Growth-positive zero-emission pathways to 2050

Technical Supplement

Citation: This report should be cited as: Drummond, P., Scamman, D., Ekins, P., Paroussos, L. and Keppo, I. 2020. *Growth-positive zero-emission pathways to 2050: Technical Supplement*, Sitra, Helsinki.

Contents

1. IPCC 1.5°C Scenarios 2
  1.1 Energy demand and efficiency 3
  1.2 Use of low-carbon energy carriers and technology 4
2. The European Union's 'Clean Planet for All' strategy 5
3. Shared Socio-Economic Pathways (SSPs) 6
4. TIAM-UCL Modelling 12
  4.1 Methodology 12
  4.2 Demands 14
  4.3 Primary energy resources 15
  4.4 Energy supply sectors 16
  4.5 CCS, BECCS and DAC 17
  4.6 End use sectors 18
  4.7 Climate Module 19
5. GEM-E3 Modelling 21
  5.1 Firms 24
  5.2 Total Factor Productivity 24
  5.3 R&D, Human Capital and knowledge spillovers 25
  5.4 Households 25
  5.5 Labour Market 26
  5.6 Trade 26
  5.7 Government 26
6. Model linking 26
  6.1 GEM-E3 to TIAM-UCL: Demand drivers 27
  6.2 TIAM-UCL to GEM-E3: Energy system data 28
  6.3 PRIMES 28
7. Policy strategies 28
  7.1 Border Carbon Adjustments (BCAs) 29
  7.2 Global co-operation 29
8. References 31

Introductory Note:

This Technical Supplement should be read in conjunction with the report 'Growth-positive zero-emission pathways to 2050', published by Sitra in March 2021, which may be found here. It goes into more detail about some of the subjects that were discussed in the report. It is not intended to be a stand-alone document, but gives supplementary information to that in the main report, as its name suggests.

1. IPCC 1.5°C Scenarios

As can be seen in Figure 1 the regional breakdown of both economic growth and emissions reduction in the 1.5°C model runs presented in the IPCC 1.5°C Special Report varies considerably, with the highest growth in Asia and the lowest in OECD countries, while emissions reductions in all regions approach or exceed 100% by 2050. The greater than 100% emissions reduction in Latin America and the Caribbean indicates that in this region there are considerable negative emissions from forests drawing down CO_2 from the atmosphere.

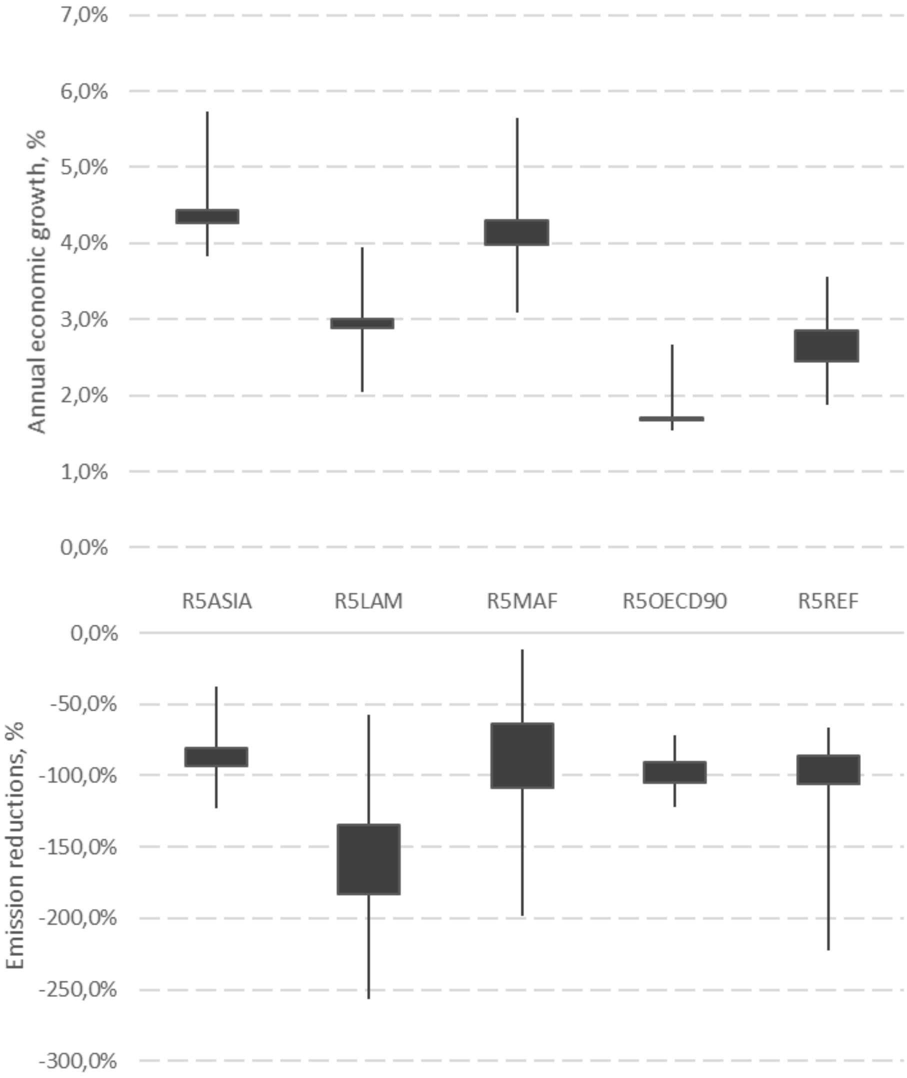

Figure 1: Regional average annual economic growth (top panel) and change in emissions (bottom panel) in IAMs for 2010 -2050 for 1.5°C scenarios. Box reflects 25-75 percentile range (n ~ 70-80), whiskers the minimum/maximum.

Author Note: Ranges reflect the outcomes of 83 individual modelled pathways, produced by a range of modelling teams and documented in (Huppmann et al., 2019). Regions refer to Asia (R5ASIA), Latin America and the Caribbean (R5LAM), Middle East and Africa (R5MAF), OECD in EU states and candidates (R5OECD90), and reforming economies of Eastern Europe and the former Soviet Union (R5REF). Exact definitions can be found here: https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/docs
Source: (Huppmann et al., 2019)

1.1 Energy demand and efficiency

As Figure 2 illustrates, 1.5°C-consistent pathways encompass a reasonably wide range of developments regarding total primary energy consumption relative to 2010 (although most pathways project only modest increases).

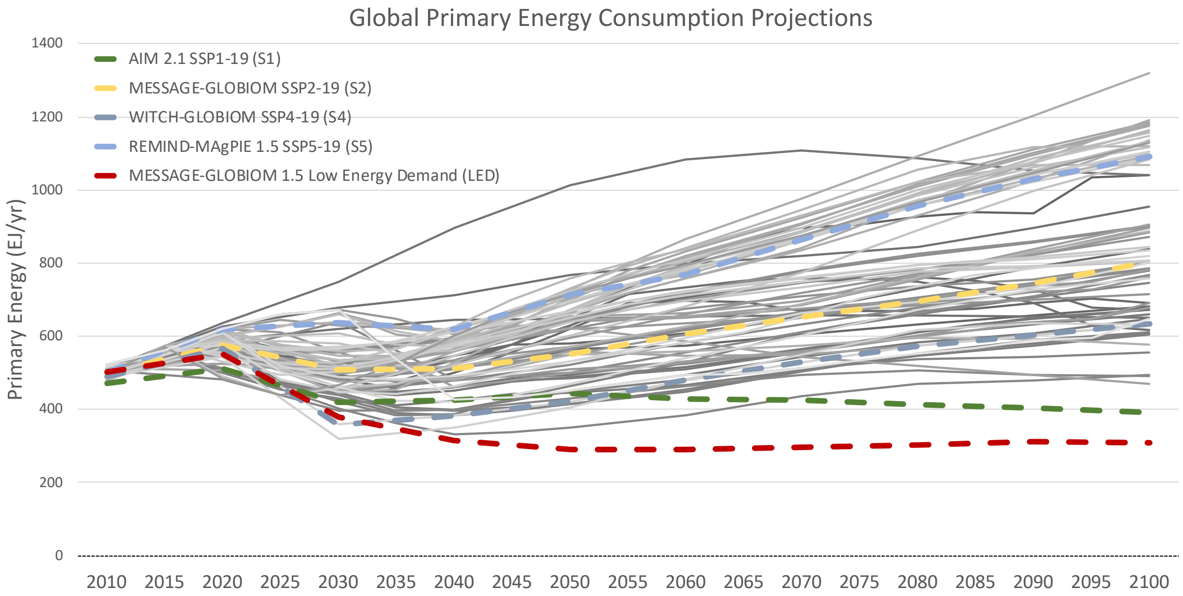

Figure 2: Global Primary Energy Consumption for 1.5°C-compliant scenarios (Data Sources: Rogelj et al., 2018a; Huppmann et al., 2019 (release 2.0)); *please note: grey lines represent the range of primary energy projections produced by all other 1.5°C-compliant scenarios reviewed by Rogelj et al. (2018a)).*

Scenarios requiring or resulting in particularly low energy demand show many synergies with other system requirements (e.g. if energy demand is reduced, so is the effort required to decarbonise what remains) (Rogelj et al, 2018a).

The S1 scenario projects the lowest energy consumption of those shown in Figure 2 (and the second-lowest of all 1.5°C-consistent pathways). This is achieved in large part through a range of other parameter assumptions that seek to implement the SSP1 narrative, including increased take up of energy efficiency measures and reduced transport service demand by households and industry, reduced consumer demand for manufactured goods, and a reduction in the input of materials required for productive activities. Energy consumption is further reduced through energy savings induced by responses to the carbon price and higher conversion efficiencies in renewable power technologies than for fossil fuel technologies.

These factors lead to rates of reductions in the energy intensity of the global economy that far exceed historic levels. For the 1.5°C-compliant SSP2 scenarios (excluding LED), energy demands are higher, the result of scenario parameters reflecting a broad continuation of existing socio-economic and technological trends. The LED scenario was designed to match, and in most cases, far exceed the activity levels or amount of energy services provided in comparable (SSP2) scenarios, but with drastically reduced energy inputs (Grubler et al., 2018), in order to examine how changing forms of energy service provision could potentially transform both the demand and the supply sides of the global energy system. The scenario and its implementation also include additional assumptions involving structural changes that avoid or shift passenger transport activity away from private cars towards other modes, such as public transport, walking and cycling, resulting in the lowest energy demand projection of all those presented in Figure 2.

1.2 Use of low-carbon energy carriers and technology

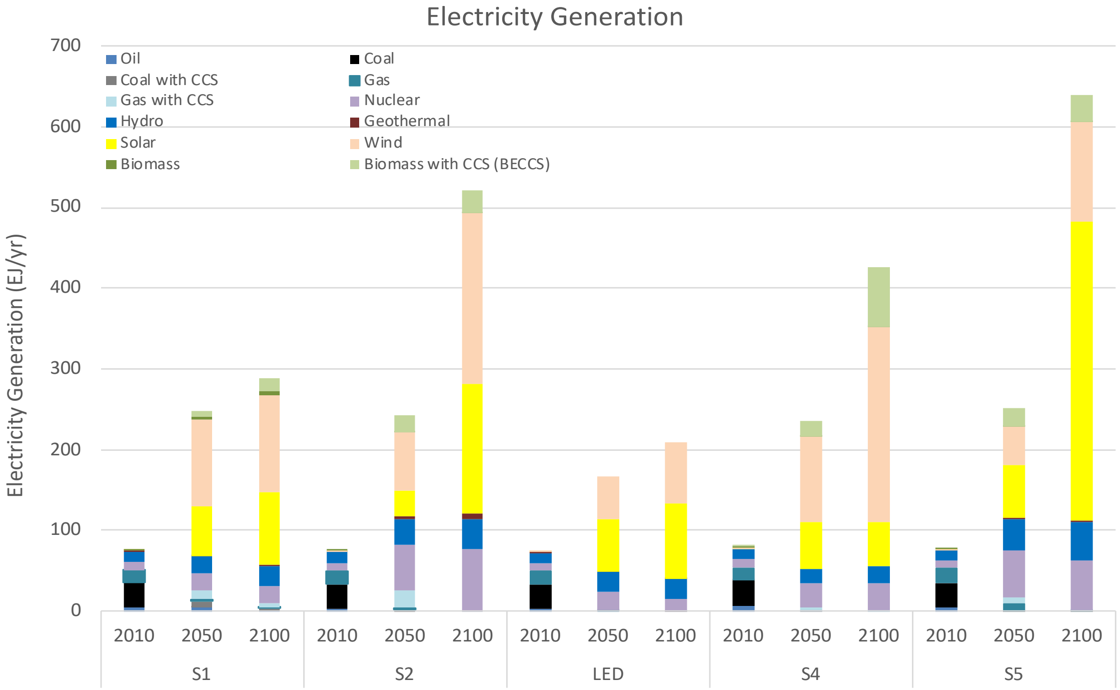

Figure 3: Global Electricity Generation (Rogelj et al., 2018a; Huppmann et al., 2019)[1].

