1.5^{o}C Climate and Energy Scenarios: Impacts on Economic Growth

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Lay Summary

In the context of calls for ‘de-growth’ (reduction in GDP) in developed countries for them to be able to reduce emissions to ‘net zero’ in time for the temperature target in the Paris Agreement to be met, this article explores the various impacts on economic growth in the IPCC scenarios that limit the average global temperature increase in 2100 to 1.5^{o}C. It finds that the impacts are generally small and that in no case is ‘degrowth’ required, although the requirements for the rate and nature of technological developments are challenging. The article then reports on a modelling exercise that investigates in more detail the economic dynamics of achieving the 1.5^{o}C target. It finds that, as with the IPCC scenarios, and assuming the feasibility of at-scale deployment of carbon capture and negative emission technologies, economic growth continues throughout this century, with a major contribution coming from the investment required to decarbonise the energy system.

Abstract

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1. *Introduction*

"Net-zero emissions by 2050" is the new target for climate policy, following the goal stipulated in the 2015 Paris Agreement of "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (UNFCCC, 2015). This paper reports on a study that used energy system and macroeconomic models to explore whether and how these objectives could be reached and, in particular, whether achieving them is compatible with continuing economic growth through to 2100.

The context of the paper is something of a resurgence of academic papers expressing the view that resolving the climate crisis, and broader environmental problems, is not consistent with continuing economic growth, in rich countries at least (see, for example, Kallis et al. 2018) and that therefore 'degrowth' (by which seems to be meant absolute reductions in GDP) in these countries is required if the climate targets are to be met.

A critique in the degrowth literature of the modelling approach that is predominantly used to address this issue, and which was followed both in the scenarios in the IPCC's 1.5^{o}C database, and in the study reported on below, is that it 'assumes' economic growth in the future (Keysser and Lenzen, 2021; Hickel et al., 2021).

All projections of the future make assumptions about future technological and social developments. For example, projections of population growth assume some continuation or departure from the human relations and social norms that produce children and affect health and life expectancy. Economic growth arises from capital accumulation, population growth, demand stimulus and technical progress that increases production factors' productivity. Such processes have been widely observed in many different countries over the past two hundred years. 'Assumptions' of economic growth are therefore based on a perception that, for the rest of this century at least, these processes will continue to produce economic growth. Given historical and current levels of investment and rates of technical change, such a perception seems not unreasonable. It is further assumed in the modelling reported below that increased incomes will lead to increased demands for energy services, as has again been widely observed in the past, which, moderated by increases in energy efficiency, will lead to increased energy use.

In order to achieve global ‘net zero’ in 2050, and maximum global average warming in 2100, using the carbon budgets from IPCC (2018), scenarios that assume continuing global economic growth have the following characteristics to a different extent (Keysser and Lenzen, 2021): high levels of decoupling of energy use from GDP growth; high rates of installation of zero-carbon energy technologies; high rates of deployment of carbon capture and storage (CCS) technologies, often using bioenergy (BECCS), and of other negative emissions technologies (NETs) that suck carbon out of the atmosphere. NETs are required to reduce global average temperatures in the second half of century, which tend to overshoot the 1.5^{o}C temperature target after 2050 because of inadequate emissions reduction before it. The scenario reported on in detail below gives details of these characteristics that are broadly reflective of this literature.

The ‘degrowth’ literature tends to regard these requirements for achieving the temperature target as either excessively risky (Keysser and Lenzen, 2021), or infeasible (Haberl et al., 2021; Hickel and Kallis, 2020). A response in this literature is to call for ‘degrowth’, a ‘societal transformation’ (Kuhnkenn, 2021) involving a dramatic near-term reduction in rich countries’ demands for energy (and, sometimes, materials too [Haberl et al., 2020]), which, it is assumed, will require not just slower rates of economic growth but absolute reductions in these countries’ GDPs from current levels (see the indicative degrowth scenarios in Keysser and Lenzen, 2021). Given that this literature also tends to envisage that currently poor countries both wish to and should be allowed to grow their economies in order to reduce global inequalities (Hubacek et al, 2017), presumably the reductions in rich countries’ GDPs would need to be substantial for global GDP to decline, but the extent of this does not yet appear to have been calculated in detail. A related literature claims that, notwithstanding the reduction in GDP, people in rich countries could expect ‘a good life’ (O’Neill et al., 2018), although it is clear that persuading them of this would be politically challenging. Nor have the policies to bring about such a societal transformation, which might include “making social services growth-independent, reducing working hours, introducing basic incomes and a maximum wage, decelerating life and democratising (economic) decision-making” (Kuhnkenn, 2021, p.9) been worked through in detail, with their economic and social, as well as their environmental implications, made apparent. Keysser and Lenzen (2021, p.9) acknowledge: “it is clear that a degrowth transition faces tremendous political barriers”.

Against this background this paper first explores some trajectories of greenhouse gas emissions and GDP growth, which show, since 2005, the beginnings of decoupling between these variables for some countries (section 2). Section 3 then delves into the IPCC 1.5^{o}C scenarios database, and draws out the key drivers of emissions reduction in these scenarios. While these drivers reduce GDP below the modelled baselines (which are very optimistic as they do not contain the climate damages of failing to decarbonise), the reductions are small, and come nowhere near degrowth, i.e. absolute reductions in global GDP. Section 4 outlines the modelling approach taken in this paper, which has similar characteristics to those in the IPCC database. The scenarios themselves are described in section 5. Section 6 gives the results of the scenarios, and explores their sensitivity to assumptions about the rate of coal phase-down and the availability of CCS and NETs. Section 7 outlines the kinds of policies and global circumstances that will be necessary for there to be any chance of achieving the scenarios in reality. Section 8 concludes.

While the debate about necessary reductions of resource use and environmental impacts required for environmental sustainability, and whether these can be achieved by decoupling economic growth from such impacts or impose limits on such growth, goes well beyond the climate issue, this paper only deals in detail with CO_2 emissions from the energy system. That said, many of the paper's arguments seem to the authors to be valid more widely.

2. *Existing knowledge about the relationship between emissions and economic growth*

Global greenhouse gas (GHG) emissions, which are responsible for anthropogenic global warming, have increased along with growth in the economy since records began (see Figure 1 for the trajectory from 1990-2016).

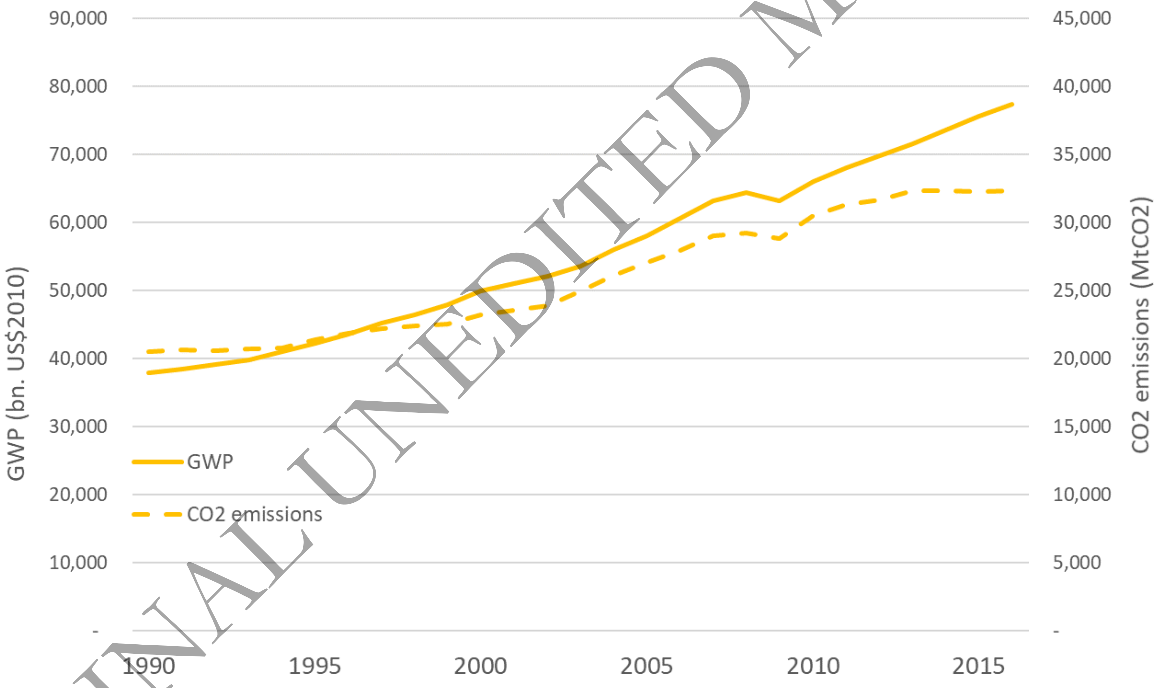


Figure 1: Gross World Product (left axis) and global CO_2 emissions (right axis) from fuel combustion 1990-2016 (data source: IEA, 2018)

This trajectory is not surprising, as the major part of GHGs are CO_2 emissions, which come from burning fossil fuels. Fossil fuels have been the predominant source of energy since the Industrial Revolution, and energy use is at the heart of most economic activity. The question now is, if emissions are reduced at the rate required to achieve the Paris target to limit global warming well below 2^oC, while aiming for 1.5^oC, can the economy keep on growing? In other words, can emissions be "decoupled" from economic growth to the required extent?

The evidence that this may be possible comes from the European Union and some individual EU member states. Between 1990 and 2016 the EU economy grew by more than 50%, while CO_2 emissions from fuel combustion fell by 25% (Figure 2).

