Climate Change and Productivity – An Exploration

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Abstract

This article explores the links between climate change and productivity. It finds that while much debate has focused on labour and multifactor productivity growth, improving productivity in the use of energy and materials is crucial to achieving net zero and requires much greater emphasis in productivity analysis. Although complementary productivity measures are available, these have not yet become mainstream. Productivity measurement also needs to be improved. Mainstream economic studies have long significantly underestimated the damaging impacts of climate change on growth and productivity. At the same time, studies today may overestimate the long-term costs of policies to address climate change.

Standard measures of productivity show few signs of a transition to more sustainable growth. Multi-factor productivity growth – the combined efficiency of factors inputs – has been falling at the global level, and the transition to net zero will likely require large investments in resource-intensive fixed capital, and not just intangible and human capital. While energy and materials productivity are improving, global material use continues to grow rapidly. Moreover, although CO2 emissions have decoupled from GDP growth in many advanced economies, the current pace of decoupling is far below what is needed for net zero.

The challenge for policy is how to design climate change policies to meet the global objective of net zero while limiting the impacts on productivity growth and living standards.

Climate change – the long-term change in the average and variability of weather patterns that define the Earth's climate – is already having negative impacts on economic performance, including on GDP, labour and multi-factor productivity (MFP). It is expected to have even greater impacts in the future, possibly threatening future living standards. Mainstream economic modelling studies have long suggested that the long-term impacts of climate change on growth and productivity

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would be relatively small, however (e.g. Tol, 2018; Nordhaus, 2019). Other studies question the findings and underlying assumptions of such modelling (Dietz and Stern, 2015; Stern *et al.* 2022; Stern and Stiglitz, 2023) and point to much larger, potentially devastating, impacts on growth and productivity (Dietz and Stern, 2015; Howard and Sterner, 2017), including impacts linked to the risk of the climate passing so-called “tipping points” (OECD, 2022). Recently, Kotz et al (2024) found that the world economy is already faced with a 19 per cent reduction of income within the next 26 years relative to a baseline of no climate change, independent of future emission choices. Bilal and Känzig (2024) find that a 1°C increase in global temperature leads to a 12 per cent decline in global GDP and that world GDP per capita would be 37 per cent higher today if no global warming had occurred between 1960 and 2019.

There are also considerable uncertainties about the impact of policies to address climate change on productivity. Many mainstream economic studies suggest that policies to address climate change could have a relatively high cost and a negative impact on growth and productivity, in particular in the context of scenarios aimed at limiting warming to 1.5°C (Dietz *et al.* 2021). Other studies find much smaller impacts of policy action, however, in particular in the long term (OECD, 2023; NGFS, 2023). Moreover, studies pointing to the high cost of policy action often do not consider the appropriate counterfactual, as they assume that climate change will have little impact on future GDP growth (Stern and Stiglitz, 2023). In addition, policies that encourage investments in innovation and technology to address climate change could support, rather than hold back, productivity and growth (Stern, 2022; Stern and Stiglitz, 2023).

The discussion on climate change and productivity is further complicated as labour and multi-factor productivity – the standard tools for productivity analysis – are not the only measures that are relevant to climate change. Other productivity measures, e.g. resource, energy and materials productivity, are not commonly discussed in the productivity and mainstream economics literature, although they are a key subject in environmental, resource and energy economics. Moreover, there are methodological challenges in measuring productivity in the context of the large environmental externalities linked to climate change. Another challenge is the absence of natural capital, as one of the ”missing capitals” (Coyle, 2023), in most productivity analysis. Furthermore, the impacts of climate change go beyond those measured in GDP, requiring complementary analysis of well-being and other measures beyond GDP.

This article aims to disentangle some of the issues related to the impacts of climate change on productivity. It first provides a brief conceptualization of the different measures of productivity that are relevant to climate change and examines several economic measures of productivity, notably labour productivity and multi-factor productivity. It then examines various indicators linked to the physical processes linked to climate change, i.e. materials (or resource), energy and carbon emissions “productivity” (i.e. CO2 emissions relative to GDP). Next, it explores several indicators of environmentally-adjusted productivity, including the role of nature capital. All these sections present a range of evidence to illustrate various indicators and their relevance to the debate on climate change. It then explores how policies can best address climate change while also supporting productivity growth and standards of living. A final section summarizes and draws some conclusions.