By around 2050 electricity generation is almost fully decarbonised in all 1.5°C-consistent pathways reviewed by Rogelj et al., (2018a), as illustrated by Figure 3, above, with electrification the most important means for decarbonisation in all SSPs, as illustrated by Figure 13 in the main report. This is particularly the case in transport (e.g. through electric vehicles) and buildings (e.g. the use of heat pumps for heating), but also industry (e.g. the use of electric arc furnaces in the steel sector). The deployment of renewables (particularly wind and solar) increases substantially and rapidly, and makes a major contribution to electricity generation by 2050 in most viable pathways, alongside a rapid reduction of unabated (i.e. with no carbon capture and storage – CCS) fossil fuel use. Bioenergy, which may be used to produce electricity, liquid fuel, biogas and hydrogen, increases substantially over time in most pathways (Rogelj et al., 2018a). The use of CCS in the power sector varies substantially but is most prevalent in pathways with higher use of coal and gas. CCS plays a major role in decarbonising industrial sector process emissions, particularly in the cement, iron and steel industries (Rogelj et al., 2018a). CCS in the power sector is discussed below (except for bioenergy with CCS).

Of the scenarios presented in Figure 13 in the main report and Figure 3 above, S1 exhibits the largest rate of electrification by 2050, and along with LED, also projects the greatest combined contribution of solar and wind to electricity generation by 2050 at around 70% (from around 1% in 2010), remaining largely stable thereafter. All other contributors to electricity generation and to total final energy

---

[1] 'Solar' includes both solar photovoltaic (PV) and concentrated solar power (CSP). 'Wind' includes onshore and offshore. 'Biomass' includes municipal solid waste, purpose-grown biomass, crop residues and forest industry waste.

consumption – are all relatively minor by 2100 in most SSP1 scenarios, but with reasonably substantial variation, due to the structure of different models, and specific scenario design and implementation.

Given substantially higher global energy demand, S2 projects substantially higher absolute electricity demand than S1. The LED scenario projects a similar rate of electrification by 2100, but with substantially increased use of hydrogen, driven by a wider diffusion of fuel cells for varied applications (including transport and home energy storage). The electricity generation profile is also similar by 2100, although the LED scenario excludes CCS technology of any description. In addition, and in contrast to other scenarios, the final energy and electricity profiles in 2100 in the LED scenario are largely in place by 2050. This rapid transformation, in the absence of CCS technology, is enabled by very low energy demand (Grubler et al., 2018).

S4 projects the highest rate of electrification by 2100 at nearly 90% of final energy demand, with the remainder mostly satisfied by direct solar energy (for heating) and coal, which continues to be used to a small degree in industry. By 2050, wind and solar generate around 70% of electricity, with the remainder largely produced by nuclear, hydropower and BECCS. Between 2050 and 2100, wind power more than doubles, with BECCS also increasing (nearly five-fold).

In S5 the rate of electrification is within the range of other scenarios. However, given the particularly high total energy consumption in this scenario, electricity demand is greater than the total final energy demand in most other scenarios. By 2050, biofuels account for around half of liquid fuels (all equipped with CCS), and almost the entirety by 2100. The majority of the remainder of final energy demand is satisfied by direct heat and hydrogen. Although SSP5 assumes relatively unfavourable conditions for non-biomass renewables (as illustrated by the relatively low penetration of wind and solar by 2050 in S5), stringent mitigation requirements mean they grow substantially by 2050) (Kriegler et al., 2017).

2. The European Union’s ‘Clean Planet for All’ strategy

The Paris agreement of December 2015 requested parties to communicate their long-term strategy looking beyond the medium term. The EU Long-Term Strategy (LTS) a “Clean Planet for All - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy” was published in November 2018 and sets out the vision of the European Commission for a climate-neutral EU, looking at all the key sectors and exploring pathways for the transition. The EU’s Clean Planet for All (CP4A) strategy aims to ‘confirm Europe's commitment to lead in global climate action and to present a vision that can lead to achieving net-zero greenhouse gas emissions by 2050 through a socially-fair transition in a cost-efficient manner’ (European Commission, 2018, p.3). The EU LTS explored a number of scenarios aiming at emission reduction pathways limiting the ambient temperature increase to 1.5°C and 2°C, covering all sectors of the economy and showcasing different possible technology paradigms to achieve the emission reduction targets. The different scenarios focused on different elements of the energy system transformation process. The different core elements around which the scenarios were built are electrification, hydrogen, Power-to-X technologies, energy efficiency, circular economy and sustainable lifestyles.

The five scenarios achieve just above 80% greenhouse gas emission reductions, excluding land use and forestry, by 2050 compared to 1990. Including the sink of land use and forestry sectors which absorb more CO_2 than they emit, these scenarios achieve around 85% net greenhouse emissions reductions by 2050 compared to 1990. The scenario combining all five elements but at lower levels, reaches net greenhouse gas reductions as high as 90% (including the land use and forestry sink).

The 1.5TECH scenario focused on the increase in the contribution of all technology options for decarbonisation, and relied more heavily on the deployment of biomass associated with significant amounts of bioenergy with carbon capture and storage (BECCS) in order to reach net zero emissions in 2050. The 1.5LIFE scenario relied less on the technology options of 1.5TECH but assumed a drive by EU business and consumption patterns towards a more circular economy. Simultaneously, the increase in climate awareness of EU citizens translates into lifestyle changes and consumer choices more beneficial for the climate. In both scenarios the technological development of supply-side, carbon-free options is a key and direct contributor to the decarbonisation of the energy system, but it operates in full synergy with the evolution of energy demand.

Although a wide range of low-carbon energy carriers are represented in the CP4A modelling, hydrogen and e-fuels (synthetic fuels produced from decarbonised electricity) are a particular focus. The deployment and use of low-carbon energy carriers assume a timely deployment of the necessary infrastructure (i.e. storage and distribution of hydrogen). Hydrogen in all scenarios has an important role as a means of storage: power-to-hydrogen that can be stored in dedicated reservoirs and retransformed into electricity or used directly as a fuel. However, hydrogen can gradually take the role of an energy vector beyond its potential role in chemical storage of electricity. It could replace natural gas (albeit often with energy efficiency losses) for heating purposes or in transport (used with fuel cells) and as feedstock for industrial applications (e.g. steel industry, refineries, fertilisers). Hydrogen could also be converted to synthetic hydrocarbons by reacting, using electricity, with CO_2. The results of all scenarios examined indicate the trade-off between efficiency loss and versatility of decarbonised e-fuels that could potentially replace fossil fuels seamlessly, as well as the likely dilemma of creating the right scale of e-fuels/hydrogen consumption; "*too small uptake would hamper technology learning, while large deployment would entail substantial additional needs on the supply side)*" (European Commission, 2018).

The modelling also suggests that GHG emissions can be drastically reduced with very small impacts on Europe's GDP. The results showed that the macro-economic impact of decarbonisation (either positive or negative) will be 2% or less of GDP in 2050[2] (European Commission, 2018). In all the scenarios examined the EU economy continues to grow[3].

3. Shared Socio-Economic Pathways (SSPs)

The Shared Socio-economic Pathways (SSPs) are a set of five internally consistent, qualitative socio-economic development assumptions, developed by the modelling community in order to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. Corresponding Shared climate Policy Assumptions (SPAs), on policy stringency, sectoral coverage and regional participation, have also been developed to guide analysis (Riahi et al., 2017). Over time, these assumptions have been increasingly quantified (e.g. Dellink et al., 2017; Samir and Lutz, 2017), further increasing consistency between analyses. The SSPs and corresponding SPAs are described qualitatively in Table 1, below.

---

[2] "The negative impact implies at worst that real GDP would be 1.30% lower in 2050 than under the baseline (JRC-GEM-E3, 1.5°C global action scenario). At best, the positive impact could imply that real GDP would be 2.19% higher than baseline in 2050 (E3ME, 1.5°C global action scenario)" EC, 2018

[3] "The EU economy [grows] at worst by 66.0% between 2015 and 2050 instead of 68.1% under the Baseline (JRC-GEM-E3, 1.5°C global action scenario), or at best by 73.7% instead of 70.7% (E3ME, 1.5°C global action scenario)" EC, 2018.

Table 1: Shared Socio-economic Pathways (SSPs) and Shared Policy Assumptions (SPAs). Sources: (Bauer et al., 2017; O'Neill et al., 2017; Riahi et al., 2017)

Name	Shared Socio-Economic Pathways (SSPs)	Shared Policy Assumptions
SSP1 **Sustainability – Taking the Green Road** (*Low challenges to mitigation and adaptation*)	The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Increasing evidence of and accounting for the social, cultural, and economic costs of environmental degradation and inequality drive this shift. Management of the global commons slowly improves, facilitated by increasingly effective and persistent cooperation and collaboration of local, national, and international organizations and institutions, the private sector, and civil society. Educational and health investments accelerate the demographic transition, leading to a relatively low population. Beginning with current high-income countries, the emphasis on economic growth shifts toward a broader emphasis on human well-being, even at the expense of somewhat slower economic growth over the longer term. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Investment in environmental technology and changes in tax structures lead to improved resource efficiency, reducing overall energy and resource use and improving environmental conditions over the longer term. Increased investment, financial incentives and changing perceptions make renewable energy more attractive. Consumption is oriented toward low material growth and lower resource and energy intensity. The combination of directed development of environmentally friendly technologies, a favourable outlook for renewable energy, institutions that can facilitate international cooperation, and relatively low energy demand results in relatively low challenges to mitigation. SSP1, with its central features of commitment to achieving development goals, increasing environmental awareness in societies around the world, and a gradual move toward less resource-intensive lifestyles, constitutes a break with recent history in which emerging economies have followed the resource-intensive development model of industrialized countries. To some extent, elements of this scenario can already be found in the proliferation of "green growth" and "green economy" strategies in industrialized and developing countries although their efficacy has been questioned. For these strategies to succeed there would need to be innovation in both industrialized and developing countries and adequate human and financial resources. Such innovation has been spurred by environmental policy, and this SSP assumes that policy changes are driven by changing attitudes. The focus on equity, and the de-emphasis of economic growth as a goal in and of itself in high-income countries, leads industrialized countries to support developing countries in their development goals, including green growth strategies, by providing access to human and financial resources and new technologies.	Fragmentation up to 2020, transition to globally uniform carbon price directly thereafter