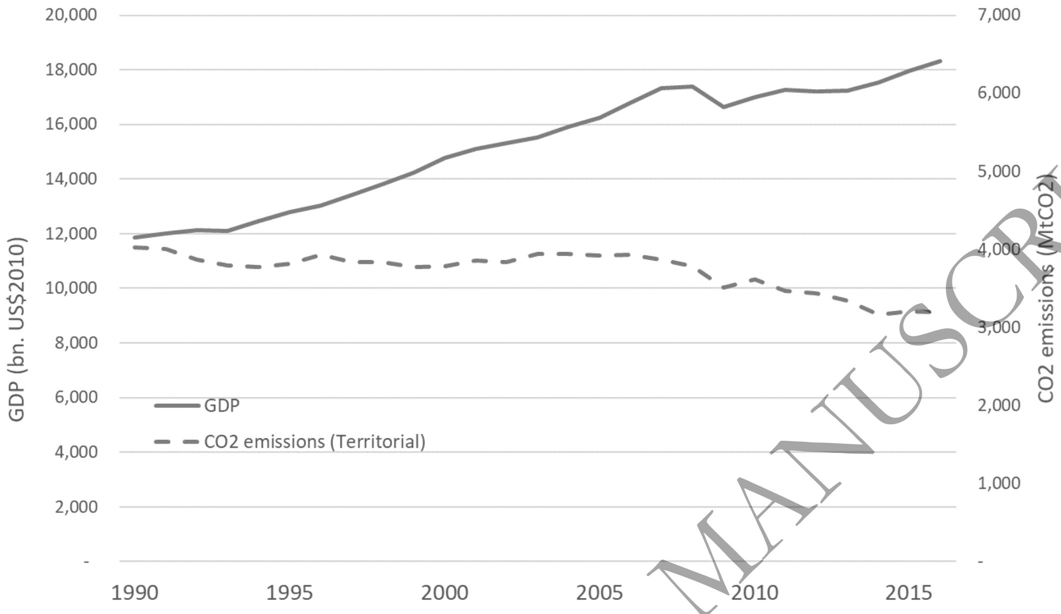
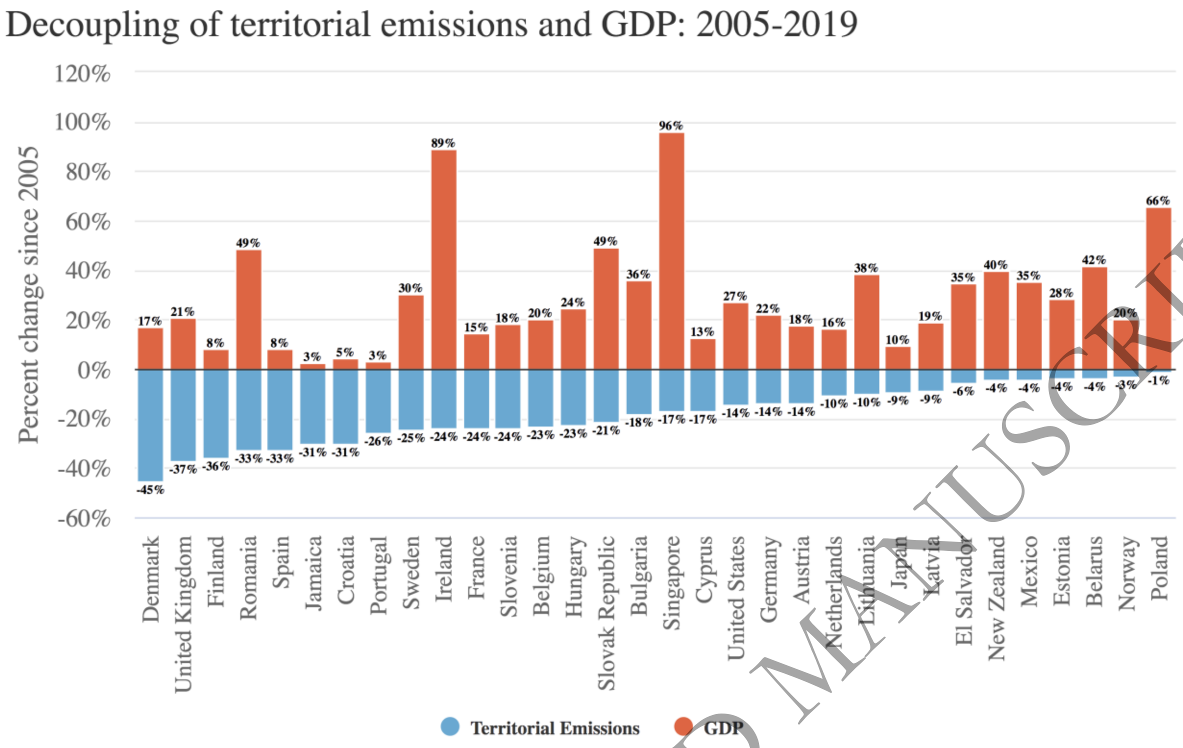


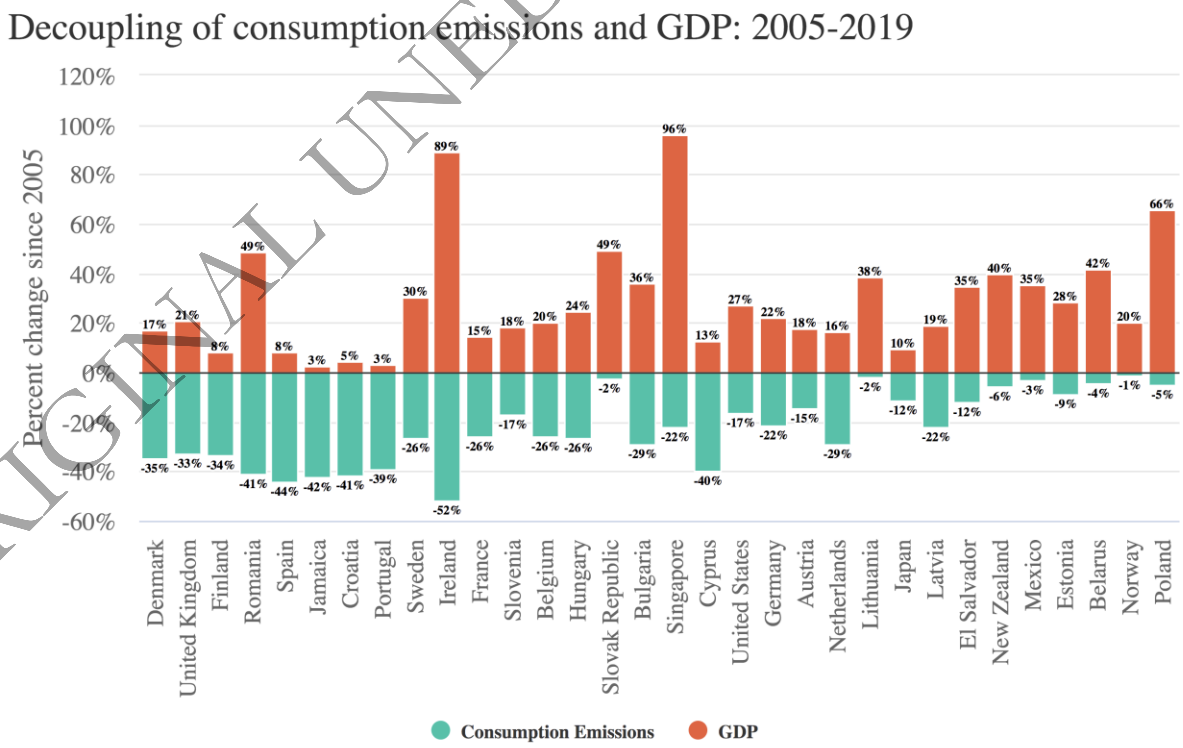
Figure 2: Gross Domestic Product (left axis) and CO_2 emissions (right axis) from fuel combustion in the European Union (EU-28, including the UK) 1990-2016 (data source: IEA, 2018)

European countries are not the only ones to have reduced CO_2 emissions since 2005, Hausfather (2021) has found that 32 countries with populations greater than one million reduced their territorial carbon emissions over 2005-2019, while their economies kept growing (Figure 3). Moreover, this emission reduction applied to consumption emissions over the same period too (Figure 4).



Decoupling of territorial emissions and GDP: 2005-2019

Figure 3: Gross Domestic Product and territorial emissions from fuel combustion for 32 countries with population in excess of one million, 2005-2019
Source: Hausfather 2021 (data: territorial and consumption emissions from the Global Carbon Project; GDP data from the World Bank World Development Indicators database)



Decoupling of consumption emissions and GDP: 2005-2019

Figure 4 : Gross Domestic Product and consumption CO_2 emissions from fuel combustion for 32 countries with population in excess of one million, 2005-2019
Source: Hausfather 2021 (data: territorial and consumption emissions from the Global Carbon Project; GDP data from the World Bank World Development Indicators database)

Emissions (Em) from economic activity may be expressed as the product of five terms through an adaptation (by adding energy services) of the so-called Kaya identity:

$$Em = P \cdot \frac{A}{P} \cdot \frac{S}{A} \cdot \frac{En}{S} \cdot \frac{Em}{En}$$

where P is population, A is affluence, measured by GDP, S is the level of energy services, En is energy use. A/P is therefore GDP per person, S/A reflects the demand for energy services per unit of GDP (energy service intensity of the economy), and En/S and Em/En are the efficiency of energy use and the emission intensity of energy respectively.

Reducing emissions for a given level of population and affluence therefore can come about in three main ways:

- increasing efficiency in the use of energy (thereby reducing En/S);
- replacing fossil fuels with low- or zero-carbon energy sources (thereby reducing Em/En);
- structural changes in the economy whereby consumption of low-carbon services replaces consumption of energy-intensive goods (thereby reducing S/A).

These developments occur in different countries in different ways and to different extents, but in most of the countries, the first two at least have been driven by public policy stimulating and reinforcing some market forces and constraining others (Penasco et al. 2021). Given that these policies have not achieved the rates of CO_2 emission reduction to reach the Paris Agreement targets, it is very likely that such achievement will require a considerable intensification of the policies that have generated or reinforced these developments.

3. *Existing knowledge about the 1.5 °C target*

As part of the IPCC's Special Report on Global Warming of 1.5 °C, Rogelj et al. (2018a) identified 90 decarbonisation scenarios in the modelling literature that were consistent with the 1.5 °C target,[1] using different modelling frameworks. The starting point for the scenarios was a set of five narratives called the Shared Socio-economic Pathways (SSPs). Each SSP has its own plausible, internally consistent storyline about how the world's socio-economy and geopolitics might develop, and different quantitative assumptions on the basis of these storylines are made for population and economic growth, education, urbanisation, trade

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[1] The scenarios fall into three categories: "Below 1.5 °C", which limit peak warming to below 1.5 °C during the entire 21st century with 50-66% likelihood (nine scenarios); "1.5 °C-low-OS", which limit median warming to below 1.5 °C in 2100 and with a 50-67% probability of temporarily overshooting that level earlier, generally implying less than 0.1 °C higher peak warming than Below-1.5 °C pathways (44 scenarios); and "1.5 °C-high-OS", which limit median warming to below 1.5 °C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying 0.1-0.4 °C higher peak warming than Below-1.5 °C pathways (37 scenarios).

intensity, environmental concern, rates of technological development and international co-operation. As shown in Figure 5, the assumptions of SSP1 make both mitigation and adaptation easiest, those of SSP3 make them both more difficult. In SSP5 mitigation, and in SSP4 adaptation, challenges, dominate. The SSP2 challenges have intermediate challenges in both dimensions.