Climate Change and Aggregate Productivity: Measurement and Evidence

Climate Change and Productivity Measurement

Exploring the links between climate change and productivity requires some elaboration of concepts and frameworks. After all, there are many possible measures of productivity and many potential links between climate change and productivity that can be distinguished. A first step in conceptualizing the relationship therefore lies in reviewing the main productivity measures that might potentially be affected by climate change. Table 1 draws on the OECD's Productivity Manual in showing the measures of labour, capital and multi-factor productivity that are commonly distinguished in productivity analysis (OECD, 2001). It includes an additional column on measures of materials and energy productivity, as climate change is closely associated with materials, resource and energy use, implying that relevant indicators of their productivity will be important to consider. It also emphasizes natural capital – defined as the living and non-living components of ecosystems that contribute to the provision of goods and services of value to people (Guerry et al. 2015) – as an additional capital input requiring attention in the context of climate-related productivity analysis. Following the OECD Manual, the table shows productivity measures for both gross output and value added, although much productivity analysis at the economy-wide level focuses on value added (and GDP), with the exception of KLEMS (Capital, Labour, Energy, Materials and Services) productivity analysis, that relies on gross output.

The measures in Table 1 all have their own relevance to climate change. Notably, and leaving the conceptual discussion of materials productivity for the next section (OECD, 2001):

- *Labour productivity and climate change.* Indicators of labour productivity relate a measure of output (gross output or value added) to a measure of labour input, typically employment or total hours worked. Measuring and understanding the relationship between climate change and labour productivity will provide an indication to which extent climate change is affecting economic performance at the firm, industry and economy-wide level and the ability of economies affected by climate change to generate growth in output and incomes.
- *Capital productivity and climate change.* Indicators of capital productivity relate a measure of output (gross output or value added) to a measure of capital (typically a measure of the services provided by a stock of capital). Changes in capital pro-

Table 1: Asset Types Included in the UK Volume Index of Capital Services

Type of Output Measure	**Type of Input Measure**				
	Labour	**Capital (including natural capital)**	**Materials or energy**	**Capital and labour**	**Capital, labour & intermediate inputs**
Gross Output	Labour productivity (based on gross output)	Capital productivity (based on gross output)	Materials or energy productivity (based on gross output)	Capital-labour MFP (based on gross output)	KLEMS multifactor productivity
Value Added	Labour productivity (based on value added)	Capital productivity (based on value added)	Materials or energy productivity (based on value added)	Capital-labour MFP (based on value added)	-
	Single factor productivity measures			**Multifactor productivity measures**	

Source: Modified from OECD (2001), Measuring Productivity - OECD Manual.

ductivity reflect the extent to which output growth can be achieved with lower welfare costs in the form of foregone consumption. Indicators of capital productivity can show how climate change is affecting – and possibly eroding – the capital stock and measure efficiency in the use of the capital stock. To be relevant to discussions on climate change, measures of the capital stock should include natural capital in addition to the standard measures of fixed and intangible capital. Some insights relevant to climate change might also be gained from the evolving composition of the capital stock, e.g. the growing importance of intangible assets such as R&D, software and data, that might signal a move towards a more knowledge-intensive and "weightless" economy involving less material use (Quah, 1999).

- *Multi-factor productivity (MFP) and climate change.* Indicators of MFP growth relate a measure of output (gross output or value added) to a measure of the combined input of labour and capital and – when related to gross output – also to intermediate inputs (energy, materials and services). Measures of MFP growth can help illustrate whether aggregate growth patterns are compatible with the transition to net zero and with sustainability more generally. More sustainable economic growth could imply growth that is for a large extent based on MFP growth, rather than on growth in factor inputs.

What Kind of Impacts Could Climate Change Have on Productivity?

Apart from considering the various indicators of productivity from a conceptual point of view, it may also be helpful to explore what kind of (direct) impacts climate change is likely to have on productivity and its various components, i.e. output, capital, labour input and intermediate inputs. For example, climate change is already having important impacts on agricultural yields that are expected to differ between different regions of the world

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[2] Although some of the impacts of climate change may be positive for specific regions and with small changes in temperature, the global impacts are expected to be strongly negative and highly damaging to the global economy.

(Pörtner *et al.* 2022).[2] Climate change will also have impacts on production in many other sectors directly influenced by weather conditions, e.g. tourism, fisheries and construction, or indirectly (e.g. insurance), and could affect many other sectors depending on its intensity.

