity productivity improvements

Projections of reductions to levelised cost of electricity to 2050 for wind and solar, combined with the rising share of wind and solar in clean electricity sector generation (different shares in baseline and net zero), will drive cost reductions per unit of outputs.[69] A share of this productivity improvement to these technologies is included in the 3°C world scenario, reflecting the fact that these cost reductions will likely continue irrespective of policy, driven by learning by doing, economies of scale and supply chain efficiencies.[70] An incremental productivity improvement driven by policy is included in the close to 1.5°C world scenario, reflecting the fact that the share of solar and wind in electricity production will grow more rapidly, lowering production costs within this industry.

3.1.4 Transition assistance

The Deloitte Economics Institute models coordinated government investment to offset structural adjustment costs in industries and regions as decarbonisation accelerates. The investment is targeted at industries that are neither emissions-intensive nor in high demand as the world decarbonises. For example, coordinated government effort does not go to emission-intensive conventional energy or emerging clean energy as they primarily respond to price and changing demand.

Coordinated government transition assistance does, however, reflect economic and regulatory settings that create new economic activity for economies 'to transition into'. For example, in an emission-intensive country such as Italy, government transition assistance is targeted to diversify economic activity into areas such as construction, private sector service industries, retail and public services. This smooths the structural disruption to economies and their workforces, resulting in increased job creation earlier in the phases of decarbonisation.

This exists in current policy commitments, such as the European Green Deal and the RegenerateEU programs, and is likely to feature prominently in fiscal policies of national governments throughout a transition to 2050.[71]

A failure to provide coordinated transition assistance increases the cost of the transition for industry, and most significantly for those employed in those industries. There are no new or emerging job opportunities for workers to transition into, resulting in reduced job creation and significant dislocation for regional workforces – the disruption is highly place-based.

3.2 Emission-abatement results: Scenario outputs

3.2.1 Emissions pathway

The emissions reduction pathway in figure 9 reflects rapid decarbonisation across Europe as firms, households and governments respond to the drivers described in section 3.1. Although Europe (including EU and non-EU countries) does not have a single emissions reduction target, of those countries that have adopted 2030 and 2050 targets, this pathway is in line with those rates of change.

This pathway reflects gross emissions excluding LULUCF, man-made and natural negative emissions technologies. By 2050, it is assumed that 1,332 Mt CO2e will be captured by these sources, although they are not explicitly modelled. Within the modelling framework, a carbon price that reaches US$190-225/tonne across European regions is thought to make a number of these currently less economical abatement options viable.

Benchmarking this number against previous work, Europe's emissions at 2050 that are assumed to be captured by negative sources are within a range of feasibility. While evidence on the natural and man-made carbon sinks of Europe as a whole is not available, scenario analysis for the EU suggests that this could range from 500 to 600Mt of CO2.[72] The estimate of EU's emissions in the D.CLIMATE model at 2050 is 807 Mt CO2e, including both CO2 and other GHGs. The residual emissions across EU and non-EU countries that are not able to be captured locally are assumed to be offset by negative emissions sources that are available internationally.