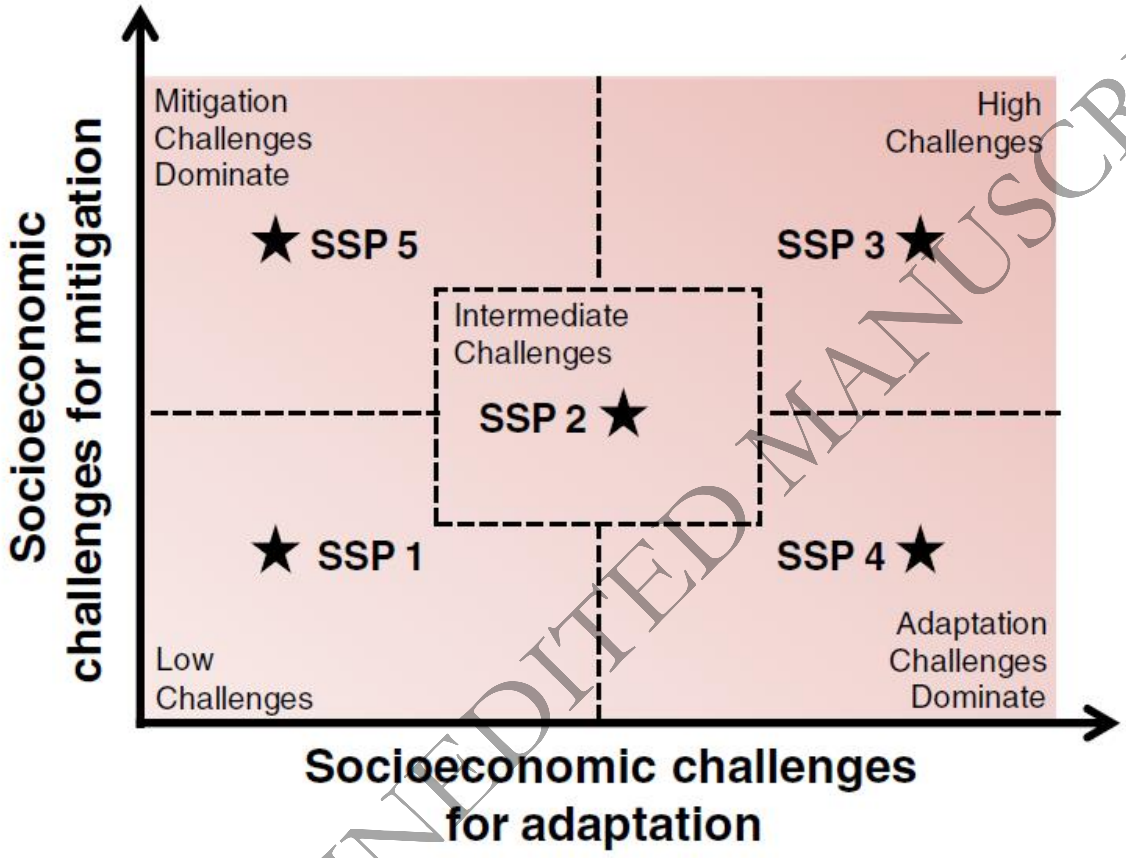

Figure 5: The five Shared Socioeconomic Pathways (SSPs)
Source: Adapted from O'Neill et al. 2014, Figure 1

Using these broad assumptions around the SSPs, the modellers in the studies reported by Rogelj et al. (2018a) chose the values of parameters that seemed broadly consistent with the selected SSP in the following areas:

- Developments in economic structure and output
- Energy demand and efficiency
- Material demand and efficiency
- Use of low-carbon energy carriers and technology
- Availability and use of Carbon Capture and Storage (CCS) and Negative Emission Technologies (NETs[2])

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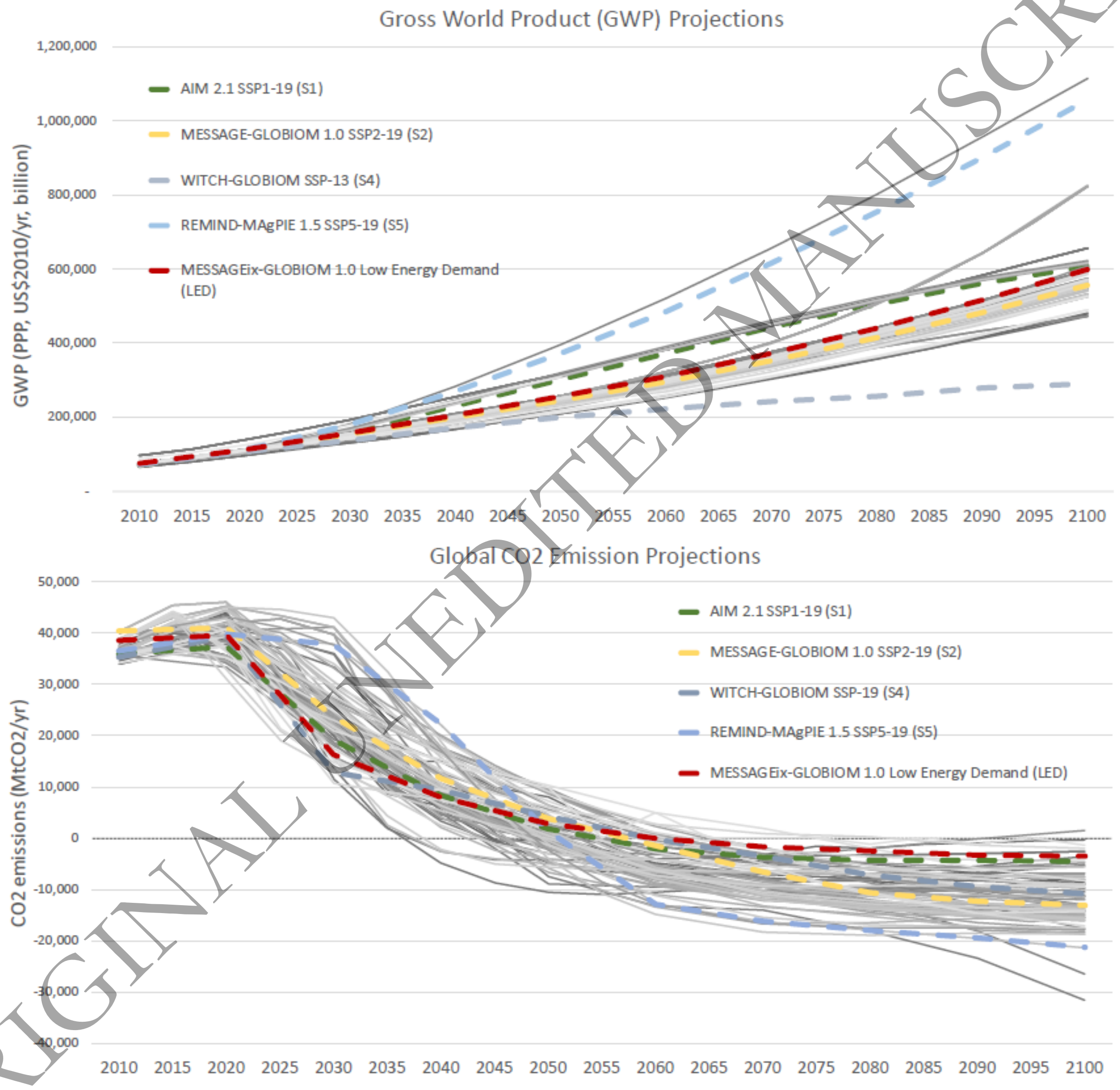
[2] NETs comprise technologies that remove CO_2 from the atmosphere and then store it securely so that it does not re-enter it. NETs include bioenergy with CCS (BECCS), afforestation with the resulting timber left intact, carbon sequestration in soils or "Direct Air Capture" (DAC) machines that scrub CO_2 from the air. DAC technology is at an early stage of development.

- Land use and the availability of biomass for energy
- Choice and implementation of policy measures
- Costs of carbon reduction technologies.

Depending on the assumptions and models used, a wide variety of different pathways of GHG emission reduction were generated. Many of them were in line with the Paris target of limiting warming to 1.5 °C by 2100, though usually not without overshooting[3] it in the later decades of this century (as happened also in the modelling reported on further below). The scenarios are shown in Figures 6a, b.



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[3] "Overshooting" refers to the global average temperature increase rising above 1.5 °C. In the modelling the temperature increase is then reduced to 1.5 °C by technologies that remove large quantities of CO_2 from the atmosphere. There is in fact considerable uncertainty as to whether global temperatures would behave in this way, or whether allowing temperature increases to go beyond 1.5 °C would result in crossing "tipping points" that generated large GHG emissions from other sources and caused the climate to flip permanently into a different state that was worse for humans and other lifeforms. See Lenton et al. (2019).

Figure 6a (top): Brief illustration of the impact on Gross World Product in four Shared Socio-economic Pathways (SSPs), and a Low Energy Demand (LED) scenario, based on SSP2
Figure 6b (bottom): Brief illustration of the impact on CO_2 emissions in four Shared Socio-economic Pathways (SSPs), and a Low Energy Demand (LED) scenario, based on SSP2
(graphs created with data from Rogelj et al., 2018a; Huppmann et al., 2019) (Authors' note: grey lines represent the range of results produced by all other 1.5 °C-compliant scenarios reviewed by Rogelj et al. (2018a))

As can be seen from Figure 6a, all the scenarios also showed continuing growth in the economy, as well as meeting the 1.5^{o}C climate target; although no scenario could successfully achieve this target under the SSP3 narrative. None of the scenarios came anywhere near declines in economic output from the 2020 level (i.e. they all experienced economic growth). The scenarios therefore all exhibited steady and absolute "decoupling".