Changing weather conditions could also affect labour input, for example as the intensity of work efforts will be affected by increasingly difficult working conditions due to extreme heat and due to growing migration from regions and countries that could become inhabitable. Impacts on the stock of fixed capital could include damages caused by extreme weather events, obsolescence of certain capital goods, or the impacts of increased weathering on the capital stock. Moreover, climate change could affect the costs and availability of intermediate inputs e.g. linked to the increased costs of cooling, lack of water, adaptation to climate change, insurance, etc. In principle, climate change might also affect technological change, e.g. in reducing investment in research and development (R&D) as firms and governments might focus more on the short term.

Finally, and potentially the most important, climate change is expected to have large impacts on the natural capital and ecosystems upon which the global economy is founded, with potentially disastrous consequences for many areas of economic activity, in particular when some of the planet's so-called "tipping points" would be exceeded.[3] As shown in the work of IPCC Working Group II, some of the impacts of climate change are already highly certain, while others are still somewhat uncertain (Pörtner *et al.* 2023).[4] What is clear is that they will all grow in magnitude with the extent of global warming. Tipping points, in particular, have long been ignored in the economics literature but are now regarded as possibly the most important and dangerous impacts of climate change, significantly increasing the magnitude of previously estimated economic impacts (OECD, 2022). Recent research suggests that some tipping points might be passed sooner than previously expected (Willcock *et al.* 2023).

These various direct impacts on outputs and inputs would affect productivity in specific firms and industries, and could lead to reallocation between firms and industries, with some firms and industries growing in size and others declining. Such reallocation might also occur across countries, with certain activities, such as agriculture or tourism, potentially relocating from countries heavily affected by climate change to others that are less affected. Climate change is also likely to have indirect impacts on productivity, linked to the policies implemented to address climate change. These will be discussed later in the article.

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[3] Tipping points include the disintegration of the Greenland ice sheet, the collapse of the West Antarctic ice sheet, the saturation of oceans as a carbon sink, the collapse of the Atlantic meridional overturning circulation (AMOC), and the dieback of the Amazon Forest as a carbon sink, among others (OECD, 2022).

[4] Successive IPCC reports provide further detail on what the impacts of climate change might entail (IPCC, 2023).

The Macroeconomic Impacts of Climate Change on Growth and Productivity

What do we know about these direct impacts? Estimates of the future impacts of climate change on GDP and productivity, based on economic modelling, have been produced since the early 1980s and multiplied in the early to mid-1990s. Modelling studies typically focus on impacts on GDP instead of (labour) productivity, but often include assumptions about an exogenous pace of technological progress, that is driving MFP growth, and about capital deepening and labour input. However, with low and declining growth in labour input in many countries (Van Ark *et al.* 2023), impacts on long-term GDP growth are a close approximation of impacts on long-term labour productivity growth and thus instructive for this article.

Nordhaus (2019) notes that the available evidence suggests that the impacts of climate change will be nonlinear and cumulative, with relatively small impacts when climate change is limited and gradual, allowing economy and society to adjust, but that more extensive climate change can be highly disruptive to society and to natural systems. Tol (2018), in an overview of 27 studies from 1982 to 2013 finds small positive impacts of climate change on GDP with a modest degree (1°C) of global warming, to sizeable negative impacts with more extensive global warming. However, as noted by Tol (2018), there are considerable uncertainties with such estimates with a high change of negative surprises. Overall, he concludes that the impacts of climate change are considerable, but that "A century of climate change is likely to be no worse than losing a decade of economic growth." At the same time, the study points out the large differences between countries as regards the impacts of climate change, with the largest impacts expected in developing economies.

Howard and Sterner (2017) provide another meta-analysis and address a number of problems with previous studies, that they consider having created a significant downward bias in the literature. Their preferred estimate points to non-catastrophic damages of climate change on the level of GDP of between 7 and 8 per cent of GDP for a 3°C increase in global temperature, and between 9 and 10 per cent when factoring in catastrophic risks, considerably higher than the studies summarized by Tol (2018) and some three times higher than the average from previous studies.

Aligishiev *et al.* (2022) provide a recent overview of (some 40) studies on the macro-economic impacts of climate change. The estimates they report suggest relatively limited impacts of global warming on GDP, i.e. a median loss of only 1.5 per cent of annual global GDP in 2100 with respect to its reference level without climate change with global warming between 1.5° and 2.5°C, and a median loss of 3.3 per cent of annual global GDP in 2100 with global warming between 2.9° and 4.3°C.