Name	Shared Socio-Economic Pathways (SSPs)	Shared Policy Assumptions
SSP2 **Middle of the Road** (*Medium challenges to mitigation and adaptation*)	The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Most economies are politically stable. Globally connected markets function imperfectly. Global and national institutions work toward but make slow progress in achieving sustainable development goals, including improved living conditions and access to education, safe water, and health care. Technological development proceeds apace, but without fundamental breakthroughs. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Even though fossil fuel dependency decreases slowly, there is no reluctance to use unconventional fossil resources. Global population growth is moderate and levels off in the second half of the century as a consequence of completion of the demographic transition. However, education investments are not high enough to accelerate the transition to low fertility rates in low-income countries and to rapidly slow population growth. This growth, along with income inequality that persists or improves only slowly, continuing societal stratification, and limited social cohesion, maintain challenges to reducing vulnerability to societal and environmental changes and constrain significant advances in sustainable development. These moderate development trends leave the world, on average, facing moderate challenges to mitigation, but with significant heterogeneities across and within countries. SSP2 does not imply a simple extrapolation of recent experience, but rather a development pathway that is consistent with typical patterns of historical experience observed over the past century. For example, emerging economies grow relatively quickly and then slow as incomes reach higher levels, the demographic transition occurs at average rates as societies develop, and technological progress continues without major slowdowns or accelerations. Thus it is a dynamic pathway, yet one in which future changes in various elements of the narrative are consistent with middle of the road expectations, rather than falling near the upper or lower bounds of possible outcomes. There are likely many reasons that trends in SSP elements could end up being moderate, and no specific stance is taken here as to motivating forces.	Fragmentation up to 2020, transition to globally uniform carbon price up until 2040
SSP3 **Regional Rivalry – A Rocky Road**	A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. This trend is reinforced by the limited number of comparatively weak global institutions, with uneven coordination and cooperation for addressing environmental and other global concerns. Policies shift over time to become increasingly oriented toward national and regional security issues, including barriers to trade, particularly in the energy resource and agricultural markets. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development, and in several regions move toward more authoritarian forms of government with highly regulated economies. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time, especially in developing countries. There are pockets of extreme poverty alongside pockets	Fragmentation up until 2020. Regions with income > 12,600 US$/capita in 2020 start linear transition to global carbon price up until 2040. Others start 10 years later with

Name	Shared Socio-Economic Pathways (SSPs)	Shared Policy Assumptions
(*High challenges to mitigation and adaptation*)	of moderate wealth, with many countries struggling to maintain living standards and provide access to safe water, improved sanitation, and health care for disadvantaged populations. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions. The combination of impeded development and limited environmental concern results in poor progress toward sustainability. Population growth is low in industrialized and high in developing countries. Growing resource intensity and fossil fuel dependency along with difficulty in achieving international cooperation and slow technological change imply high challenges to mitigation. SSP3, with its theme of international fragmentation and a world characterized by regional rivalry can already be seen in some of the current regional rivalries and conflicts, but contrasts with globalization trends in other areas. It is based on the assumption that these globalization trends can be reversed by a number of events. For example, economic woes in major economies could spark increasing discontent with globalization and spur protectionist instincts. Alternatively, regional conflict over territorial or national issues could produce larger conflict between major countries, giving rise to increasing antagonism between and within regional blocs. Such a reversal of globalization trends due to regional conflict has happened before, for example on the eve of World War I. Regional rivalries reduce support for international institutions and development partners, thus weakening progress toward development goals, resulting in substantial changes to current trends in population growth, human health and well-being, and environmental protection in some low- and middle-income countries.	transition up until 2050.
SSP4 **Inequality – A Road Divided** (Low challenges to mitigation, high challenges to adaptation)	Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that is well educated and contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labour intensive, low-tech economy. Power becomes more concentrated in a relatively small political and business elite, even in democratic societies, while vulnerable groups have little representation in national and global institutions. Economic growth is moderate in industrialized and middle-income countries, while low income countries lag behind, in many cases struggling to provide adequate access to water, sanitation and health care for the poor. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. Uncertainty in the fossil fuel markets lead to underinvestment in new resources in many regions of the world. Energy companies hedge against price fluctuations partly through diversifying their energy sources, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas. The combination of some development of low carbon supply options and expertise, and a well-integrated international political and business class capable of acting quickly and decisively, implies low challenges to mitigation.	Fragmentation up to 2020, transition to globally uniform carbon price directly thereafter.

Name	Shared Socio-Economic Pathways (SSPs)	Shared Policy Assumptions
	Expanded education has been an important contributor to lowering inequality in the recent past; this narrative assumes the converse, that limited access to education can increase inequality. In addition, less affluent groups are assumed to have weak political power, fewer economic opportunities, and limited access to credit, constraining both educational opportunities and income growth and making inequality more persistent. At the same time, those at the top end of the income scale see their relative position reinforced through institutional changes that strengthen their bargaining power at the expense of low earners. Across countries, the assumption that growth results in separation into different country income groups is consistent with the idea of “convergence clubs”, as opposed to the conditional convergence hypothesis. Historical experience regarding within-country inequality is mixed, while SSP4 assumes that it increases in the long term. For some countries this means that recent trends will eventually reverse. This is plausible because such improvements can be temporary. SSP4 assumes increasingly restricted access to education, which could plausibly halt or reverse improvements. It is also important to note that this pathway envisions a slowdown, but not a halt to or reversal of the growth of the global middle class.	
SSP5 **Fossil-fueled Development – Taking the Highway** (*High challenges to mitigation, low challenges to adaptation*)	Driven by the economic success of industrialized and emerging economies, this world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated, with interventions focused on maintaining competition and removing institutional barriers to the participation of disadvantaged population groups. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary. While local environmental impacts are addressed effectively by technological solutions, there is relatively little effort to avoid potential global environmental impacts due to a perceived trade-off with progress on economic development. Global population peaks and declines in the 21st century. Though fertility declines rapidly in developing countries, fertility levels in high income countries are relatively high (at or above replacement level) due to optimistic economic outlooks. International mobility is increased by gradually opening up labour markets as income disparities decrease. The strong reliance on fossil fuels and the lack of global environmental concern result in potentially high challenges to mitigation. SSP5 foresees accelerated globalization and rapid development of developing countries, including a significant improvement of institutions and the economic participation of disadvantaged population groups. The economic success of emerging economies and more recently least developed countries has given rise to an emergent global middle class	Fragmentation up to 2020, thereafter, transition to globally uniform carbon price up until 2040.

Name	Shared Socio-Economic Pathways (SSPs)	Shared Policy Assumptions
	that has been lacking in most regions of the world. The new middle class could stabilize global economic development by promoting robust growth in demand for services and goods. It may also generate societal pressure toward improved institutions and more participatory societies. Second, the digital revolution enables a global discourse of a significant and increasing fraction of the global population for the first time in human history which may lead to a rapid rise in global institutions and promote the ability for global coordination.	

4. TIAM-UCL Modelling

This study used the TIAM-UCL global energy systems model (the TIMES Integrated Assessment Model at University College London) to describe the development of the global energy system and its related emissions. The model includes a series of features which make it a suitable model for evaluating global zero-emission pathways compliant with Paris targets for this study:

1. Detailed description of the global energy system from primary resources through their conversion, transport, distribution and eventual use to meet energy demands in a range of end-use sectors.
2. Quantification of emissions throughout the energy system, allocating them to the processes that are responsible for them, and consideration of non-energy emissions and their impact on the climate.
3. Time-evolution approach to investigate transitions in the energy system from the current day to the medium-term (2030), mid-century (2050) and long term (up to 2100).
4. Technology transitions driven by least-cost optimisation across the full time horizon of the model
5. Climate module that generates temperature projections from calculated greenhouse gas emissions.

TIAM-UCL has been used to investigate a range of topics e.g. fossil fuel resource assessment (McGlade and Ekins, 2014, 2015; McGlade et al., 2014; Bauer et al., 2018; Bradley et al., 2018), fossil fuel trade (De Cian et al., 2013; Pye et al., 2016), bioenergy use (Butnar et al., 2020), industrial energy demand (Edelenbosch et al., 2017), energy demand response (Kesicki and Anandarajah, 2011), technology learning (Anandarajah et al., 2013), transport decarbonisation (McCollum et al., 2018), role of CCS (Ekins et al., 2017), sensitivity of emissions to drivers (Marangoni et al., 2017), macroeconomic impacts (Winning et al., 2019) and climate ambition (Anandarajah and Gambhir, 2014; Dessens et al., 2016; Winning et al., 2018; S. Pye et al., 2019; Cronin et al., 2020).

Full descriptions of the model are available in the TIAM-UCL documentation (Anandarajah et al., 2011; IAMC, 2016), with an update scheduled for publication in early 2021 (Pye et al., 2021). Brief summaries of the model descriptions are reproduced here; fuller details can be found in the model documentation.

4.1 Methodology

TIAM-UCL is a multi-region, multi-sector energy system model built in the TIMES framework (Loulou et al., 2005), which uses a linear programming approach to explore cost-optimal systems. Decisions around what energy sector investments to make across regions to meet these energy service demands are determined on the basis of the most cost-effective investments, taking into account the existing system in 2020, energy resource potential, technology availability, operation of the technologies and policy constraints such as emissions reduction targets. The model's objective is to minimise the discounted total system cost over the full time horizon of the model (until 2100). Features of this formulation include perfect competition (no market power held by specific firms) and perfect foresight (market players have all information, now and in the future, to inform investment decisions), though stochastic and myopic foresight variants of the model are also available. TIAM-UCL is a partial equilibrium model, meaning that it only considers the energy sector, and that it finds the equilibrium points on cost-demand curves.

The model has 16 regions which allows for a detailed characterisation of regional energy sectors, and the trade flows between them. These regions include Africa (AFR), Australia (AUS), Canada (CAN), Central and South America (CSA), China (CHI), Eastern Europe (EEU), Former Soviet Union (FSU), India (IND), Japan (JAP), Mexico (MEX), Middle-east (MEA), Other Developing Asia (ODA), South Korea (SKO), United Kingdom (UK), USA (USA) and Western Europe (WEU). The countries included in each region are listed in the documentation (Anandarajah et al., 2011)

TIAM-UCL is an inter-temporal model, solving for the global energy system between the years 2005-2100. While the model can be run in different time step configurations, the model typically uses five-year time steps until 2060, and ten-year time steps thereafter. Within a given year, the structure consists of six periods (or time slices), based on three seasons (summer, winter and intermediate), and two diurnal periods. This is important for allowing changes in electricity and heat load based on sector demand profiles.

A representation of the structure of the energy system within each region in TIAM-UCL is shown in Figure 4. A resource sector represents the fossil and renewable resources available across different regions. However, this is not a closed system, with trade in energy commodities and CO_2 / GHG certificates (offsets) possible between regions (disabled in this study for the EU due to the inclusion of emissions data from PRIMES, but enabled for the non-EU regions). An upstream sector extracts, processes and distributes those resources, and supplies them to the power and end use sectors directly, or enables secondary transformation (hydrogen, biofuels). Five end use sectors use the energy supplied to meet energy service demands for a range of services (mobility, industrial products, thermal comfort in buildings). There is normally a range of technological alternatives available for each of the service demands explicitly modelled. CO_2 can also be captured and stored at different points across the system and transported and stored. At all parts of the energy system, GHG emissions are accounted for.

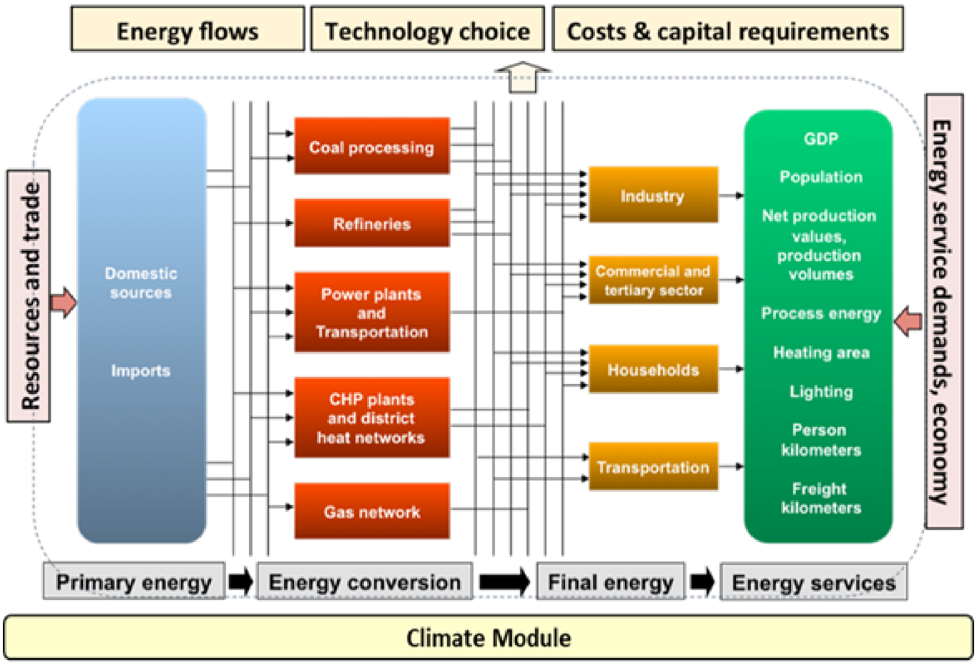

Figure 4: The TIAM-UCL global energy system model

TIAM-UCL is calibrated to the global energy system in 2005.[4] Current and projected cost and technical data (including capital costs, variable and fixed operating costs, discount rates, efficiency, lifetime, availability and emission factors) for the large number of processes and commodities in TIAM-UCL are derived from a wide range of official and peer-reviewed publications and regularly updated; current values used are reported in the forthcoming TIAM-UCL documentation update (Pye *et al.*, 2021). The historical development of technology data in some sectors (particularly power and transport) up to 2020 as well as global CO_2 emission data was included for this study. Existing technologies are eventually phased out in most sectors and new technologies deployed with different costs, efficiencies and fuels. A large array of growth constraints are deployed to maintain realistic transition rates to reduce the occurrence of stranded assets and to reflect the time taken to create new supply chains. Other model constraints restrict the availability of key resources, based on the estimates of their availability or potential, or explore different scenarios (*e.g*. SSP1 assumptions). Constraints can be imposed on commodities and processes and can vary by region and timeperiod, and large models like TIAM-UCL can have large numbers of constraints.