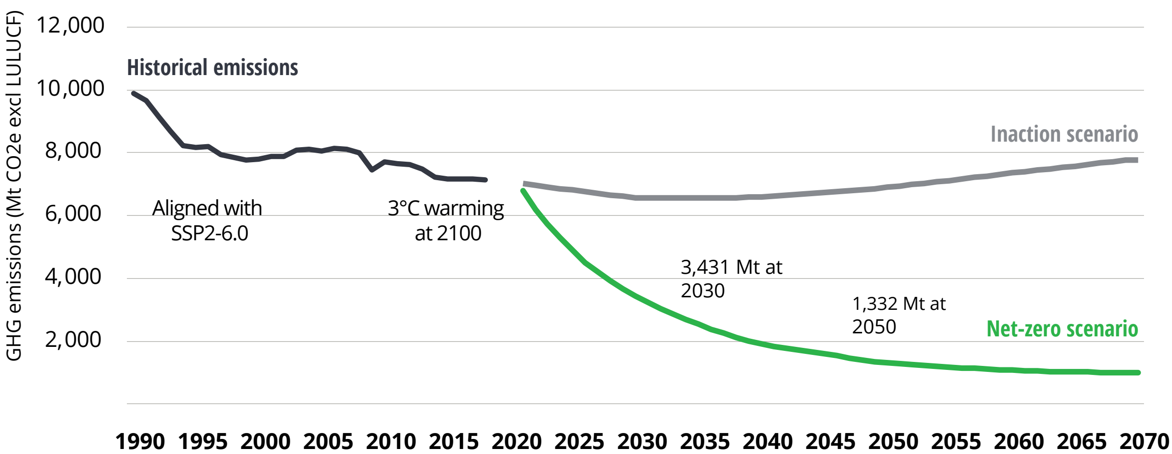
The global potential for negative emissions sources is assumed to be 13.4 Gt CO2e at 2050 (see section 1). Globally, there is a great deal of uncertainty around the potential for man-made negative-emissions technologies. The IPCC SR1.5 scenarios that reach net zero by 2050 have a median level of carbon capture, utilisation and storage (CCUS) of 15 Gt CO2 and a range of carbon direct removal (bioenergy with carbon capture and storage and direct air carbon capture and storage) of 3.5-16 Gt CO2.[73] The IEA's *Net zero* report includes a less optimistic projection of 7.6 Gt CO2 in 2050 being captured by a range of negative-emissions technologies.[74] Despite great uncertainty, the assumption of 13.4 Gt CO2e being removed from the atmosphere at 2050 appears feasible.

3.2.2 Energy mix transition

The global transition to net zero will require a total transformation of the current energy system. There is no single path along which that may occur. The energy mix at 2050 has been benchmarked to two prominent transition scenarios (figure 10). While these employ different modelling approaches and assumptions, they nevertheless demonstrate alignment on the broad energy transition narrative: a significant reduction of fossil fuel use, a scale up of clean electricity and a wider adoption of clean fuels (such as hydrogen) in sectors and applications where electrification is not possible.

FIGURE 9

Summary of emissions pathways and drivers in both scenarios



Source: World Resources Institute (2021) and Deloitte Economics Institute.

FIGURE 10

Global energy mix shares of total final energy demand

Time period	2020	At 2050		
Source	**Historical**	**D.CLIMATE**	**IEA Net-Zero Scenario[75]**	**BloombergNEF (green and red scenario)[76]**
Clean electricity	7%	56%	51%	48%
Conventional electricity	19%	~0%	1%	1%
Oil	46%	30%	13%	7%
Gas	18%	1%	6%	5%
Coal	10%	~0%	3%	1%
Hydrogen	0%	12%	10%	22%
Bioenergy*	0%	0%	15%	11%
Other*	N/A	N/A	N/A	4%

*Bioenergy definitions vary. The 'other' category is exclusive to BloombergNEF modelling and likely includes sources such as heat. Shares will not necessarily sum to 100% due to rounding.

Source: Deloitte Economics Institute.

Certain energy sources, such as bioenergy, have definitions that vary across sources, so are not directly comparable. D.CLIMATE's bioenergy source is limited to carbon-neutral varieties. Bioenergy associated with positive emissions will be partly captured within the oil category. Of the oil energy source that remains in 2050, this will include hard-to-abate applications, such as jet fuel and as inputs into specific chemicals manufacturing (known as feedstock). As described in section 3.2.1, the emissions from these sources will be removed from the atmosphere through negative-emissions technologies.

The energy transition in Europe is well underway, particularly in the EU. Tsiropoulos et al. (2020) review 16 scenarios of the EU's transition to net zero by 2050.[77] This review provides a useful summary of the key uncertainties around Europe's transition: the rates of energy efficiency improvements, penetration of wind and solar, scale of carbon sinks, the role of nuclear energy, among others. The share of renewable energy ranges from 65 per cent to 100 per cent. Of the 16 studies reviewed, 13 model a climate-neutral future that requires greater than 95 per cent of electricity to be generated from renewable and nuclear sources. D.CLIMATE's electricity generation share at 2050 is 100 per cent clean sources.