They note, however, that "these studies may substantially underestimate the global cost of climate change in several ways and that global averages do not reveal the unequal distribution of climate change impacts". Specifically, they note that (Aligishiev *et al.* 2022): a) the estimates hide large negative effects in developing countries that are already hot or vulnerable; b) worst-case scenarios are typically missing, due to uncertainty in the literature; c) non-market impacts, e.g. biodiversity loss, are often imperfectly included as these estimates are uncertain and hard to quantify; d) the possibility of crossing societal tipping points (social conflicts, war, disruptive migration) is not considered as empirical data are lacking; e) GDP is at best a partial measure of welfare that does not consider distributional impacts.

The macroeconomic modelling studies of climate change briefly summarized above have increasingly been criticized over the past decade in being founded on a range of flawed assumptions (Dietz and Stern, 2015; Stern *et al.* 2022).[5] This includes problems with the integrated assessment (IA) modelling underpinning most of the studies, the lack of treatment of problems outside the scope of IA models, as well as some issues that could be addressed by IA models, but that have been ignored thus far and may lead to biased results. Moreover, the IA models have also been criticized in ignoring the possibility of large-scale events due to climate change, or "tipping points", and for their inability to connect sufficiently to physical science modelling of climate change (OECD, 2022). Aufhammer (2018) points to a number of key sectors for which a better understanding is required about their climate sensitivity and sets out key areas for further empirical research. Rising *et al.* (2022) also point to the many risks that are missing in the analysis of climate change, with a wide range of impacts understudied or challenging to quantify, and thus missing from the evaluations of climate risks.

Dietz and Stern (2015) show that the original IAM modelling, notably the so-called DICE (dynamic integrated climate-economy) model developed by Nordhaus (1992), has in-built assumptions related to the exogenous nature of economic growth, damage functions, and risk, that result in a large underassessment of the scale of economic damages linked to climate change. They modify these assumptions in three areas, i.e. a) by using a model of endogenous growth, where climate change affects long-term growth, not just current output; b) by using a different damage function where damage can increase rapidly if temperatures rise; c) by using different assumptions as regards the risks associated with climate change. The resulting analysis with the DICE model shows much larger impacts of climate change on economic growth in the long run than the standard analysis with the DICE model.

Stern and Stiglitz (2023) also point to a number of analytical flaws in standard macroeconomic studies of climate change. First, they note that many studies get the counterfactual wrong by underestimating the growing scale of damages resulting from climate change. Second, they note that most studies are underestimating the risks of climate change, and do not account for the systemic nature of that risk. Third, they note that the standard argument over-

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[5] Modelling is not the only way to estimate the impacts of climate change. Several studies have estimated the impacts of climate change using weather observations. See Pilat (2024) for some further discussion.

looks many other market failures that reduce efficiency, and affect investment, innovation and growth. Fourth, they note that markets discount the future at too high a rate, leading to short-termism and underinvestment in the future, e.g. in R&D. Finally, they suggest that the standard models ignore distributional effects, notably in giving little weight to future generations, but also to poor people and poor countries, instead emphasizing efficiency.[6]

Economic analysis that incorporates the risk of one or more tipping points in the economic costs of climate change find significantly higher costs and impacts on GDP (Dietz *et al.* 2021), often with magnitudes several times higher than mainstream models. Dietz et al (2021) note that their estimates are probably underestimates, as some tipping points, their interactions and impact channels, have not yet been adequately covered in the literature. Stern and Stiglitz (2023) note that assuming that current growth rates can be sustained without stronger climate action is a misleading counterfactual. Overall, it appears therefore that macroeconomic studies have significantly underestimated the impacts of climate change on growth and productivity.

Most of the estimates on the economic impacts of climate change focus on standard measures of GDP and productivity growth, which implies they do not account for environmental externalities and the increase in "bad" outputs that would accompany climate change. The fourth section of this article will discuss some studies that adjust for these externalities.

Resource Productivity

Measures of resource productivity are particularly important for the analysis of climate change. They typically measure the efficiency of resource use, e.g. of energy or materials, but can also be used to measure the CO2 or greenhouse gas (GHG) emissions that accompany that resource use. The mainstream productivity literature generally does not devote much attention to resource productivity, as it is not considered central to the analysis of economic and productivity performance at the firm, industry or economy-wide level. However, these indicators are extensively used in environmental policy and energy policy analysis and have a good foundation in methodology and data.