As with other Integrated Assessment Models (IAMs), TIAM-UCL is often used to explore alternative futures under different levels of climate ambition, assuming action is taken to effect this change. Individual country or regional level policies are usually not modelled in detail, except for nationally determined contributions (NDCs) which are increasingly used as a reference case against which to compare more ambitious climate policies (Winning et al., 2019). TIAM-UCL has also been used to investigate scenarios of differentiated regional action, in which developed countries take a lead in cutting emissions with some nations and regions ahead of others in developing climate policy that will enable deeper emission reductions than suggested by the scenarios of unified global action (Steve Pye et al., 2019).

For this study, global CO_2 emissions for 2015 (and projected to 2020) were calibrated to reported data (GCP, 2019). This means that 2025 was the first year for which the model made decisions for reducing emissions. TIAM-UCL also permits energy demand to respond to price changes. A reference case was therefore run to generate base prices, in response to changes to which energy demands change in the runs that follow.

4.2 Demands

Projecting future energy demands is a key prerequisite before the energy system required to meet these demands can be determined. Future demands for energy services can be expected to increase due to factors such as population and economic growth. These demands are dynamic, in that they can rise or fall in response to changes in the cost of providing energy services, as noted above, via the use of long run price elasticities. Reductions of energy service demands provide another route for reducing emissions.

TIAM-UCL has 60 energy service demands (ESDs) in five major sectors, as shown below in Table 2. Note that some demands such as heating and cooling are split into up to four subregions for some regions (USA, Canada, Africa *etc*.) representing, for example, urban and rural areas. Typically energy service demands are assumed to vary according to changes in underlying drivers. TIAM-UCL normally uses drivers such as population, GDP and the number of households from external sources (*e.g*. UN statistics, World Bank, IEA) (IAMC, 2016). In this study a bottom-up approach is then used to construct TIAM-UCL's energy service demands. Data for each of TIAM-UCL's demands for each region in the

---

[4] An updated version of TIAM-UCL recalibrated to 2015 is due for release later in 2021 (the base year always needs to be in the recent past for which complete historical data is known).

base year is derived from IEA data. Demands in future timeperiods are then calculated from the demand in the preceding timeperiod and the change in the associated driver using the following equation:

$$ESD_t = k \times ESD_{t-1} \left(\frac{Driver_t}{Driver_{t-1}} \right)^{\propto_t}$$

In general (but not always) it is assumed that energy service demands grow more slowly than the underlying driver. This is reflected through the application of a decoupling factor α to decouple demand from its associated driver, where α is usually less than 1. Decoupling factors typically decrease over time as the decoupling of demands from their drivers is expected to increase during the 21st century. Also, demands are occasionally modified further with a calibration factor *k*; in this study this was not necessary as the drivers were more directly linked to the service demand than usually is the case (due to the model linkage, see discussion in section 6.1).

Energy service demands are typically measured in units of energy (PJ), distance (bvkm) or mass (mt). This is because they are demands for a particular service, which can be measured in different ways in different sectors. TIAM-UCL goes on to calculate the actual energy required to supply these services, which then takes into account issues such as improving appliance or process efficiency.

4.3 Primary energy resources

The fossil fuel upstream sector (covering coal, gas and oil) in TIAM-UCL incorporates the availability and costs of primary energy resources, extraction processes, and any upgrading / processing required to yield energy commodity carriers that can be used as inputs into end-use sectors. Conventional and unconventional resources are considered. Cost curves are included to allow more accessible and higher quality resources to be depleted first, and vary by region including regionalised extraction costs (McGlade and Ekins, 2015; Welsby, 2020). Once processed into transportable energy carriers, fossil fuel commodities can be traded between regions, allowing global markets and prices to be simulated. Regional matrices are used to determine inter-regional trade flows, with flexible forms of transportation (*e.g.* LNG) having more trade links than less flexible modes such as pipelines. Transportation costs are included.

TIAM-UCL considers six types of bioenergy feedstock: municipal waste, industrial waste, landfill gas, solid biomass, energy crops and liquid biofuels derived from food crops (Butnar et al., 2020). Cost supply curves are defined for each feedstock and for each of the 16 regions (including collection and transport costs), specifying the amount of biomass available at different costs in each region. Only solid biomass and energy crops are available for international trade or can be used for BECCS. The cost and emissions of international transport of the two traded bioenergy commodities are modelled endogenously in TIAM-UCL as a function of the distance between regions. CO_2 emissions associated with land-use change for energy crop cultivation are included in the model, while the other biomass fractions are assumed to produce no land-use change. Emissions coefficients are applied for CO_2, CH_4 and N_2O depending on how the biomass is used.

The biomass availability assumptions used in this study consider that energy crops are cultivated only on degraded agricultural land and pastures which cover 207 Mha in 2050 (Butnar et al., 2020). This area remains constant to 2100 with no competition with food production or other uses of land. Available land and energy crop yields are detailed on a regional basis and determine the maximum amount which can be produced by energy crop production technologies in each region. The emissions released from bringing degraded land into cultivation for energy crops are quantified in terms of land-use (planting, growing and harvesting the biomass) and land-use change (switching land from its current use to the production of energy crops). Indirect land use change (LUC) potentially caused by energy crops expansion and LUC emissions for other biomass fractions are not considered. The resulting biomass availability assumptions for 2050 are shown in Figure 5; the three cost categories together provide a maximum biomass availability of 103 EJ p.a. in 2050. Of this, TIAM-UCL used 93.3 EJ p.a. in the Central Scenario in 2050, rising slightly to 96.8 EJ p.a. in 2100. These are fairly close to the values of 67 EJ p.a. in 2050 and 87 EJ p.a. in 2100 found for a SSP1 pathway limiting warming to 1.5°C for the IPCC Special Report on 1.5°C (Huppmann et al., 2019). Other assumptions around biomass and land use change used in this study can be found in the documentation (Butnar et al., 2020; Pye et al., 2021).

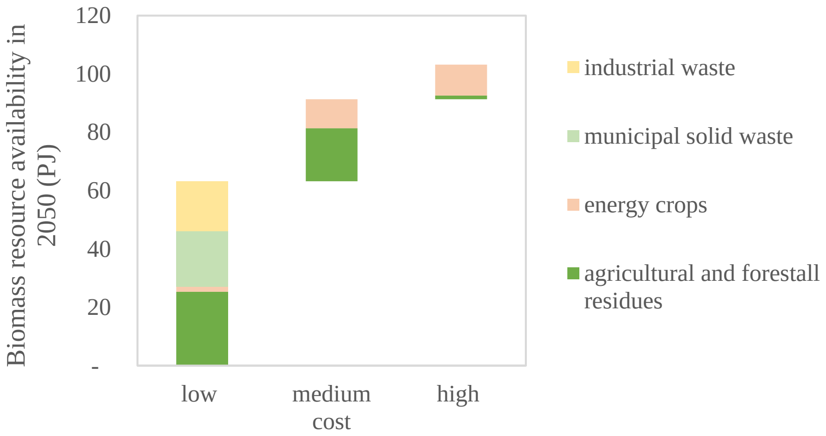

Figure 5: TIAM-UCL assumptions on global biomass resource potential. Agricultural and forestall residues (solid biomass) and energy crops are available at increasing costs, reflecting incremental difficulty of securing higher amounts of biomass (Butnar et al., 2020)

The renewable energy sources covered in TIAM-UCL include onshore and offshore wind, solar photovoltaics (PV), concentrated solar power (CSP), hydropower, tidal power and geothermal. Resource potentials for each technology are expressed as technical capacity deployment potentials for each region in the model. For onshore and offshore wind these are taken from (Eurek et al., 2017). The potentials of other renewables are taken from the ETSAP version of TIAM. Currently, electricity cannot be traded in TIAM-UCL. GHG commodities can also be traded, allowing for the formation of carbon markets, in simulations where GHG targets are regionally differentiated (not considered in this study).

4.4 Energy supply sectors

TIAM-UCL includes the conversion of primary energy into secondary energy carriers including electricity, heat, hydrogen and biofuel through energy conversion technologies. The parameters of the conversion technologies included are capital expenditure, cost of capital, fixed and variable costs, efficiency, lifetime and capacity factor. TIAM-UCL tracks the stock of technologies, meaning that investments are made on the basis that the technology will be in use for its lifetime, although early retirement of technologies is also possible. Cost improvements can be modelled using endogenous technology learning (ETL), though this study followed the normal approach and defined improvements exogenously (as summarised in Section 4.1).

Non-renewable power generations technologies in TIAM-UCL include coal (gasification and supercritical), oil, gas CCGTs, nuclear (advanced LWR) and storage. Renewables include bioenergy (combustion, gasification and MSW), hydro, onshore and offshore wind, solar (PV and CSP), tidal and geothermal. CCS is available with generation from coal, gas and biomass (energy crops and solid biomass only). Centralised producers are connected to the transmission network while decentralised production is connected to the distribution network. CHP and dedicated heat generation are included to supply heat networks. TIAM-UCL also contains a detailed representation of the hydrogen sector, including production, transportation, distribution, blending, refuelling and end-use technologies in buildings, transport and industry.

4.5 CCS, BECCS and DAC

Carbon capture and sequestration (CCS) is available in a number of sectors in TIAM-UCL: electricity and heat production, hydrogen production, synthetic fuel production (via Fischer Tropsch processes), and industry. The latter includes CCS for combustion emissions from process heat production in the iron and steel, non-metallic minerals and other industry sub-sectors [but not in the chemicals, non-ferrous minerals and pulp & paper sectors]. There are also CCS technologies that capture CO_2 process emissions from cement production and the use of petrochemical feedstocks. CO_2 captures rates of 90% are assumed for all fossil CCS technologies. TIAM-UCL assumes that CCS is available from 2030 and allowed to grow at between 2-5% *p.a*., reaching 15-24 GtCO2 p.a. by 2100

BECCS is available for various bioenergy processes in TIAM-UCL, including power generation by combustion or gasification of energy crops or of solid biomass (agricultural and forest residues), heat production by solid biomass combustion, and hydrogen production from a mix of solid biomass and energy crops. BECCS is also available on the production of advanced transport fuels produced through Fischer Tropsch (FT) processes either from energy crops or biomass. BECCS is assumed to be available in this study from 2030.

Direct air capture and storage (DACS) is currently a speculative technology that may be able to capture CO_2 from the atmosphere for geologic storage. Costs and energy consumption are currently high, but may reduce as the technology is commercialised. DACS is represented in TIAM-UCL based on the two-loop hydroxide-carbonate system, and is assumed to be available from 2040.