The impacts of the costs of mitigation on economic growth, are shown in Figure 7, which illustrates Gross World Product (GWP) projections for the S1, S2, S4 and S5 and LED scenarios. The GWP in each scenario is projected compared to the respective baselines (the difference between the solid and dashed lines in each case). For reasons given in section 1 (the Introduction), the projection of economic growth in the baseline came from assumptions about population growth, capital accumulation and technical change. The models included in the study have semi-endogenous growth mechanisms (endogenous decision on investment or learning induced productivity) allowing for GDP to vary under different policies. It can be seen from Figure 7 that, in general, the reduction in the rate of increase of the economy by 2100 from a baseline without decarbonisation was very small. It should be remembered that neither the baselines nor the scenarios take account of the potentially very substantial costs of unabated climate change, though these may be expected to be much higher in the baselines because of the higher levels of GHG emissions, so that the baseline projections of GDP growth are very probably optimistic.

To understand the economic results of these scenarios, it may be noted that economic growth for the world as a whole could be negatively affected by decarbonisation if reducing carbon emissions were to raise the cost of energy or reduce rates of technical progress. With renewable electricity now competitive with that produced from fossil fuels in many countries (IRENA, 2021), the cost impact on economic growth from the switch to zero-carbon energy sources seems likely to be limited and may even be positive. With regard to technical progress, this is likely to be stimulated by decarbonisation, rather than the reverse, with fossil-fuel industries being relatively mature and low-carbon energy generating whole new industries (Jiang, 2017). At a national level, additional key considerations for the impacts of decarbonisation on economic growth are whether investments in low-carbon energy generate a domestic supply chain or imports, whether they result in a reduction in the net imports of fossil fuels (and, conversely for fossil fuel-exporting countries, whether they reduce exports of these fuels), and whether such activities draw on unused resources (capital or labour) or result in the "crowding out"[4] of other activities (Paroussos et al. (2019)). In the Rogelj et al. (2018a) studies reported on above it can be seen that none of these effects prevented

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[4] "Crowding out" occurs when new investment replaces existing investment rather than adding to it. In situations where existing investment is more productive than new investment, crowding out will reduce GDP growth. In the scenario reported on in this paper, full crowding out was assumed.

continuing growth in the global economy as it decarbonised in line with the Paris Agreement 1.5°C target.

It will be seen that, notwithstanding the costs of mitigation, in all cases economic growth remains positive, i.e. absolute decoupling is achieved in all the scenarios which achieve the 1.5 °C target, and decarbonisation is achieved by 2100 in conjunction with an economy that is very much larger than in 2020. In the S1 and S2 scenarios, decarbonisation is achieved with relatively small reductions in GWP compared to the baseline.

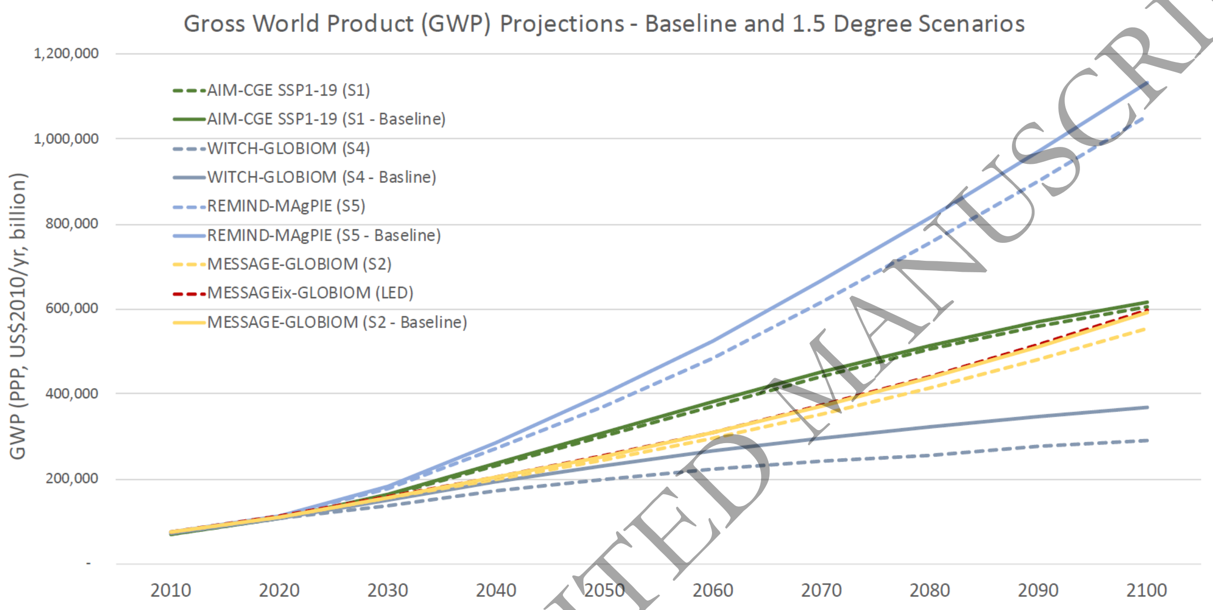

Figure 7: Gross World Product projections – Baseline and 1.5 degree scenarios (graph created with data from Rogelj et al., 2018a; Huppmann et al., 2019)

These issues are discussed further in relation to the study that is the main topic of this paper.

4. *The modelling approach in this study*

Scenarios, such as the SSPs described above, are plausible and internally consistent projections of future events. They are not predictions or forecasts, but "thought experiments" as to how the future might turn out given certain assumptions and circumstances. Models are means of quantifying the outcomes of scenarios by specifying formal mathematical relationships between different variables, which may come from economic theory (calibrated) or econometric estimations of past experience. As has been seen with respect to the IPCC 1.5 °C report, scenarios and models have proved core tools for assessing long-term emission mitigation strategies and the vast majority of global, stringent decarbonisation scenarios demonstrate decoupling of GDP growth from emissions, as has been seen above, through dramatic and sustained technological developments.

The key determinants of maintaining average global warming to below 1.5 °C are the availability and costs of energy efficiency and low-carbon **technologies**, the extent of required **economic restructuring** away from resource-intensive activities and the **rate of transition** to zero or negative emissions (IPCC, 2018; Rogelj et al., 2018a).

Technology: Technologies play a key role in reducing the carbon intensity of energy provision and can, through investments in more efficient technologies, also be used to reduce the volume of energy needed for a specific level of energy service. The widespread diffusion of novel, low-carbon technologies, however, requires cost reductions that are achieved through the uncertain processes of innovation, achievement of economies of scale, and learning by research and by doing (Zhou and Gu, 2019; Verdolini et al. 2018). Improving energy efficiency can result in net positive economic benefits when cost-effective options are available for it. In addition to the technologies themselves, consumer behaviour and preferences are crucial, but highly uncertain, enablers of technology diffusion on the end-use side. Finally, reaching zero carbon requires either negative-emission technologies or full decarbonisation of all sectors, including those that are difficult to abate, and the cost and availability of the technology options in these sectors therefore play an important role. Key variables in scenarios are the assumptions made about these various developments and processes, in order to reach zero and negative carbon emissions. Some technologies may turn out to be more important than others, and some may be absolutely critical to achieving the 1.5 °C temperature target. All these technology characteristics in 1.5°C scenarios can be found in Rogelj et al. (2015, 2018a).

Changes in the structure and resource efficiency of the economy: Energy and industrial processes are major sources of carbon emissions and changes in the structure of the economy in a less resource-intensive direction could help alleviate the pressures on technologies and behavioural change to deliver emissions reductions. The nature and strength of the assumptions in this area are obviously important factors in scenarios, as well as their impacts in different regions across the world (Schäfer, 2005).

Ramping up of the mitigation efforts: Reaching emission levels consistent with 1.5 °C not only requires very deep emission reductions, but these also need to happen very rapidly. The technologies and infrastructures that would need to be replaced, however, are highly interconnected and many have long lifetimes – and the new alternatives tend to start with a higher initial cost than the costs of the incumbent technologies. Moreover, consumers are generally risk averse, which can further slow down the speed with which mitigation efforts can be ramped up. In light of this, scenario assumptions about the level of co-ordination, behavioural change and other barriers, to allow a rapid transition to the zero-carbon system, are important (Rogelj et al., 2018b).

The purpose of the modelling reported in the study below was to explore in detail the characteristics of energy system and other developments that would be necessary to meet two targets: global net-zero CO_2 emissions by 2050; and a maximum 1.5 °C global temperature increase by 2100. The modelled scenarios consist of one central scenario and sensitivity runs[5] that stress-test the scenario in order to identify some of the most important assumptions needed to reach the required levels of decarbonisation. The sensitivity runs explore whether the targets can still be met if emissions reduction from phasing out coal or the ability to capture and store CO_2 is constrained, as described further below. The modelling also generates the economic results of imposing these global constraints on the world's economy.

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[5] This is the term applied to a model run that varies just one assumption or parameter in order to gauge its influence on the model results.

Two energy system models and a macroeconomic model have been used for this exercise. The PRIMES[6] energy system model deals with the EU level, while the TIAM-UCL[7] energy system model is a global model. The computable general equilibrium (CGE) GEM-E3-FIT global macroeconomic model is used to assess the economic impacts at global, European and national levels. Some details about the models used in this project are given in Annex 1.

The starting point for the scenarios explored in the modelling was the SSP1 scenario, which, because of its assumptions about how the world develops, is most favourable for global decarbonisation. The assumptions include global co-operation, rapid technology development, strong environmental policy, low population growth, declining inequality, dietary shifts and forest protection. The use of any of the other SSPs would have made decarbonisation more difficult and expensive, and this should be borne in mind when interpreting the results. However, all the assumptions in SSP1, while not necessarily pertaining to today, may be considered reasonable.