Addressing climate change will require large improvements in the efficiency of resource use, notably in the use of materials contributing to GHG emissions, i.e. fossil fuels, as well as certain materials contributing to such emissions linked to agriculture, industry and construction (OECD, 2019). Moreover, increasing resource productivity is important as growing materials use is accompanied by a range of negative side effects on the environment, such as loss of biodiversity (OECD, 2019). This section explores some of the key indicators and ev-

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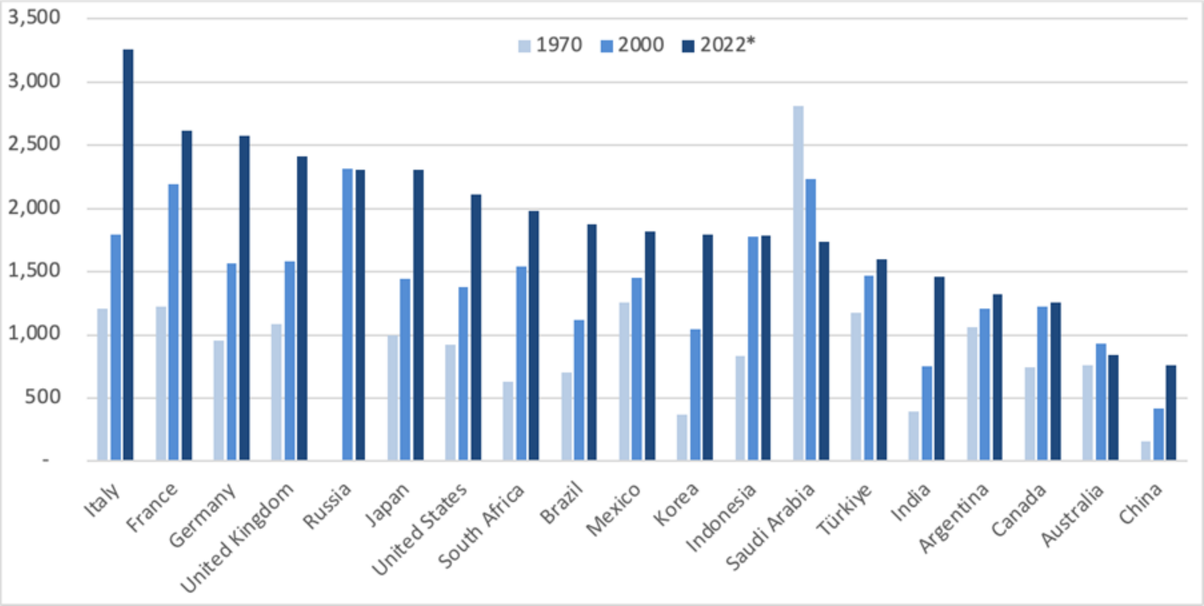
[6] The large macroeconomic impacts of climate change are accompanied by large variations across countries, regions, sectors, firms and social groups. For space reasons, this article will not review the extensive sectoral literature on climate change, nor the country-specific and regional impacts. See Pilat (2024) for some references.

Chart 1: Materials Productivity in G20 Countries, 1970, 2000, and 2022 (GDP relative to material footprint, in USD per tonne, 2015 PPPs)



Note: * 2019 for EU countries and Türkiye, 2022 for all other countries.
Source: OECD, Material Flow Accounts, OECD Data Explorer, accessed 6 June 2024.

idence.

Measuring Materials Productivity

Conceptually, measures of materials productivity relate gross output, GDP or value added to the total volume of materials used to produce that output. For example, OECD measures of materials include the volume of biomass (mainly linked to agriculture and forestry), fossil fuels, metals and non-metallic minerals (with the bulk linked to the construction sector) used in the production process (OECD, 2019). Materials productivity is then defined as the monetary value (in terms of real GDP) generated per unit (tonne) of materials used (OECD, 2017). This measure is often expressed in terms of domestic material consumption (DMC), which is calculated as the domestic extraction used minus exports plus imports and expressed in terms of weight (OECD, 2017). However, indicators based on DMC do not include the indirect material flows associated with internationally traded products, and countries might improve their materials productivity by drawing more on material flows embodied in imported goods.