This study sought to reduce reliance on CCS, BECCS and DACS technologies due to their uncertain nature. As can be seen from the emissions charts in the Main Report for the Central Scenario, TIAM-UCL implemented relatively low amounts of fossil fuel CCS for the electricity and industrial sectors (around 1 and 2 $GtCO_2$ *p.a*. respectively). TIAM-UCL sought to use higher amounts of BECCS and DACS; to reduce their usage, a limit of 10 $GtCO_2$ *p.a*. was imposed on their combined implementation (TIAM-UCL combines the CO_2 sequestered from BECCS and DACS in the reporting as these emissions can be considered to come directly from the atmosphere). In addition, a limit of 4 $GtCO_2$ *p.a*. was imposed directly onto DACS. The results indicate that the Central Scenario used around 3 $GtCO_2$ *p.a*. of BECCS and 4 $GtCO_2$ *p.a*. of DACS. Total CCS, BECCS and DACS usage remained at around 10 $GtCO_2$ *p.a*. or below throughout the second half of the century. For comparison, the RCP 1.9 pathways (limiting warming to 1.5 °C or below) in the SSP database (Rogelj et al, 2018b) average around 12 $GtCO_2$ *p.a*. of BECCS and 15 $GtCO_2$ *p.a*. of total CCS (DACS is not included in the SSP pathways). Further details of the technology assumptions for CCS, BECCS and DAC can be found in the TIAM-UCL documentation (Pye et al., 2021).

4.6 End use sectors

The industrial sector in TIAM-UCL currently has six major subsectors: iron and steel, non-ferrous minerals, non-metallic minerals, chemicals, pulp and paper, and other industry. Each of these subsectors contain five types of fuel technology: heat, machine drive, steam, electro-chemical process, and other, the shares of which are fixed to those in the calibration year, in each region and for each of the subsectors. These technologies are powered by a range of fuels (oil, natural gas, coal, electricity, biomass and heat) and derived fuels such as coke, blast furnace gas and naptha. Two other industry sectors ("Industry and other non-energy consumption" and "Other non-specified consumption") have fixed shares of fuels exogenously specified for different periods to 2100. The primary low-carbon fuels available to the industry sector are electricity and biomass. A few industry technologies can use CCS to capture CO_2 emissions; these are primarily technologies producing heat from coal or natural gas in the iron and steel, non-metallic minerals, and other industry sectors. Note that although biomass can be used in some industrial processes, TIAM-UCL does not currently allow these to be fitted with CCS. The net result is that TIAM-UCL currently has limited mitigation options available for industry, leading to an increased requirement for negative emission technologies outside the industry sector.

The buildings end-use sector in TIAM-UCL is driven by various residential and commercial energy service demands (ESDs). The residential and commercial sectors have similar ESDs to each other, and are typically constructed to reflect the assumption that each economy will eventually transition to more service-intensive economic activity. Table 2 lists the residential and commercial ESDs used in TIAM-UCL along with the drivers and decoupling factors used in this study, as explained in Section 6.1. The buildings sector in TIAM-UCL allows some geographic disaggregation, *e.g*. allowing energy services to distinguish between different heating and cooling demand within large regions, or to be split into rural and urban demand. This is particularly useful in regions with a large and relatively cheap natural gas resource such as Africa, India, China and Other Developing Asia but without a widespread gas distribution network, to prevent usage of large volumes of gas for some energy services (*e.g*. cooking). The buildings sector is set up to allow the phaseout of initial technologies and transition to cleaner technologies (*e.g*. heat pumps for residential and commercial heating, and cleaner-burning biomass technologies).

The transport sector is characterized by 14 energy-services plus one non-energy use demand segment. The road transport sector consists of passenger vehicles (two/three wheeled vehicles, cars, light duty vehicles and buses) and road freight (commercial, medium and heavy trucks). Off-road transport consists of rail (passengers and freight), aviation (domestic and international) and shipping (also domestic and international). These energy service demands are listed in Table 2. The shift between transport modes as a reaction to their price changes (*e.g*. from cars to buses or trains) is not modelled endogenously in the standard TIAM-UCL. There is a range of fuels represented in TIAM-UCL to supply existing and new transport technologies, including gasoline, diesel, heavy fuel oil, kerosene, electricity, bio-ethanol, hydrogen, natural gas, LPG, coal and methanol. The version of TIAM-UCL used in this study also allowed the use of a number of low-carbon fuels in rail (bio-diesel, hydrogen and electricity), shipping (also bio-diesel, hydrogen and electricity) and aviation (bio-kerosene and electricity).

Table 2: Energy service demands in TIAM-UCL

Sector	Energy service demands
Residential	Cooling (Regions 1-4), Clothes Drying, Clothes Washing, Dishwashing, Other Electric, Space Heat (Regions 1-4), Hot Water, Cooking (Regions 1-3), Lighting (Regions 1-3), Refrigeration, Other Residential
Commercial	Cooling (Regions 1-4), Cooking, Space Heat (Regions 1-4), Hot Water, Lighting, Office equipment, Refrigeration, Other Commercial
Transport: Road	Auto Demand, Light Vehicle Demand, Bus Demand, Two Wheels Demand, Three Wheels Demand, Commercial Trucks Demand, Road Medium Trucks Demand, Heavy Trucks Demand
Transport: Other	Rail passengers, Rail freight, Domestic shipping, International shipping, Domestic aviation, International aviation, Non-energy use
Industry	Chemicals, Iron and steel, Non-ferrous metals, Non-metallic minerals, Pulp and paper, Other industries, Other industrial consumption, Industrial and Other Non-Energy Uses, Other non-specified consumption
Land Use	Agriculture

The land use sector in TIAM-UCL (also called the agriculture sector) includes both combustion and process emissions. Combustion emissions (*e.g.* from agricultural equipment) are modelled using a single energy service demand (Table 2) which can be met by different fuels. The main low-carbon fuels available for reducing emissions in this sector are bio-diesel and electricity; this study allowed higher fractions of these fuels to allow deep emission cuts in this sector. Process emissions are net CO_2 emissions from deforestation and reforestation (land use and forestry emissions, *i.e.* LULUCF). This study used a fixed trajectory using outputs from the IMAGE model based on the RCP2.6 SSP2 case (which are similar to the SSP1 values), available from the SSP Database (IIASA, 2016). These are negative from 2060 and reach -1.5 $GtCO_2$ *p.a.* in 2100 and, with combustion emissions falling towards zero, lead to negative overall emissions from the land use sector.

4.7 Climate Module

TIAM-UCL contains an in-built climate module for generating temperature projections based on TIAM-UCL's predicted greenhouse gas emissions (Loulou et al., 2016), and an overview of the module is provided here. The climate module contains three stages, as described in Figure 6:
1) from emissions to atmospheric concentrations
2) from concentrations to radiative forcing
3) from radiative forcing to realised temperature

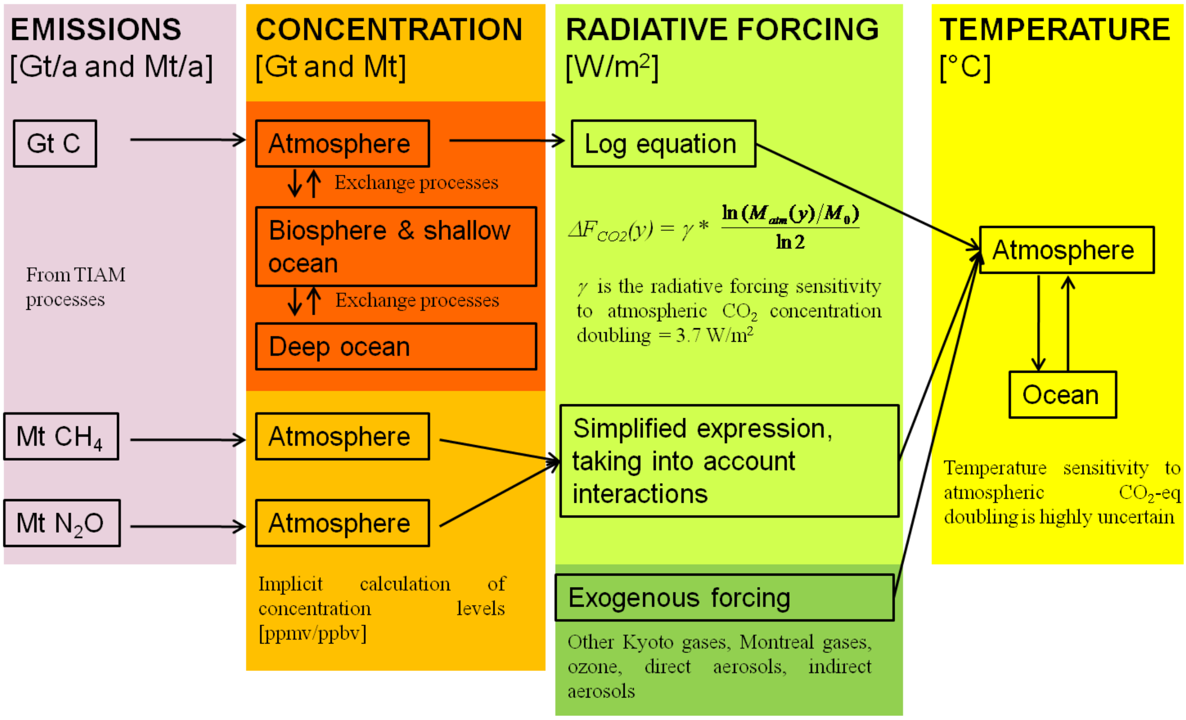

Figure 6: Overview of the TIAM-UCL climate module representation (Pye et al., 2021).

A three-reservoir model is used for the carbon dioxide cycle (the atmosphere, a quickly-mixing reservoir including the biosphere and shallow ocean, and the deep ocean). This leads to linear recursive equations for calculating CO_2 concentrations in each reservoir (Nordhaus and Boyer, 1999). This is a well-documented (albeit simple) approach, which gives a good approximation of more complex climate models. The non-linear forcing equation is used in most climate models, and is linearised for use in TIMES models with an approximation with good accuracy when calibrated for the forcing region of interest. Finally, temperatures are calculated using a two-reservoir approach also involving linear equations.

Two other greenhouse gases also included in the module are methane and nitrous oxide. These are not converted into CO_2-equivalents, but their life cycles are modelled separately. This involves the linearisation of equations used in more complex models but with good accuracy (Nordhaus and Boyer, 1999; Drouet et al., 2004). The parameterisation of the three forcing equations for CO_2, CH_4 and N_2O is widely-accepted. Finally TIAM-UCL uses the best estimate values for the equilibrium climate sensitivity (ECS) and climate feedback parameter (λ) of 2.9°C and 1.34Wm^{-2}/°C respectively, as provided by the IPCC AR5 assessment report (IPCC, 2013). However, these values are uncertain, with a 66% chance that the true value of ECS lies in the range of 1.5°C-4.5°C.

The climate module calculates only a single global value for temperature change with no regional differentiation. The climate module interacts with the main TIAM-UCL model only in constraining the emissions of GHGs (and through that the corresponding technologies within the energy system). For example temperature projections are not used inherently to adjust energy supply (*e.g.* wind and solar), demand (heating and cooling) or the impact of extreme events (though this could be done exogenously). More details on the climate module and the underlying equations can be found in the TIMES and TIAM-UCL documentations (Loulou et al., 2016; Pye et al., 2021).

The values for the TIAM-UCL climate module parameters used in this project are calibrated to the MAGICC climate model (Meinshausen et al., 2011)[5], and can be found in the TIAM-UCL documentation (Pye et al., 2021). As a consequence, and due to the inherent uncertainties in the climate system, the calibration to the MAGICC model implies the emission pathway for a scenario in TIAM-UCL will achieve a 66% chance that the “true” value of the global temperature change falls below the temperature change calculated by the climate module. Therefore, 33% of values can be expected to be above the temperature pathway calculated.

5. GEM-E3 Modelling

GEM-E3 is an applied general equilibrium model which provides details on the macro-economy and its interaction with the environment and the energy system. It is a multi-country, multi-sectoral, dynamic model of the global economy. Each country in the model is linked with the rest of the countries/regions through endogenous trade of goods and services. The model covers the period up to 2100 with a five year time step. The dynamic properties of the model include stock/flow relationships for capital, durable goods and financing, technical progress, and agents’ adaptive or rational expectations driving investment by sector. Economic agents (Firms, Households, Government, Banks and the External Sector) adopt an optimisation behaviour that is subject to technological options and resource constraints. Figure 7 illustrates the overall structure of the GEM-E3 model.