The GEM-E3-FIT CGE model was used to quantify the economic implications of the central scenario within a dynamic socio-economic context. The key drivers of economic growth in the GEM-E3-FIT[8] model are technical progress, population growth and capital accumulation. The projection of population is not calculated by the model and outside sources are used (e.g. population projections from the International Labour Organisation). The model calculates endogenously the investments needed to build the production capacity that optimises the firms' operations. Technical progress (total factor productivity) has an endogenous and an exogenous part: i) An exogenous rate of TFP is introduced into the model reflecting the autonomous technical progress. Decisions on public R&D are also exogensouly specified, ii) Using two factor learning curves (learning by doing and by R&D) the model links cumulative production and private R&D spending with firm level specific TFP.. For the baseline the model's exogenous growth drivers have been calibrated to sources outside the model[9] and the energy system of the model is calibrated to match the results of the energy system model, TIAM-UCL.

5. *The scenarios*

The starting point for the scenarios to be modelled was the SSP1 assumptions about economic growth and other relevant issues as discussed above. These assumptions produced sectoral economic activity and sectoral demands for energy services from the PRIMES and GEM-E3 FIT models, which were fed into the global energy system model TIAM-UCL, which has a detailed representation of energy supply and demand technologies across the energy system. TIAM-UCL was constrained to satisfy the energy service demands, while producing net-zero CO_2 emissions in 2050, and a maximum global average temperature increase in 2100 of 1.5 °C (as projected using TIAM-UCL's in-built climate module, which gives, as per the best estimate in IPCC (2018), a 66% probability of achieving this temperature with a carbon budget of 420 $GtCO_2$. Additionally, the peak temperature before

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[6] Model details available at https://e3modelling.com/modelling-tools/primes/

[7] Model details available at https://www.ucl.ac.uk/energy-models/models/tiam-ucl

[8] Model details available at https://e3modelling.com/modelling-tools/gem-e3/

[9] Non-EU GDP projections are based on the IMF "World Economic Outlook" (IMF, 2018) and the IEA/OECD "World Energy Outlook" (IEA, 2017). EU population projections follow the DG-ECFIN Ageing Report (EC, 2018; EUROPOP2019, 2019) and non-EU population projections are based on SSP1 (Samir and Lutz, 2017).

2100 was minimised. Resulting detailed data by global region from TIAM-UCL on electricity investment, capacity and generation, along with final energy consumption in the residential, commercial, industrial, transport and land-use sectors, were then used to modify the economic projections of the GEM-E3-FIT model including those for economic growth. This was the central decarbonisation scenario (hereafter "the central scenario"), the results of which are shown in the next section.

Inspection of these results showed that two factors, concerning which there is considerable uncertainty, were important in generating the central scenario results.

The first factor is the rate of phase-down of coal use. In the central scenario this rate was a 5.4% reduction p.a., which is the rate achieved in recent years in the USA. It therefore has some real-world basis. However, it is also in the centre of the distribution of coal phase-down rates in the 78 IPCC 1.5°C scenarios that report primary coal use, which is shown in Figure 8. It can be seen that the range is large (0-14% annual reduction in coal use), but the median is 4% and the mean is 5% - close to the 5.4% used in the central scenario of this paper. The 0% p.a. reduction scenario, based on SSP5 with high continuing fossil fuel use, is an outlier in terms of CCS use, requiring some 30 $GTCO_2$ CCS per annum each year between 2060 and 2070.

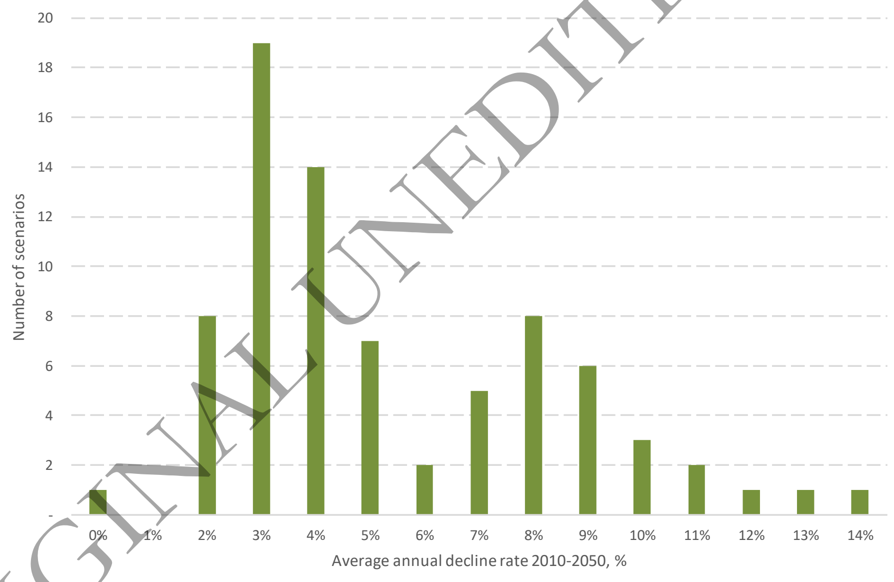

Figure 8: Coal phase-down rates in 78 IPCC 1.5°C scenarios (graph created with data from Huppmann et al., 2019)

This is relevant to the second factor that was seen to be important in generating the results of the central scenario: the availability of CCS and NETs, which were both heavily used in the central scenario.

In order to explore the sensitivity of the central scenario's results to these factors, further model runs were carried out with:

- half the rate of coal phase-down in the central scenario (i.e. 2.7% p.a., close to the mode of the IPPC scenarios' distribution);
- no availability of CCS and NET technologies;
- a combination of the reduced rate of coal phase-down and no availability of CCS and NET technologies.

6. *Results*

6.1 *The central decarbonisation scenario*

Figure 9 shows the CO_2 emissions trajectory for the central scenario.[10]

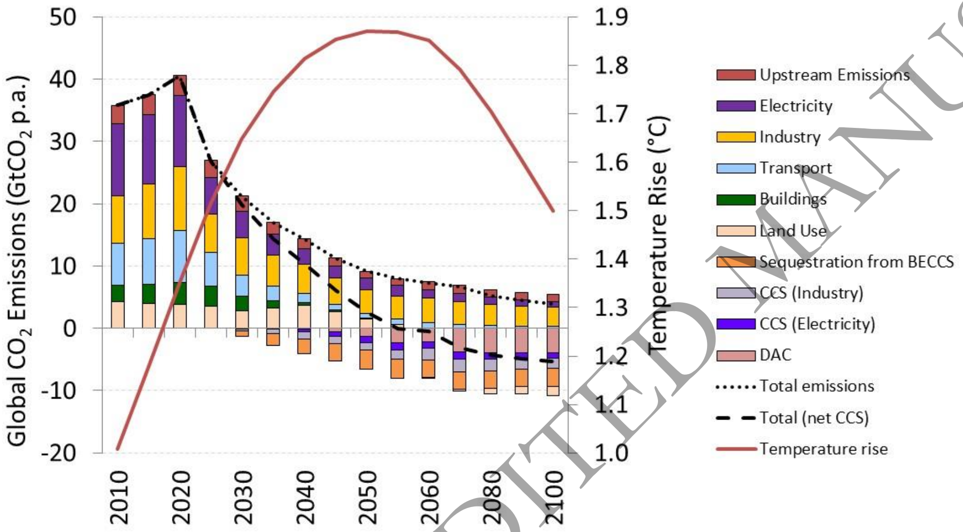

Figure 9: CO_2 emissions trajectory (central scenario) (Authors' note: land use includes all CO_2 emissions from agriculture, forestry, land use and land-use change)

It can be seen that emissions reach net zero in 2055, slightly missing the 2050 target. The average global temperature increase in 2100 is just below 1.5 °C, but it reaches nearly 1.9 °C around 2050, before declining to the end of the century. This temperature reduction is caused by a substantial use of CCS and NETs technologies (the bars below the zero-emission line), which by 2100 are capturing and storing carbon emissions or removing carbon from the atmosphere, in excess of 10 $GtCO_2$ per year. This outcome is broadly comparable to those of the SSP1 IPCC studies discussed above. However, there is significant uncertainty as to whether, even if it were possible to deploy CCS and NET technologies on this scale, the climate would respond in such a way as to reduce global average temperatures as shown. As noted in section 1 (Introduction), a desire to avoid the uncertainties concerning both the scale and operation of these technologies, and whether the climate would react to them in the way modelled here, provides a major rationale for 'degrowth' instead (e.g. Kuhnhenn et al., 2020).

Figure 10 and Figure 11 show the primary energy and electricity use in the central scenario respectively.

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[10] Our illustrations focus on CO_2 (from all sources) as the dominant GHG and one for which there is an additional net-zero target in the model. However, the temperature constraint and trajectory reflect all GHGs.

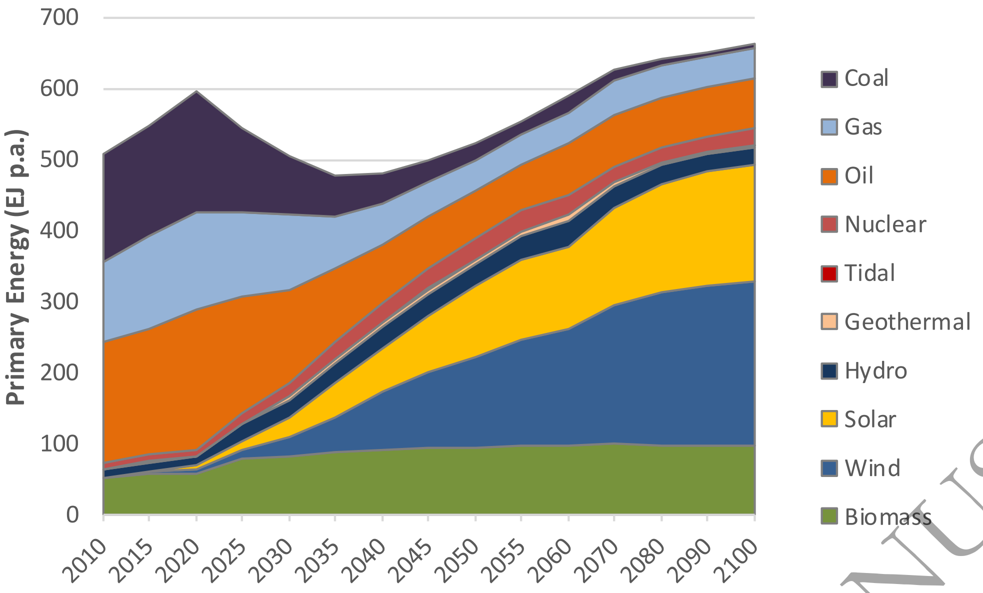

Figure 10: Primary energy (central scenario)