Productivity measures based on the so-called material footprint of an economy adjust for these international flows and are shown in Chart 1.[7] It shows large differences between countries in 2022, with a range from around 750 USD of value added per tonne of materials in China, to over 3200 USD per tonne in Italy. These

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[7] Material footprint represents the portion of raw materials extracted anywhere in the world that are needed to satisfy final demand of an economy. It includes materials that are directly used by an economy in the form of raw materials, semi-processed materials or processed goods, and materials that are associated with the production of imported goods but not physically imported. See OECD (2020).

differences partly reflect structural factors, such as the relative importance of extractive sectors such as mining (e.g. in Australia and Canada); the level of economic development, including the importance of the construction sector; the dependency of a country on fossil fuels; the relative importance of agriculture and forestry, etc. Despite these structural differences, the cross-country differences also point to further scope for productivity growth. Between 2000 and 2022, some countries (e.g. China, India, Italy and Korea) significantly improved materials productivity. Others (e.g. Australia, Indonesia, Russia and Saudi Arabia), however, experienced stagnant of negative productivity growth.

A global study of materials and resource productivity for the period from 1970 to 2010 (Schandl *et al.* 2017) shows an increase in materials use (excluding fossil fuels) from 22 billion tonnes in 1970 to 70 billion tonnes in 2010, and a rapid acceleration in material extraction since 2000. It finds that materials productivity globally has declined since 2000, due to a shift in production from materially-efficient economies, e.g. Japan, Korea and many European countries to less efficient ones, e.g. China, India and Southeast Asia.

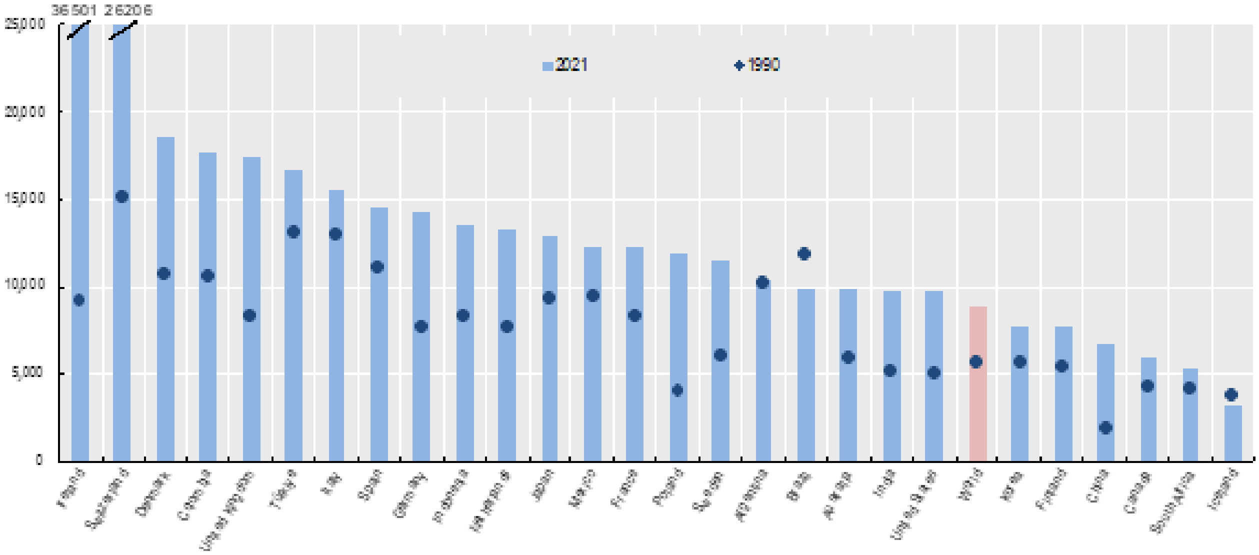
Understanding the factors that influence materials and resource productivity over time can help devise strategies to reduce their use and improve productivity. Gan *et al.* (2013) examine a range of factors that influence resource productivity across countries. They point to a few stylized facts, notably that: 1) resource productivity increases with income; 2) countries with high population density tend to have higher resource productivity; 3) the process of economic development and changing economic structures affect resource productivity; 4) raw material exports tend have a negative impact on resource productivity, as a strong focus on exporting may reduce pressures to improve efficiency in resource use.