The formulation of labour markets (differentiated by five skills) allows for the existence of involuntary unemployment at equilibrium. Through its flexible formulation, it enables the representation of hybrid or regulated situations, as well as perfect and imperfect competition market regimes. Technical progress in GEM-E3 can be either exogenous or endogenous depending on user choice.

The model database is based on GTAP v10[6] complemented by data of Eurostat, IMF, IEA and OECD[7]. The PRIMES energy system model and GEM-E3 can operate in inter-linked form closing the loop between economy, energy and environment.

The energy supply sectors in GEM-E3 are modelled so that certain features such as the finite nature of the fossil fuel resource base are taken into account. In addition, a bottom-up approach is applied for the representation of the electricity sector (i.e. the model identifies ten discrete power producing technologies) and for the transport sectors covering technology transformation.

The model covers the major aspects of public finance including all substantial taxes, social policy subsidies, public expenditures and deficit financing, as well as policy instruments specific for the environment/energy system.

---

[5] http://www.magicc.org/

[6] GTAP has full datasets for 2007,2011 and 2014.

[7] The EUROSTAT accounts are used mainly to include employment, GHG emissions and the inter-institutional transactions (i.e. transactions between households and government such as direct taxes, pension payments etc). The IMF data are used to extract 10yr bond interest rates. IEA is use to extract the non-EU energy balances and OECD is used for economic outlook.

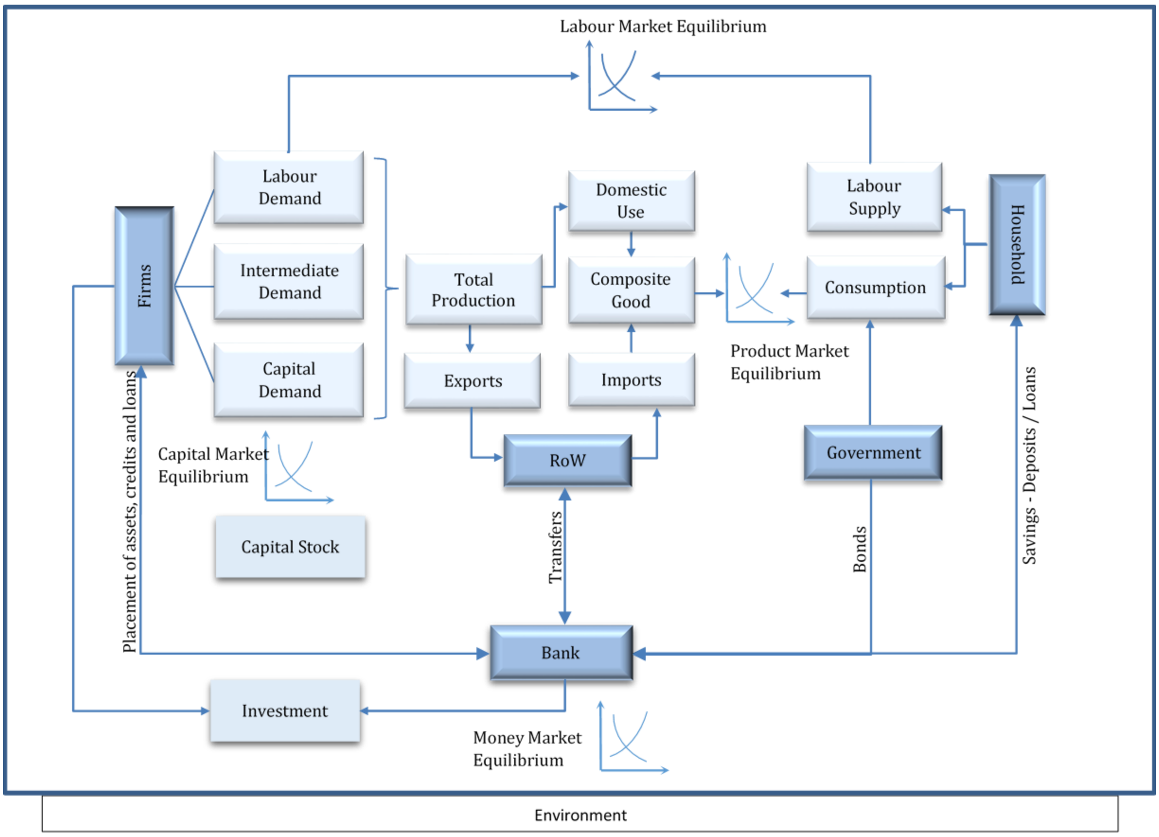

Figure 7: Economic Structure of the GEM-E3 model

The results of GEM-E3 include projections of full input-output tables by country, national accounts, employment and capital flows, balance of payments, public finance and revenues, household consumption, energy use and supply. The computation of equilibrium is simultaneous for all domestic markets of all regions and foreign trade links.
The model is not limited to comparative static evaluation of policies. The model is dynamic in the sense that projections change over time. Its properties are mainly manifested through stock/flow relationships, technical progress, capital accumulation and agents' (myopic) expectations.

The model is calibrated to a base year data set that comprises a full Social Accounting Matrices for each country/region represented in the model. Bilateral trade flows are also calibrated for each sector represented in the model, taking into account trade margins and transport costs. Consumption and investment is built around transition matrices linking consumption by purpose to demand for goods and investment by origin to investment by destination. The initial starting point of the model therefore, includes a very detailed treatment of taxation and trade.

Total demand (final and intermediate) in each country is optimally allocated between domestic and imported goods, under the hypothesis that these are considered as imperfect substitutes (the "Armington" assumption). Institutional regimes, that affect agent behaviour and market clearing, are explicitly represented, including public finance, taxation and social policy. The model represents goods that are external to the economy as for example damages to the environment.

The internalisation of environmental externalities is achieved either through taxation or global system constraints, the shadow costs of which affect the decision of the economic agents. In the GEM-E3 model global/regional/sectoral constraints are linked to environmental emissions, changes in consumption or production patterns, external costs/benefits, taxation, pollution abatement investments and pollution permits. The model evaluates the impact of policy changes on the environment by calculating the change in emissions and damages and determines costs and benefits through an equivalent variation measurement of global welfare (inclusive environmental impact).

Once the model is calibrated (i.e. it reproduces exactly the base year), the next step is to define a reference case scenario. The reference case scenario includes all already decided policies. The key drivers of economic growth in the model are labour force, total factor productivity and the expectations on sectoral growth. The “counterfactual” equilibria can be computed by running the model under assumptions that diverge from those of the reference scenario. This corresponds to scenario building. In this case, a scenario is defined as a set of changes of exogenous variables, for example a change in the tax rates. Changes of institutional regimes, that are expected to occur in the future, may be reflected by changing values of the appropriate elasticities and other model parameters that allow structural shifts (e.g. market regime). These changes are imposed on top of the assumptions of the reference scenario thereby modifying it. To perform a counterfactual simulation it is not necessary to re-calibrate the model. The different steps for performing a counterfactual simulation in GEM-E3 are depicted in Figure 8 .

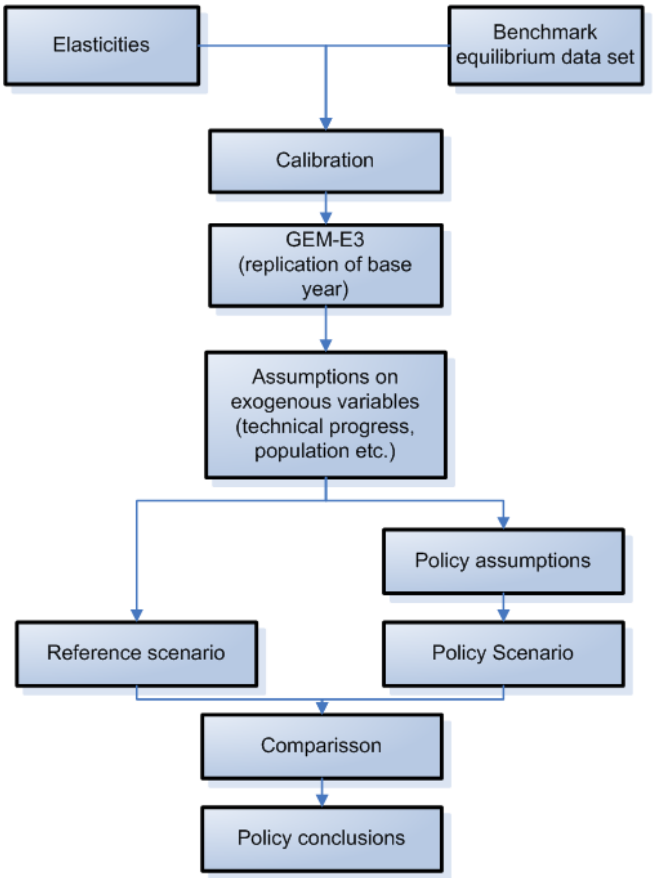

Figure 8: Key stages in operating the GEM-E3 model

A counterfactual simulation is characterised by its impact on consumer welfare or through the equivalent variation of the consumer welfare function. The equivalent variation can be, under reasonable assumptions, directly mapped to some of the endogenous variables of the model such as consumption, employment and price levels. The sign of the change of the equivalent variation gives then a measure of the policy's impact and burden sharing implications. The most important results, provided by GEM-E3, are as follows:

- Dynamic annual projections in volume, value and deflators of national accounts by country.
- Full Input-Output tables for each country/region identified in the model
- Distribution of income and transfers in the form of a social accounting matrix by country.
- Employment by economic activity and unemployment rate by country
- Capital and investment by country and sector.
- Greenhouse gasses, atmospheric emissions, pollution abatement capital, purchase of pollution permits and damages.
- Consumption matrix by product and investment matrix by ownership branch.
- Public finance, tax incidence and revenues by country.
- Full bilateral trade matrices.

5.1 Firms

Firms adopt an optimization behaviour under either a perfect competition[8] or a monopolistic competition[9] regime (in the model both the perfect competition and imperfect – monopolistic competition regimes co-exist). In both market representations, a nested multi-factor CES[10] production function is used. Firms choose the optimum level of factor inputs (including capital, labour by skill, energy, intermediate inputs and reserves). The model identifies a number of i firms, j intermediate inputs, s labour skills, one type of land, reserves (where applicable, i.e. in oil and gas production sectors) and capital. To facilitate readability, the description below refers to a one-level production function; the expansion to multi-level (nested) production is considered straightforward.

5.2 Total Factor Productivity

Total factor productivity (TFP) is composed of an exogenous and an endogenous part. The exogenous part is commonly derived through a dynamic calibration process to simulate the growth of the sector in the baseline case. This part is also consistent with historical growth trends and is econometrically estimated. The exogenous part does not change in alternative scenarios and remains at the baseline levels.

---

[8] Firms that operate in perfectly competitive sectors decide upon production factor inputs so as to minimize their production costs. Each production factor is paid at its marginal product and firms' unit cost prices are set to exactly cover the production costs (inclusive of capital payment), hence not allowing for non-normal profits. It is assumed that each firm produces a single good which is differentiated from any other good produced. The firms output, factor demands and associated unit costs are presented below. Each firm uses a constant elasticity of substitution (CES) production technology, operates under perfect competition and demands production inputs in order to minimize its production cost. The nesting of the CES production function depends on the substitution possibilities that characterize the production technology of each firm.

[9] A limited number of firms may operate under oligopoly assumptions. The modelling of oligopoly is based on the concept of product varieties, derived from the theory of industrial organisation and the concept of economies of scale. Firms in these sectors operate under non-constant returns to scale involving a fixed cost element, endogenously determine their price/cost mark-ups based on Nash-Bertrand or Nash-Cournot assumptions. Firms in these sectors can make profits/losses which will alter the concentration and firm size in the sector. Demand then is also firm-specific in the sense that changes in product varieties directly affect the utility of the consumers.

[10] The CES elasticity parameters are mainly derived from the Fragkiadakis C. et al (2012) study and are documented in the GEM-E3 manual available at https://e3modelling.com/modelling-tools/gem-e3/ .

The endogenous part depends on:

1. Knowledge based productivity driven by public and private R&D expenditures
2. Direct and indirect knowledge spillovers stemming from R&D expenditures
3. Learning by doing effects
4. Investment in infrastructure that increase productivity of firms, i.e. investment in telecommunications, etc.