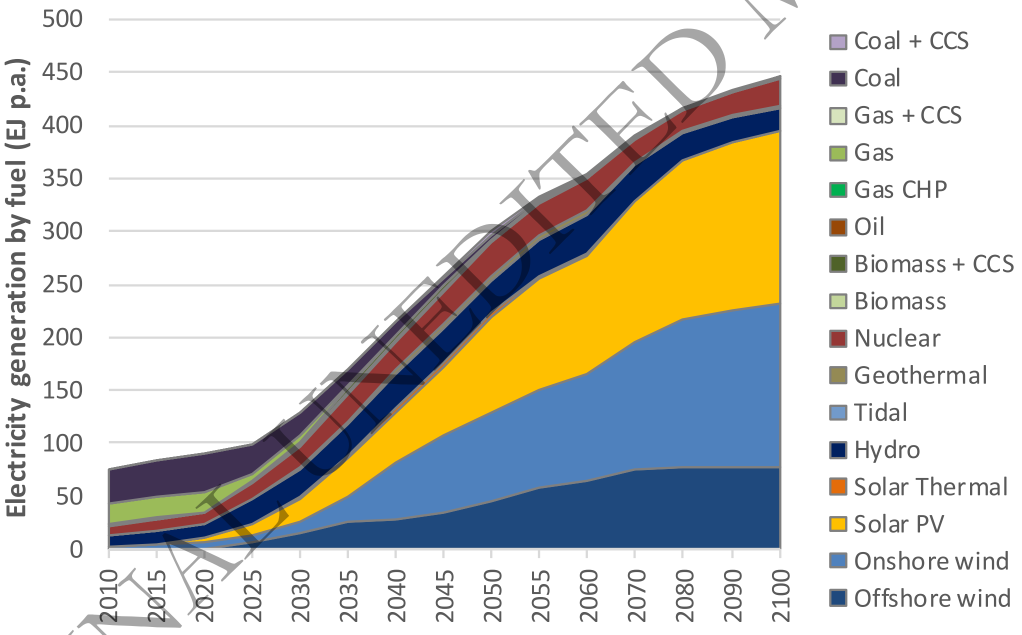

Figure 11: Electricity generation (central scenario)

Figure 10 shows the huge growth in the use of wind and solar resources. This is used, as shown in Figure11, to decarbonise almost completely the electricity system in 2100, even while it generates seven times as much electricity as in 2010. This extra electricity goes to decarbonise heat in buildings, mainly cars in transport, and some industrial processes. Hydrogen is also used in transport for HGVs, buses, trains, ships and some cars, while aviation largely switches to biofuels. Such natural gas, oil and coal as remains in the energy system is largely used in industry in sectors that are hard to decarbonise (e.g. steel and cement).

The economic implications of this revolution in the energy system are shown in Figure 12 and Figure 13.

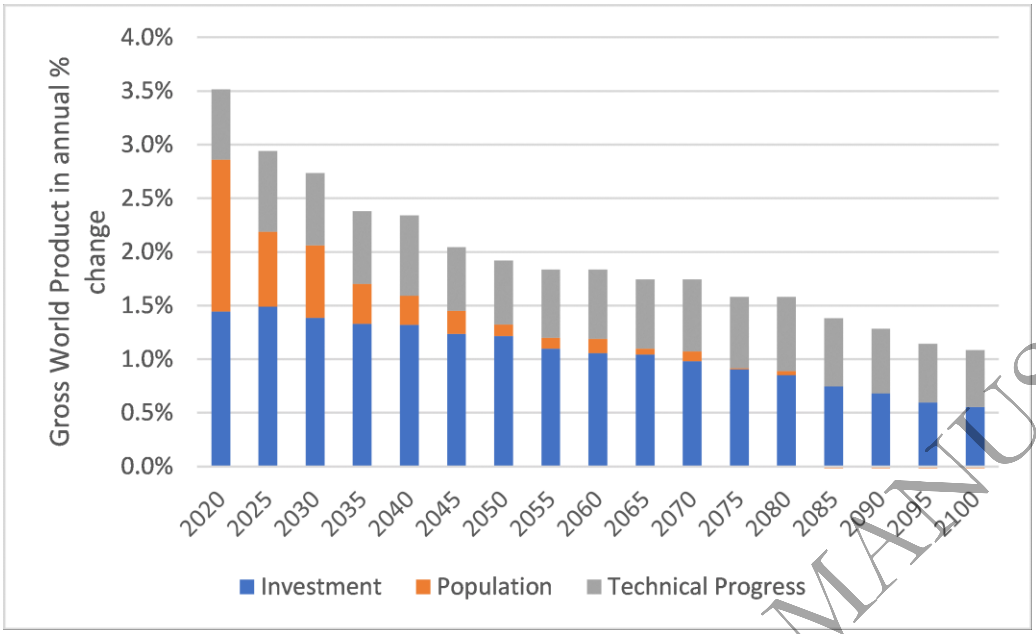

Figure 12: Decomposition of Gross World Product's annual growth rate to its key drivers

Figure 12 shows how the drivers of economic growth develop under decarbonisation. Population growth falls away over the century, leaving continuing growth in investment and technical progress, but at lower rates. Figure 12 shows that economic growth after 2020 declines from 3.5% p.a. to just over 1% p.a. However, this decline represents the long term convergence to a steady state growth rate reflecting decreasing returns to scale and the stabilisation of population. Per capita GWP growth just about halves over these 80 years as the growth of investment (which has been essential for decarbonisation) slows, largely after 2040. The average annual growth rate of Gross World Product (GWP) over the period 2020-2100 consistent with an energy system that achieves 1.5°C in 2100 is 1.76%.

Figure 13 shows that this results in continuing economic growth over the century (note the compressed time scale in the later years), although per capita GWP growth in 2100 is about half what it was in 2020. Even so, the world economy in 2100 is five times its size in 2015, having grown at an average rate of 1.76% p.a. over the period 2015-2100.

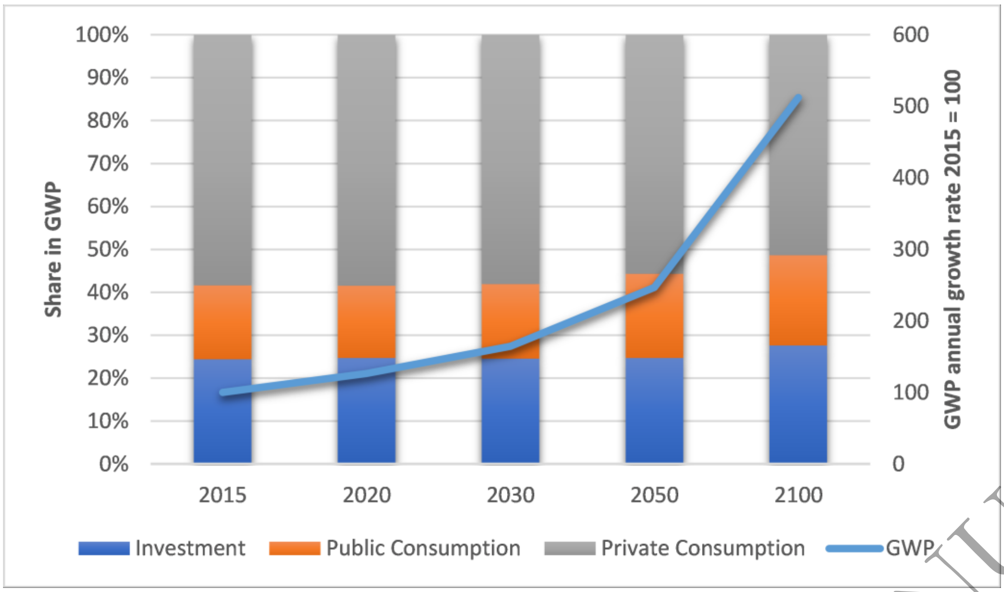

Figure 13: Annual Gross World Product (GWP), growth rate and components

Semeniuk et al. (2021) raise an issue concerning the relationship between economic growth energy demand in low- and middle-income countries when those countries are industrialising. They point out that the (relatively low) primary and final energy demands and (relatively high) economic growth rates to 2040 projected in low- and middle-income countries in both most of the IPCC 1.5°C scenarios and the central scenario reported on above are historically unprecedented. The paper says that economic growth in these countries proceeds through industrialisation and this has never been seen with such reductions in primary and final energy. They wonder whether faster energy supply decarbonisation would be a preferable way of modelling the energy transition in these countries.

This issue is somewhat outside the scope of this paper, but a relevant point is that, as far as low- and middle-income countries are concerned, the main issue is investment in new low-carbon energy supply, rather than the replacement of high-carbon energy assets. Such investment will both generate, and be made easier by, economic growth. Much of it may need to come from foreign investment from developed countries, but there is no problem with that in principle provided that the risk/return ratio makes sense. The foreign investment is more likely to be available if the developed countries are experiencing economic growth, rather than degrowth, themselves. Such considerations do not seem to undermine the essential message of this paper that economic growth in developed countries will help rather than hinder, and may even be essential for, the low-carbon energy transition.

6.2 *The sensitivity runs*

Table 1 presents the results of the sensitivity runs, which focus on technologies and dynamics that are important in the central scenario but characterised by considerable uncertainty.

	Central scenario	**Slow coal phase-down**	**No CCS or NETs**	
Coal phase-down rate	5.4% p.a.	2.7% p.a.	5.4% p.a.	2.7% p.a.
Net-zero date	2055	2055	-	-

Offset emissions from CCS, BECCS and DAC (2020-2100)	583 $GtCO_2$	638 $GtCO_2$	0 $GtCO_2$	0 $GtCO_2$
Peak temperature	1.87 °C	1.89 °C	1.89 °C	1.92 °C
Final temperature by 2100	1.5 °C	1.5 °C	1.74 °C	1.79 °C

Table 1: Sensitivity results

With a slower coal phase-down it is still possible to reach the 1.5 °C target by 2100, but only by making significantly greater use of CCS and NETs – the cumulative emissions stored or removed by these technologies rise from 583 $GtCO_2$ to 638 $GtCO_2$, compared to total CO_2 emissions in 2020 of around 40 $GtCO_2$. The peak temperature under this scenario rises from 1.87 °C to 1.89 °C. If CCS is not available, even with the fast coal phase-down, cumulative CO_2 emissions double over the central scenario, and it is no longer possible, with the rest of the assumptions of that scenario, to keep the temperature rise to 1.5 °C by 2100 – it rises to 1.74 °C by then. With a slower coal phase-down, the 2100 rise in temperature is even greater.