A significant component of Europe's transition to net zero will be the continued development of the hydrogen fuel production industry.[78] D.CLIMATE generates a share of final energy demand of 17 per cent in Europe. This compares to a slightly higher share in the EU in modelling by Hydrogen4EU between 21 and 22 per cent.

The energy and electricity transition that is modelled in D.CLIMATE is within the range of comparable scenario analysis.

FIGURE 11

Europe's net-zero transformation in three parts

On a net-zero pathway, Europe's energy mix would rapidly shift towards clean sources

Within our modelled pathway, all electricity will be clean after 2035, and would be 68% of the total energy consumed. It's the electrification of the economy that makes the deeper structural changes possible.

Note: Due to rounding, percentages may not equal 100%.

Source: Deloitte Economics Institute.

④ Discounting the future

It is inherently difficult to 'discount' the future, particularly concerning an issue as socially and economically complex as global climate change.

In considering this issue, it is important to recognise the intergenerational impact of climate change on society and in doing so, how to value 'income', 'consumption', 'utility' or 'well-being' and one point in time relative to another. In comparing these conditions across generations, the discount rate must reflect a preference for short-term consumption over the long-term and the opportunity cost of saving.

In determining the rate, the question becomes what rate is appropriate to embody these preferences in estimating the net present value of impacts to economies and societies from climate change and various climate change policy responses.[79]

GHG emissions have a long residence time in the atmosphere, which means that the value of the impacts of today's emissions must be considered for future generations. Equally, policy responses regarding mitigation and adaptation to altered climatic conditions impact future generations significantly.

In this context:[80]

- The use of a 'high discount rate' implies that society puts less weight on future impacts and therefore less emphasis on guarding against such future costs.
- The use of a 'low discount rate' highlights the importance of future generations' well-being.[81] Society should act now to protect future generations from climate change impacts.

A discount rate of 2 per cent has been used by the Deloitte Economics Institute in this analysis, after considering the differing perspectives within literature, the economic framework adopted for analysis in D.CLIMATE and broader policy actions modelled.[82] This rate reflects a consistent view social discounting in climate change economic analysis.

Further, the results of a survey of economists in the American Economic Journal: Economic Policy (the sample contains over 200 academics who are defined as experts on social discounting by virtue of their publications) indicate that most favour a low discount rate: with more than three-quarters comfortable with a median discount rate of 2 per cent.[83]

⑤ Limitations

Modelling the full physical consequences of climate change on the global economic system, and the economic impacts of mitigation and adaptation pathways, can be fraught, but not insurmountable. The approach outlined in this paper provides a detailed view of the literature and science that underpins our analysis. There nevertheless remain many uncertainties, technical limitations and areas of future research that will benefit from recognition and separate discussion.

The Deloitte Economics Institute recognises that there are legitimate critiques and limitations of IAMs – and the complexity involved in determining relationships between GHG emissions' global surface temperature and economic impacts.[84] But equally we recognise that such a framework can provide useful insights for policymakers who are making choices today that will have far-reaching consequences. We should not discount the pragmatic in pursuit of the perfect. There is value that these frameworks provide in their capacity to consistently model such complex relationships, policies and technologies.[85] Our approach is to incrementally improve and build on previously identified limitations in these modelling frameworks, rather than dispensing with their use altogether.