5.3 R&D, Human Capital and knowledge spillovers

R&D expenditures are distinguished in the public and private sectors in order to capture the different roles and effectiveness of the public and private sectors in the innovation process. Public R&D expenditures are decided exogenously and add up to a global stock of expenditure/knowledge that is linked to a universal TFP. Private R&D is endogenously decided by firms simultaneously with decisions about acquiring capital, labour, energy, and material. Private R&D adds up to the firm's knowledge stock and leads to productivity improvements that are firm specific. The capacity of a country to perform R&D depends on human capital availability. R&D independently of its financing (private or public) is performed by one sector in each country that performs R&D activities demanded by other sectors. The private R&D expenditures accumulate to a stock of knowledge with a certain depreciation rate. Then this stock of knowledge is linked to total factor productivity. The potential to increase productivity through R&D expenditures depends on human capital availability. In the model, the knowledge spillovers follow the patent – citations approach. The associated productivity from spillovers depends on the cumulative expenditures of the firm and its human capital stock weighted by the patent citations matrix. Learning by doing reflects the reduction of unit costs as a result of experience and repetition of the same task and economies of scale. In the model cumulative experience is proxied through cumulative production with a focus on clean energy technologies with high learning-by-doing potentials. The decision to invest in infrastructure is set exogenously, and it is assigned to the government either in a budget neutral way or financed by increasing / decreasing its public deficit / surplus. The construction/installation of infrastructure is provided by different firms depending on the type of infrastructure required (i.e. building roads creates demand mainly for the construction sector, building telecommunications creates demand mainly for electronic equipment). Infrastructure is an expenditure that increases the stock of existing infrastructure and is positively linked with productivity improvements, as is widely demonstrated in the scientific literature. Infrastructure is linked to productivity improvement through an exponential function whereby productivity increases for each doubling of capacity.

5.4 Households

For each region/country different groups of households are considered, differentiated according to their income. A multi-stage selection process is adopted for projecting the consumption of households: At the first stage each household group maximizes a Klein-Rubin utility function that leads to a linear expenditure demand system; at this stage, households select the optimum level of aggregate consumption and savings given their budget constraint. At the second level aggregate consumption is split into different consumption goods taking into account: i) households heterogeneous preferences, ii) prices of different goods and iii) the linked consumption required between certain durable (e.g. cars) and non-durable (e.g. fuels) goods. Households' disposable income is composed of: i) labour income (differentiated by skill level), ii) firms ownership (stocks), ii) institutional transactions on the revenue side (social benefits, rents, interest on money assets etc.), iii) institutional transactions on the expenditure side (taxes on income, interest payments etc) and iv) loans.

5.5 Labour Market

The total labour force is determined exogenously based on estimations of population (derived from the UN population estimates), active population and participation rates. The formulation of the labour market adopted in the GEM-E3 model assumes the presence of imperfections and rigidities which shift the exogenous labour supply to the left and upwards. Wages drive the balancing of the shifted labour supply with labour demand. Thus involuntary unemployment arises as a result of the distorted labour market equilibrium. The balancing of labour demand with effective, rather than potential, labour supply implies that equilibrium unemployment is determined as the difference between potential and effective labour.

5.6 Trade

Each firm produces a homogeneous product that is blended with a respective imported product to form a composite good - the total supply of the product. The demand of products by households, firms and the public sector constitutes the total domestic demand. This total demand is allocated between domestic products and imported products, following the Armington specification. In this specification, branches and sectors use a composite commodity which combines domestically produced and imported goods, which are considered as imperfect substitutes, based on the Armington assumption. Each country buys and imports at the prices set by the supplying countries following their export supply behaviour. The buyer of the composite good (domestic) seeks to minimise his total cost and decides the mix of imported and domestic products so that the marginal rate of substitution equals the ratio of domestic to imported product prices. Based on currently available data, the GEM-E3 model assumes that there is no trade in power generation technologies and in electricity distribution; electricity trade occurs only in the transmission sector.

5.7 Government

Government consumption is set exogenously in the model. The public budget is allocated to upgrade/extent current infrastructure and to support public services (i.e. education, health). Spending on infrastructure (i.e. telecommunications, road network) creates an infrastructure stock that is linked to economy wide productivity improvements as discussed above.

6. Model linking

A key feature of this study was the establishment of a soft link between an energy system model and an economic model in order to analyse the potential for zero-emission growth more accurately. Soft linking allowed the models to be used in a complementary way. The bottom-up energy system model provided the exact adjustment of power generation mix and associated investments to the economic model whereas the economic model provided the economic activity and hence the driver for energy demand (Figure 9). This section provides more detail on how the models used in this study were linked to each other.

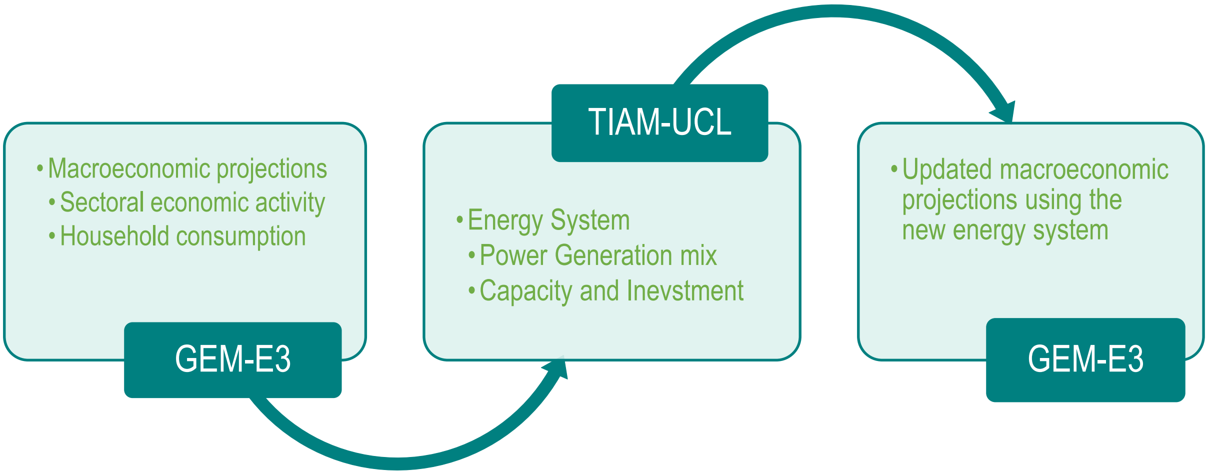

Figure 9: Soft link between GEM-E3 and TIAM UCL

6.1 GEM-E3 to TIAM-UCL: Demand drivers

The primary linkage from the GEM-E3 economic model to TIAM-UCL in this study was through the provision of economic drivers for constructing energy service demands (ESDs) in TIAM-UCL. As discussed earlier in section 4.2, TIAM-UCL normally uses drivers such as population, GDP and number of households for constructing ESDs. However it can be challenging to identify suitable drivers for some energy subsectors, whose behaviour could be markedly different to high-level indicators such as GDP. In this study GEM-E3 was able to provide much more sector-specific drivers, improving the understanding of how particular sectors are expected to develop. These region-specific drivers were also consistent with SSP1 conditions.

The energy service demands in TIAM-UCL were shown above in, and were allocated appropriate drivers for the purposes of this study. Most of these drivers were sectoral value-added drivers supplied by GEM-E3. In some cases, direct 1:1 mapping was possible, including in industry (chemicals, iron and steel, non-ferrous metals, non-metallic minerals, pulp & paper) and rail (both freight and passenger). A couple of additional sectoral demands like agriculture and other industry were linked to sectoral energy consumption drivers from GEM-E3 rather than sectoral value added. Where direct 1:1 mapping was not available, the same GEM-E3 driver was used for several TIAM-UCL demands including road passenger (auto and light vehicle), road freight (commercial, medium and heavy trucks), shipping (domestic and international), aviation (domestic and international) and commercial (the whole commercial sector in TIAM-UCL). Household expenditure data was provided by GEM-E3, but it was decided that demographic drivers were more appropriate for the residential sector for this study. GEM-E3's population driver was used for TIAM-UCL's residential hot water and cooking demands, and GEM-E3's GDP per person driver was used for lighting, other electric and other residential demands. Heating, cooling, clothes washing, clothes drying, and dishwashing demands used the 'number of households' driver; this was not explicitly supplied by GEM-E3, but was derived using TIAM-UCL's existing people per household data and GEM-E3's population data. Likewise, it was decided to use GEM-E3's population driver for TIAM-UCL's bus and two/three wheel demands. Some demands (Non Energy Use, Industrial and Other Non-Energy Use, and Other Non-specified consumption) had no direct GEM-E3 equivalent so TIAM-UCL's existing Total GDP driver was used for these (but using GEM-E3's GDP data). The Other Industrial Consumption demand was kept constant, as currently occurs in the standard TIAM-UCL model. The regional variation in all these drivers and demands was included throughout this linking process.

6.2 TIAM-UCL to GEM-E3: Energy system data

TIAM-UCL provided the detailed description of the energy system which was fed into the GEM-E3 model. The GEM-E3 model, although not an energy system model, has a sufficiently granular representation of the energy system so as to allow the establishment of a feedback loop with the TIAM UCL. The model identifies 10 power generation technologies and the main aggregates of the conventional fuels. Once TIAM-UCL was solved with the sectoral projections received from the GEM-E3, the resulting detailed technology and regional data from TIAM-UCL on electricity investment, capacity and generation were exported to GEM-E3 to generate updated economic growth projections. Final energy consumption data in the residential, commercial, industrial, transport and land use sectors were also exported to GEM-E3. This data was exported for the Central scenario and for the slow coal phaseout and no-CCS sensitivities.

The GEM-E3 model replicated the investments on the energy system while taking into account the source of financing and the sector of performance. In particular in GEM-E3 the deployment of power generation technologies requires materials, services and equipment that are provided by specific economic activities (with a different imported and local content). The model translates investment by firm to investment deliveries by sectors using investment matrices that are appropriately extended to account for power generation technologies and energy carriers. The GEM-E3 model calculates how the demand for the sectors that produce the capital goods affects the rest of the economic system taking into account the direct, indirect and induced effects. In addition the model identifies the agents that finance the additional investments that take place and accounts for the multiplier impact of investments that were crowded out. Energy system investments and their impact on energy prices affect the dynamics of the economic system through changes in innovation, competitiveness, and household disposable income. The revised economic projections then are made consistent with the energy system of the TIAM UCL model.

6.3 PRIMES

An important feature of the PRIMES energy system model for this study is that it models each European country's energy system and emissions individually. Hence it provided greater granularity on the European energy system than TIAM-UCL, which groups European nations together into several regions. This granularity was provided to TIAM-UCL in the form of an emissions trajectory for greenhouse gases for the whole of Europe compliant with SSP1 conditions, and this information was included in TIAM-UCL's assumption for this study. In this study PRIMES served as the basis to calibrate the energy system of the GEM-E3 model both in the base year and in its base projection. The energy system capital costs and consumer preferences regarding transport models and heating and cooling were based on PRIMES capital and O&M costs.

7. Policy strategies

Additional information is provided here on two important policy strategies that have an impact on the modelling that was carried: Border Carbon Adjustments (BCAs), which seek to protect European competitiveness in a context where not all countries adopt ambitious policies on carbon emission reduction; and the related issue of global co-operation on such emission reduction.

7.1 Border Carbon Adjustments (BCAs)

Border Carbon Adjustments (BCAs) aim to effectively remove the incentive to relocate CO_2-intensive industrial production. It works through applying a carbon price to products imported from a jurisdiction with no carbon pricing (or with a low effective rate), to a jurisdiction in which domestic producers of the same product do face a carbon price. Similarly, when products produced in a jurisdiction that applies a carbon price are exported to jurisdiction where it is not, the carbon price is not applied (or is refunded). The European Green Deal contained a proposal for a BCA to be introduced for certain sectors in the EU in 2021, to supplement or replace existing carbon leakage measures (a consultation on this proposal took place between July and October 2020). BCAs may also encourage increasing international ambition, if countries seek to reduce the carbon intensity of their manufacturing sector as a way to avoid the border adjustment (through carbon pricing or other means), or to join a ‘carbon club’ – a group of countries or other jurisdictions characterised by strong action on climate change, which as a result share preferential trade and other arrangements exclusive to members (Keohane et al., 2017). Although such clubs do not yet exist[11], the idea is receiving increasing attention.