Slow coal phase-down reduces GWP growth by a small amount compared to the central scenario, especially during the period 2030-2060, since other more expensive emission-reduction options have to be used for emission reductions. Notwithstanding, GWP continues to grow during the entire period to 2100. Lack of CCS and NETs does not affect GWP growth much, although, as shown in Table 1, it does mean that the 1.5^{o}C target in 2050 is not reached. But these technologies are critical to reach the temperature target.

7. *Policy implications*

The modelling results of this study clearly suggest that, with stringent public policy, the Paris target of a maximum warming of 1.5 °C in 2100 is feasible, albeit with overshooting this temperature increase in the decades after 2050, and that this can be achieved with continuing global economic growth. However, for this outcome public policy will need to generate increases in energy efficiency, investment in renewables, coal phase-down and CCS and NETs deployment at rates that greatly exceed anything that has yet been achieved at the global level. The required scale of CCS and NETs, especially, may strain credibility as to its possible achievement. Moreover, the results also rest on the assumption that the removal of CO_2 from the atmosphere by future deployment of CCS and NETs will cause the global average temperature to fall as shown. No-one knows whether this would actually be the case. Avoiding the uncertainties related to this and the possibility of triggering tipping points would require emissions to be reduced even faster than the already unprecedentedly fast rates shown in the modelling. This provides a major rationale for the calls for ‘degrowth’ in rich countries, as has been seen.

Decarbonisation at scale and at speed will require a mix of different policy instruments and approaches to remove the many barriers and constraints that impede it (Kern et al., 2019, van den Bergh et al., 2021)). The instruments and approaches include regulation, consumer information, digitalisation, carbon pricing, infrastructure provision, innovation support, and institutional and behaviour change across a range of policy areas (Penasco et al. 2018). The changes required are both systemic and transformational. Most of society’s fundamental techno-socio-economic systems will need to be refashioned: the energy system and the transport system; how buildings are constructed, and how businesses and individuals occupy and heat and cool them; the food system, what people eat and where it comes from; and how practically everything is made, used and disposed of at the end of its life. The International Energy Agency wrote of its Net Zero by 2050 Scenario: “Our pathway requires vast amounts of investment, innovation, skilful policy design and implementation, technology deployment, infrastructure building, international co-operation and efforts across many other areas. (IEA, 2021, p.3).

As the IEA says in the passage just cited, the relevant systems will need to be transformed through ‘vast’ increases in investment. In the context of a growing economy, these increases in investment can be accommodated, as shown in Figure 13, by reducing the share of consumption in the economy, but not its absolute amount. With degrowth, consumption would need to decline by a greater amount than the increase in investment (given that investment itself contributes to GDP growth, as seen in Figure 12).

The investment itself could be driven by public fiat, as in a wartime economy. To the extent that it is envisaged that the investment would come from the private sector, incentives that de-risk and generate a normal return to capital would need to be provided. These incentives would need to be larger to the extent that degrowth made the relevant markets (e.g. for electric vehicles) smaller. Thus, degrowth would make achieving increased private-sector investment flows for decarbonisation more difficult (even without considering the effect that degrowth would have on the unemployment rate, private disposable income and aggregate demand) . From this perspective, and unless it is envisaged that the entire financial sector is taken into the public sector, degrowth would make it more difficult rather than easier to achieve the carbon reduction targets.

To the extent that the private sector is to provide the increased investment to achieve systemic transformation is provided, the necessary policies to incentivise this must be consistent, coherent, credible and comprehensive to be effective, and be projected to be maintained over the decades that the low-carbon transition will take, so that the businesses that invest in the products and processes of decarbonisation in the various systems know that they will get the financial return that such investment requires.

No government in the world is yet close to the kind of policy architecture that will enable its country to achieve the level of emission reductions that would play its part in achieving the global goals of the Paris Agreement, and reaching the Paris target will require all the world’s major emitters to do so. The 2020s is the decade that will either put the world’s emission trajectory on track for this target or put it beyond reach.

8. Conclusions

This study began by enquiring what the conditions were for the world to achieve net-zero CO_2 emissions by mid-century and to limit the average global temperature increase to 1.5 °C by 2100. Evidence from the IPCC has already shown that it is possible to reach 1.5 °C by 2100 under the wide range of future worlds characterised by four of the SSP scenarios – but not under all of them. The baseline assumptions that make it easiest to reach the Paris targets are global co-operation, rapid technology development, strong environmental policy, low population growth, declining inequality, dietary shifts and forest protection, and these assumptions provided the foundation for the modelling in this study. Absence of any of these assumptions would make the achievement of the Paris 1.5 °C target more difficult or impossible.

The following developments, which arise from the modelling that has been implemented, are likely to be necessary to achieve net zero of CO_2 in or soon after 2050, and the Paris temperature target in 2100, in the context of the population and economic growth projections in the model:

- Increases in energy efficiency need to slow the growth of global primary energy demand so that in 2100 primary energy demand is little more than it is in 2020.
- The deployment of renewable technologies needs to decarbonise electricity generation almost completely by 2100 and produce seven times as much power as the world used in 2010, in order to replace fossil fuels in transport, heating and in some industrial processes.
- The use of coal must be phased out globally as fast if not faster as it has reduced in the USA in recent years.
- CCS technologies need to be installed at scale from 2030 to prevent residual industrial emissions from getting into the atmosphere. NETs and direct air capture technologies are necessary for reducing temperature from its peak levels to 1.5 °C by 2100.
- Investment in the global energy system needs to be increased substantially, both in absolute terms and as a share of Gross World Product.
- Soils and trees need to become carbon sinks on a large scale.
- And there need to be, through innovation and deployment at scale, the kinds of reduction in the costs of energy storage and hydrogen technologies as have already been seen in the generation of electricity from renewable sources.

In addition, to reduce greenhouse gas emissions from agriculture, there will need to be a significant reduction in the amount of meat in the diets of the world's middle class (IPCC, 2019).

None of this will happen without a strong and comprehensive policy framework, to bring about the changes above.

As far as the economy is concerned, one remarkable thing about economic modelling in this area is that there is widespread agreement that decarbonisation on this scale does *not* require economic contraction (degrowth), even in industrial countries. Every study in the IPCC database of Paris-compliant economic development through to 2100 has shown global economic growth over this period, though with considerable differences in national impacts, depending on whether countries are fossil-fuel importers or exporters. This economic growth is driven by the forces of technical change and capital accumulation that have led to such growth in the past and, in the absence of environmental catastrophes that climate policy is intended to prevent, there seems little reason why such forces should not continue to produce this result.

Another economic conclusion is that investment needs to take a larger share of national income, with the share of private consumption falling, to create the new infrastructures and industries required by a zero-carbon world. GDP is consumption plus investment (leaving aside net exports), so unless GDP as a whole is growing more than investment, then consumption will fall, in rich countries especially, given that degrowth advocates envisage that the economies (and consumption) of poor countries will keep growing. Quite apart from the difficulties of persuading rich country populations to accept this, it is not at all clear how, in a context of economic contraction (degrowth), the private sector would provide the necessary level of financial resources and investment. Certainly it would need strong government interventions to de-risk, where necessary, investments and to provide a stable investing environment with clear and ambitious policies and measures. If degrowth advocates consider that the financial sector will come under public control, in order to ensure that the necessary investments are undertaken, then, given the control over the demand side that also seems to be envisaged in degrowth scenarios (e.g. Kuhnhenn, 2020), this argues for a degree of central control over economic direction that is unprecedented in Western economies outside wartime. So far, popular backing for such central control seems almost completely lacking, despite growing awareness about climate change.

Policymakers committed to the 1.5°C target need to understand the two very different routes to decarbonisation with which they are faced. On the one hand, they could, encouraged by the enormous reductions in renewables costs that have already been achieved, bet on achieving the same technical advances with electricity storage, CCS and NETs and hope that the massive deployment of NETs in the second half of this century will indeed reduce the average global temperature to 1.5°C by 2100. This would allow a pace of emissions reduction now that was considerably higher than that achieved historically (as the modelling above shows), but which was still consistent with some consumption growth in rich countries as well as poor countries. Economic growth might then be expected to continue along broadly historical lines as outlined above.

On the other hand policy makers could seek directly to channel an even higher proportion of economic output into investment for decarbonisation and strictly constrain consumption of energy-intensive goods and services (to reduce the capacity of low-carbon generation that needed to be built) and other goods and services (like meat) associated with high levels of non-CO_2 greenhouse gas emissions. This degrowth strategy might avoid the risky bet on CCS, NETs and nuclear technologies (as in Kuhnhenn, 2020), but its effectiveness is quite uncertain while it implies a direction of economic travel and degree of central economic control that currently has very little popular support.

Neither route can be followed except through policies that are far from easy to implement. In our opinion, because the former can be couched in a narrative of transformation towards greater prosperity, rather than retrenchment, it seems more likely to succeed in avoiding the worst of the very large climate damage costs that an absence of these policies seems likely to bring about.