In particular, a key area of earlier criticism, the damage function, has benefited from a rapidly expanding econometric literature, which has enabled the parameterisation of plausibly causal relationships that more accurately capture relationships between climate and the economy.[86] We have incorporated these into a more disaggregated, multisectoral view of damages and have updated damage estimates based on more recently available science and research.[87] For example, a number of our damage functions reflect a core finding that temperature increases have a nonlinear relationship with economic outcomes.[88] We nevertheless recognise there are a range of impact channels that are not explicitly modelled here. In this sense, this work can be considered a conservative estimate of impacts, and the ongoing model development will look to incorporate these channels over time. A selection of these include:

- individual natural disasters and extreme events (see McKibbin et al., 2021)[89]
- changes in household energy demand (see Hsiang et al., 2017)[90]
- water availability (see Howells et al., 2013)[91]
- crime and other social impacts (see Hsiang et al., 2017)[92]
- ocean acidification (see Howard and Sterner, 2017).[93]

An extensive literature focuses on climatic nonlinearities that are not captured in this framework. Within climate-economic modelling, the most renowned argument for considering these impacts is made by Martin Weitzman.[94] These 'tipping points' include events, such as the partial disintegration of ice sheets, biosphere collapses or permafrost loss, that pose a threat of abrupt and irreversible climate change. Positively, the most recent IPCC report argues that there is growing confidence that taking action to reduce emissions will significantly lower the likelihood of certain tipping points being reached.[95] The AR5 report was more pessimistic about the range of tipping points that are at risk of being crossed regardless of abatement and mitigation action. Once again, given these uncertainties, we consider our analysis of primarily chronic impacts of warming to underestimate the potential future damages of climate change.

Economic modelling of climate impacts is not only interested in the direct effects of climate outcomes on physical spaces, but also the behavioural responses that occur in response to those changes.[96] These can variously be referred to as adaptation responses.[97] D.CLIMATE considers adaptation in two main ways:

- The damage functions are informed by empirical relationships that reflect long-term, ongoing adaption processes that are already embedded in underlying data.
- The CGE component of the model captures decision-making by firms and households who are able to switch between consumption sets and inputs based on relative prices and productivity changes in the economy. This flexible switching is akin to adaptation.

There will be some adaptation that is not able to be explicitly modelled, in particular adaptation that seeks to reduce the marginal damage caused by warming beyond that which is already captured by the damage function parameters (e.g. the building of sea walls or other technological change). The advantage of the D.CLIMATE approach is that some adaptation and dynamic economic change do take place in response to a changing climate, which improves upon approaches that project historical patterns forward. Improving the ability of the model to account for a wider range of adaptive responses is the focus of ongoing work.

Endnotes

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The pace and scale of global economic, social, environmental, and digital disruption is rapid, and we all now operate in a world that we no longer readily recognise. This creates a need to understand how structural economic change will continue to impact economies and the businesses in them, and the livelihoods of the world's citizens.

In pursuit of economic prosperity, progressive organisations need future-focused, trusted advisors to help them navigate complexity and deliver positive impact. The Deloitte Economics Institute (the "Institute") combines foresight with sophisticated analysis to shape and unlock economic, environmental, financial, and social value. Connecting leading global insight and local knowledge with an independent perspective, the Institute illuminates future opportunities and drives progress.

The Institute's economic rigour comes from its cutting-edge analytic tools; experience working with businesses and governments; and the expertise of Deloitte firm practitioners who help shape public policy, deliver business insights, and inform investment strategy. The Institute shares practical policy, industry know-how, and evidence-based insights to help businesses and governments tackle the most complex economic, financial, and social challenges.

With **more than 400 economists practicing in Deloitte firms across Asia-Pacific, the Americas, and Europe,** the Institute's depth and breadth of experience is matched by a strong understanding of trends in global economies and their effect on business. Its dedicated team of economists works closely with the Deloitte network's industry leaders across the globe to apply economic thinking and commercial acumen to everyday business problems.

The Institute prides itself on rigorous qualitative and quantitative analysis, and is supported by proprietary and specialist models refined over many years. The Institute's highly qualified economists practicing in Deloitte firms have a strong reputation for objectivity and integrity. All client services offered by the Institute are performed by practitioners at Deloitte firms.

For more information on the Deloitte Economics Institute, please visit the website:
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