However, there are a range of potential legal, technical and political challenges that may stand in the way of an effective BCA. A key legal challenge is the potential for a BCA to be construed as disguised protectionism, potentially leading to challenges in the World Trade Organisation (WTO) which has rules to prevent the exclusion of imports from other countries where such imports are effectively the same (‘like products’) as those produced by domestic industries. The technical challenges are varied, and include the ability to accurately define the products and sectors that are covered by the BCA, the need for clear, mutually-agreed and verifiable methods for calculating the emissions from producing the product in question, and determining the appropriate price that should be paid for those emissions. Political challenges would likely come from domestic actors, such as those sectors that may ultimately benefit from the introduction of a BCA but feel that existing measures to prevent carbon leakage such as carbon tax discounts and exemptions are preferable, and international actors, such as those countries with a strong dependence on the export of emission-intensive products. There are a range of potential BCA designs and methods of implementation that may reduce or negate these concerns, however they are in large part yet to be tested, with no BCAs yet introduced at the national level. The US state of California introduced one in 2013 for electricity imports from neighbouring states under its cap-and-trade scheme, but it experienced considerable problems in implementation (Prag, 2020).

7.2 Global co-operation

Article 6 of the Paris Agreement contains three potential mechanisms for advancing global co-operation. Article 6.2 allows for the creation of ‘Internationally-traded mitigation outcomes’ (ITMOs), which would allow countries that are underachieving against their objectives to purchase (or otherwise trade) accountable emission reductions from those that are overachieving. The specific form and definition of ITMOs and their accounting are yet to be agreed, but such a mechanism could facilitate the creation of ‘carbon clubs’, as discussed above. Article 6.4 would create an international carbon market governed by the UNFCCC, and Article 6.8 would create a framework for ‘non-market’-based approaches to international co-operation (i.e. where no trade is involved).

Allowing for such co-operation, it is argued, would reduce the cost of achieving deep decarbonisation, facilitate the sharing of technology, finance and expertise, and allow for enhanced ambition. However,

---

[11] With the possible exception of the European Union.

others argue that without sufficiently robust rules, ‘double-counting’ of emission reductions may occur (Carbon Brief, 2019), or insufficient attention may be paid to sectors in which emissions reductions are currently difficult or expensive to achieve, but which must be addressed if net-zero emissions are to be achieved, until too late.

The ‘rulebook’ that would allow implementation of these articles has been the subject of intensive negotiation, with many items outstanding. These were due to be addressed at COP26, originally scheduled to be held in Glasgow in November 2020, but now delayed until November 2021 as a result of the Covid-19 pandemic. However, different countries and country groupings around the world have varied priorities, concerning which a range of different issues are yet to be fully decided, which may prevent or delay an efficient and robust resolution to this ‘rulebook’. Outstanding issues include international finance, capacity building, technology transfer, adaptation arrangements, and ‘loss and damage’ (i.e. whether compensation should be paid from largely high-income countries that have produced the majority of GHG emissions, to those mostly low-income countries that will – and are – being most affected by the consequences of these emissions).

8. References

Anandarajah *et al.* (2011) *TIAM-UCL Global Model Documentation*. UK Energy Research Centre (UKERC). Available at: https://www.ucl.ac.uk/drupal/site_energy-models/sites/energy-models/files/tiam-ucl-manual.pdf.

Anandarajah and Gambhir (2014) 'India's CO2 emission pathways to 2050: What role can renewables play?', *Applied Energy*. doi: 10.1016/j.apenergy.2014.06.026.

Anandarajah *et al.* (2013) 'Decarbonising road transport with hydrogen and electricity: Long term global technology learning scenarios', *International Journal of Hydrogen Energy*. Elsevier Ltd, 38(8), pp. 3419–3432. doi: 10.1016/j.ijhydene.2012.12.110.

Bauer *et al.* (2017) 'Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives', *Global Environmental Change*. Pergamon, 42, pp. 316–330. doi: 10.1016/J.GLOENVCHA.2016.07.006.

Bauer *et al.* (2018) 'Divestment prevails over the green paradox when anticipating strong future climate policies', *Nature Climate Change*. doi: 10.1038/s41558-017-0053-1.

Bradley *et al.* (2018) *Carbon Risk and Resilience: How Energy Transition is Changing the Prospects for Developing Countries with Fossil Fuels*. London, UK.

Butnar *et al.* (2020) 'The role of bioenergy for global deep decarbonization: CO2 removal or low-carbon energy?', *GCB Bioenergy*. doi: 10.1111/gcbb.12666.

Carbon Brief (2019) 'COP25: Key outcomes agreed at the UN climate talks in Madrid', *Carbon Brief*, 15 December. Available at: https://www.carbonbrief.org/cop25-key-outcomes-agreed-at-the-un-climate-talks-in-madrid.

De Cian *et al.* (2013) 'European-Led Climate Policy Versus Global Mitigation Action. Implications on Trade, Technology, and Energy', *Climate Change Economics*, 4(Suppl. 1).

Cronin *et al.* (2020) 'Biomass , afforestation and energy demand reduction : trade-offs in the route to decarbonisation', (March).

Dellink *et al.* (2017) 'Long-term economic growth projections in the Shared Socioeconomic Pathways', *Global Environmental Change*. Pergamon, 42, pp. 200–214. doi: 10.1016/J.GLOENVCHA.2015.06.004.

Dessens *et al.* (2016) 'Limiting global warming to 2 °C: What do the latest mitigation studies tell us about costs, technologies and other impacts?', *Energy Strategy Reviews*. Elsevier Ltd, 13–14, pp. 67–76. doi: 10.1016/j.esr.2016.08.004.

Drouet *et al.* (2004) 'Coupling Climate and Economic Models in a Cost-Benefit Framework: A Convex Optimization Approach', *Environmental Modeling and Assessment*.

Edelenbosch *et al.* (2017) 'Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models', *Energy*. Elsevier Ltd, 122, pp. 701–710. doi: 10.1016/j.energy.2017.01.017.

Ekins *et al.* (2017) *The role of CCS in meeting climate policy targets*. University College London, UK.

Eurek *et al.* (2017) 'An improved global wind resource estimate for integrated assessment models', *Energy Economics*, 64(February), pp. 552–567. doi: 10.1016/j.eneco.2016.11.015.

European Commission (2018) *A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN.

Fragkiadakis *et al.* (2012) ‘A Multi – Country Econometric Estimation of the Constant Elasticity of Substitution’, in *Final WIOD Conference: Causes and Consequences of Globalization*. Groningen, The Netherlands.

GCP (2019) *Global Carbon Budget 2019*. Global Carbon Project. Available at: https://www.globalcarbonproject.org/carbonbudget/19/data.htm.

Grubler *et al.* (2018) ‘A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies’, *Nature Energy*, 3, pp. 515–527. doi: doi:10.1038/s41560-018-0172-6.

Huppmann *et al.* (2019) ‘IAMC 1.5°C Scenario Explorer and Data hosted by IIASA’. doi: 10.5281/ZENODO.3363345.

IAMC (2016) *Model Documentation - TIAM-UCL, Integrated Assessment Modeling Consortium*. Available at: https://www.iamcdocumentation.eu/index.php/Model_Documentation_-_TIAM-UCL (Accessed: 4 December 2020).

IIASA (2016) *SSP Public Database Version 1.1, Hosted by IIASA*. Available at: https://tntcat.iiasa.ac.at/SspDb/dsd.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by T. F. Stocker et al. Cambridge, UK and New York, USA: Cambridge University Press.

IPCC (2018) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*.

Keohane *et al.* (2017) ‘Toward a club of carbon markets’, *Climatic Change*, 144(1), pp. 81–95. doi: 10.1007/s10584-015-1506-z.

Kesicki and Anandarajah (2011) ‘The role of energy-service demand reduction in global climate change mitigation: Combining energy modelling and decomposition analysis’, *Energy Policy*. Elsevier, 39(11), pp. 7224–7233.

Kriegler *et al.* (2017) ‘Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century’, *Global Environmental Change*. Pergamon, 42, pp. 297–315. doi: 10.1016/J.GLOENVCHA.2016.05.015.

Loulou *et al.* (2005) *Documentation for the TIMES model, Part II, Energy Technology Systems Analysis Programme (ETSAP).*

Loulou *et al.* (2016) *IEA-ETSAP Optimization Modeling Documentation*. https://iea-etsap.org/index.php/documentation.

Marangoni *et al.* (2017) ‘Sensitivity of projected long-term CO2 emissions across the Shared Socioeconomic Pathways’, *Nature Climate Change*, 7(2), pp. 113–117. doi: 10.1038/nclimate3199.

McCollum *et al.* (2018) ‘Interaction of consumer preferences and climate policies in the global transition to low-carbon vehicles', *Nature Energy*. Springer US, 3(August), pp. 1–10. doi: 10.1038/s41560-018-0195-z.

McGlade *et al.* (2014) *A bridge to a low carbon future? Modelling the long-term global potential of natural gas*. UKERC Research Report, London, UK.

McGlade and Ekins (2014) 'Un-burnable oil: An examination of oil resource utilisation in a decarbonised energy system', *Energy Policy*, 64, pp. 102–112. doi: 10.1016/j.enpol.2013.09.042.

McGlade and Ekins (2015) 'The geographical distribution of fossil fuels unused when limiting global warming to 2 °C', *Nature*. Nature Publishing Group, 517(7533), pp. 187–190. doi: 10.1038/nature14016.

Meinshausen *et al.* (2011) 'Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration', *Atmospheric Chemistry and Physics*, 11(4), pp. 1417–1456. doi: 10.5194/acp-11-1417-2011.

Nordhaus and Boyer (1999) *Roll the DICE Again: Economic Models of Global Warming*. Yale University, manuscript edition.

O'Neill *et al.* (2017) 'The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century', *Global Environmental Change*. Pergamon, 42, pp. 169–180. doi: 10.1016/J.GLOENVCHA.2015.01.004.

Prag (2020) *The Climate Challenge and Trade: Would border carbon adjustments accelerate or hinder climate action?, 39th Round Table on Sustainable Development*. Paris. Available at: https://www.oecd.org/sd-roundtable/papersandpublications/The Climate Challenge and Trade... background paper RTSD39.pdf.

Pye *et al.* (2016) 'Exploring national decarbonization pathways and global energy trade flows: a multi-scale analysis', *Climate Policy*, 16, pp. S92–S109. doi: 10.1080/14693062.2016.1179619.

Pye, Steve *et al.* (2019) *Modelling ' leadership - driven ' scenarios of the global mitigation effort. the Committee on Climate Change's (CCC) 2019 report Net Zero: The UK's contribution to stopping global warming*. London, UK.

Pye, S. *et al.* (2019) *Modelling 'leadership - driven' scenarios of the global mitigation effort*.

Pye *et al.* (2021) *The TIAM-UCL Model (Version 4.1.1) Documentation*. UCL (Forthcoming).

Riahi *et al.* (2017) 'The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview', *Global Environmental Change*. Pergamon, 42, pp. 153–168. doi: 10.1016/J.GLOENVCHA.2016.05.009.

Rogelj, Shindell, *et al.* (2018) 'Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development', in Masson-Delmotte, V. et al. (eds) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,*.

Rogelj, Popp, *et al.* (2018) 'Scenarios towards limiting global mean temperature increase below 1.5 °C', *Nature Climate Change*, 8, pp. 325–332.

Samir and Lutz (2017) 'The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100’, *Global Environmental Change*. Pergamon, 42, pp. 181–192. doi: 10.1016/J.GLOENVCHA.2014.06.004.

Welsby (2020) *Modelling uncertainty in global gas resources and markets (forthcoming)*. University College London.

Winning *et al.* (2018) *How low can we go? The implications of delayed ratcheting and negative emissions technologies on achieving well below 2 °c*, *Lecture Notes in Energy*. doi: 10.1007/978-3-319-74424-7_4.

Winning *et al.* (2019) ‘Nationally Determined Contributions under the Paris Agreement and the costs of delayed action’, *Climate Policy*. Taylor & Francis, pp. 1–12.