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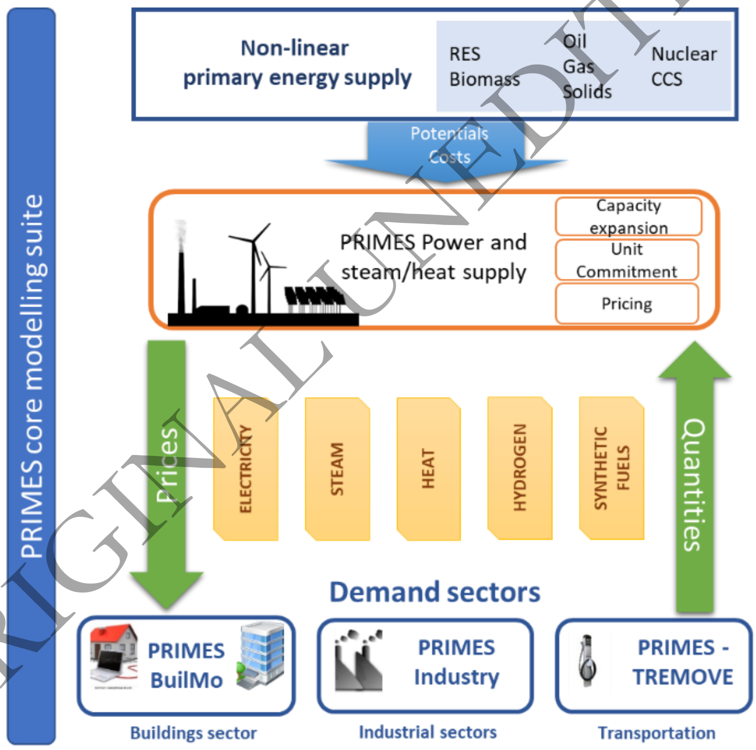
ANNEX 1

The energy system and macroeconomic models: PRIMES, TIAM-UCL, GEM-E3

Two energy system models and a macroeconomic model have been used for this project to assess the feasibility and sensitivity of limiting global warming to 1.5 degrees with positive GDP growth. The PRIMES energy system model will deal with the national (Finland) and EU level, while the TIAM-UCL energy system model is a global model. The GEM-E3-FIT macroeconomic model is used to assess the economic impacts.

PRIMES energy system model

The PRIMES (Price-Induced Market Equilibrium System) is a large-scale applied energy system model that provides detailed projections of energy demand, supply, prices and investment to the future, covering the entire energy system including emissions (see Figure4). The distinctive feature of PRIMES is the combination of behavioural modelling (following a microeconomic foundation) with engineering aspects, covering all energy sectors and markets. The model has a detailed representation of instruments of policy impact assessment related to energy markets and climate, including market drivers, standards and targets by sector or overall. It handles multiple policy objectives, such as GHG emissions reductions, energy efficiency and renewable energy targets, and provides pan-European simulation of internal markets for electricity and gas.



Source: E3Modelling

Figure 14: Diagram of the PRIMES model[11]

PRIMES offers the ability to handle market distortions, barriers to rational decisions, behaviours and market co-ordination issues and it has full accounting of capital and operating costs (CAPEX and OPEX) and investment on infrastructure needs. The model covers the horizon up to 2070 in five-year interval periods and includes all member states of the EU-28 individually as well as 10 other European countries. PRIMES is designed to analyse complex interactions within the energy system in a multiple agent-multiple markets framework. Decisions by agents are formulated based on microeconomic foundations (utility maximisation, cost minimisation and market equilibrium), embedding engineering constraints and explicit representation of technologies and their age; optionally perfect or imperfect foresight for the modelling of investment in all sectors. PRIMES is well placed to simulate long-term transformations for long-term (rather than short-term) transitions and includes non-linear formulation of potentials by type (resources, sites, acceptability, etc.) and technology learning.

TIAM-UCL energy system model

This study uses a global energy systems model, TIAM-UCL, to describe the development of the global energy system and the related emissions. The representation in the model covers the full energy system from primary resources (oil, gas, coal, nuclear, biomass and various renewables) through their conversion (e.g. electricity production), transport and distribution, and eventual use to meet energy demands across a range of economic sectors (various demands, e.g. in the transport, residential and industrial sectors). The model keeps track of emissions throughout the system, allocating them to the processes that are responsible for them (e.g. combustion in power plants, internal combustion engines in cars) and also includes a rudimentary representation of the emissions emerging from non-energy sectors. Technology choice in the model is driven by least-cost optimisation across the full time horizon of the model (until 2100) and future energy demands, which are price elastic, are projected based on a number of projected drivers (e.g. GDP, population, number of households) (Figure).

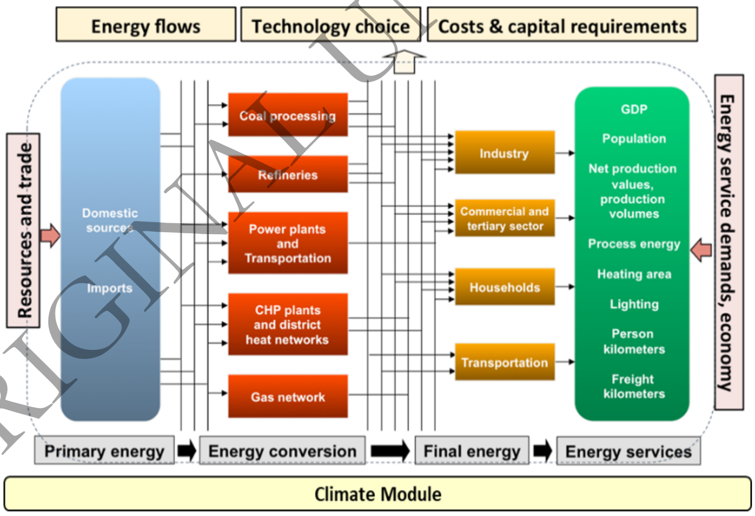


Figure 15: The TIAM-UCL global energy system model[12]

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[11] Further information about the PRIMES model can be found here: https://e3modelling.com/modelling-tools/primes/.

Macroeconomic modelling and analysis: GEM-E3-FIT

To analyse the macroeconomic impacts in a quantitative manner, a computable general equilibrium (CGE) model will be used: GEM-E3-FIT will undertake the analyses of the macroeconomic impacts at a global, regional (EU) and national level. The macroeconomic model models the same scenarios as the energy system models.

GEM-E3-FIT, the main components of which are shown in Figure, is an advanced and detailed CGE model that enhances the standard version of GEM-E3 in the following aspects:

- it represents the financial sector explicitly
- it represents policy-induced technical change and innovation-induced growth by two-factor learning curves (learning by doing and learning by research) associated with knowledge spill-over matrices based on patent citations data
- it represents household decisions on education that affect human capital, and links human capital with the creation of knowledge and the ability to absorb knowledge spill-overs
- it has an explicit representation of infrastructure
- it provides built-in options for Monte Carlo simulations to perform sensitivity analysis
- it includes a detailed representation of transport (freight and passenger by mode)
- it includes a discrete representation of sectors producing clean energy technologies (wind, PV, CCS, electric vehicles, biofuels, batteries, insulating materials)
- it has a high degree of sectoral (economy is disaggregated into 53 productive sectors) and regional resolution (46 countries/regions are represented), and it has a new calibration of energy volumes that combine in a consistent way data from energy balances and input-output tables
- it has detailed data on energy subsidies globally based on an IEA dataset
- it accounts for the number of firms by economic activity and calculates the profitability rates of each activity.

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[12] More information about the model can be found here: www.iamcdocumentation.eu/index.php/Model_Documentation_-_TIAM-UCL.

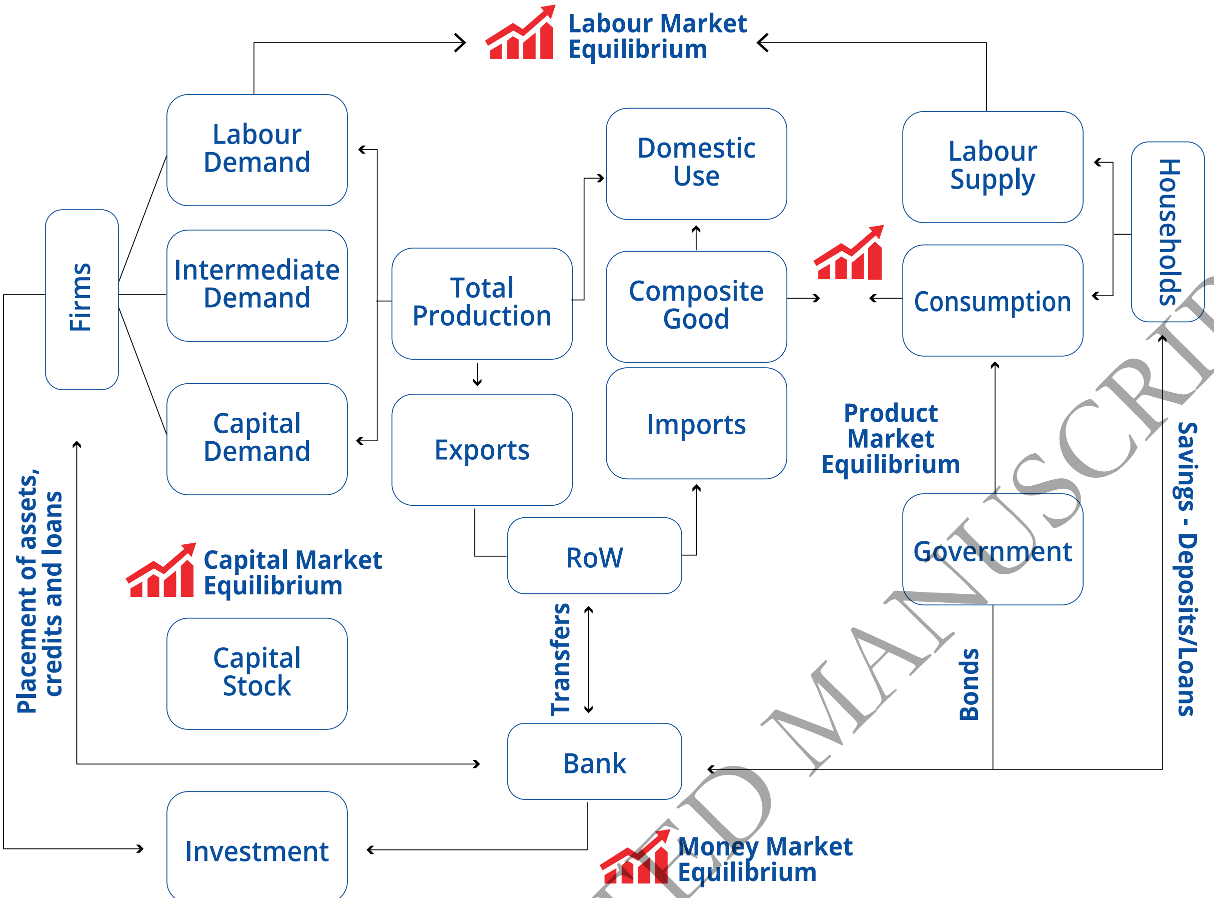

Figure 16: Diagram of GEM-E3-FIT (Capros et al., 2017)[13]

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[13] Available at: https://e3modelling.com/modelling-tools/gem-e3/.