Studies are now emerging on the potential of improvements in materials productivity for addressing climate change. Scott *et al.* (2019) examined the contribution of improvements in materials productivity for the UK emissions gap. They estimated that a range of policies could improve materials productivity. This includes policies focused on the redesign of products, so they would use less carbon-intensive products, or on reducing the demand for new products and extending the life-cycle of products. In another study, Flachenecker and Kornejew (2019) find that firms' improvements in material productivity reduce the CO2 footprint of firms. Moreover, improvements in material productivity had a positive and causal impact on the microeconomic competitiveness of firms.

Haas *et al.* (2015) suggest that improved circularity – and thus improved materials productivity – will require a shift to renewable energy, a reduction in the growth of societal stocks, and a significant increase in circularity of all products. OECD (2023b) emphasizes that rising global material extraction means that most materials are either wasted, lost or remain unavailable for reuse as they are locked in long-lasting stocks such as buildings. It also notes that reaching net zero will require the development of a more circular economy and a reduced material footprint.

The likely impacts of policy actions to

Chart 2: Energy Productivity, selected OECD and G20 countries, 1990 and 2021 (USD per tonne of oil equivalent, 2015 PPPs)



Source: OECD, Green Growth Database, accessed on 28 March 2023.

move to net zero on materials productivity are uncertain and may be limited. Studies have shown that the volume of resource extraction (including metals) needed for the transition to renewable sources of energy is many orders of magnitude smaller than the current volume of resource extraction associated with fossil fuels (Nijnens *et al.* 2023). Some materials, notably fossil fuels, should be phased out to achieve net zero, boosting overall materials productivity, but the scope and importance of productivity improvements in the use of other materials is less certain. The transition to net zero and move to renewable energy is expected to lead to greater demand for metals, in particular. Metals extraction and use have a wide range of environmental consequences, including toxic effects on humans and ecosystems (OECD, 2019). On the other hand, metals are more easily recycled than many other materials. Other materials also have a wide range of environmental impacts, not all related to climate change, but on areas such as biodiversity (e.g. due to changing land use or the extraction of construction materials). Improving materials productivity is therefore not only important for climate change, but also for the state of the environment more generally.

Energy Productivity

Another measure of productivity relevant to climate change is the productivity of energy use, i.e. the output generated (typically in terms of real GDP) per unit of total primary energy supply (TPES), where energy supply is typically expressed in tonnes of oil equivalent (OECD, 2017). Energy use will have different impacts on climate change depending on the sources of energy, e.g. fossil fuels versus renewable sources, but climate change is also affected by the efficiency of energy use, notably the use of energy-efficient technologies and processes, as well as the degree of electrification. Available indicators of energy productivity (Chart 2) show large differences between leading countries such as Ireland,[8] Switzerland and Denmark, and countries with low levels of energy productivity such as China, Canada and South Africa.

The OECD's data suggest that global energy productivity rose by over 50 per cent between 1990 and 2021 (i.e. an annual average growth rate of just over 1.3 per cent), with particularly high productivity growth in several central European countries (e.g. Poland), as well as in China and Ireland. Brazil and Iceland experienced negative growth in energy productivity over the period, however, and Argentina's energy productivity grew by only 2.5 per cent. The cross-country differences suggest scope for improvement, with potential benefits for climate change. Chart 2 suggests that countries with very low levels of energy productivity have not experienced faster productivity growth than those with high levels of energy productivity, however.

Du and Lin (2017) estimated a more complex measure of total-factor productivity energy change for 123 economies worldwide. They find an increase in energy productivity globally of almost 35 per cent between 1990 and 2010, mainly driven by technological progress, with higher energy productivity growth in the more developed economies and no evidence of convergence in energy productivity between developed and developing economies. In a study for a more limited number of advanced economies, Apergis and Christou (2016) also find no evidence of full convergence but point to the presence of some convergence "clubs". They do, however, suggest that energy productivity across countries will converge in the long run. Atalla and Bean (2017), in a study of energy productivity for 39 countries over the period 1995-2009 find that improvements in sectoral energy productivity were the main driver behind aggregate improvements in energy productivity, with a more limited role for structural shifts, e.g. from industry to services. They also found that higher income levels and higher energy prices were associated with greater energy productivity.

Energy productivity is linked to CO2 emissions and climate change through the emissions intensity of energy. In principle, countries could move from fossil fuels to clean sources of energy without improving in energy productivity. Measures of energy productivity will therefore not necessarily move at the same speed (or even always in the same direction) as measures of carbon emissions productivity (OECD, 2017), discussed below. For example, Iceland has a very low level of energy productivity, but low levels of carbon emissions, linked, amongst others, to its high use of renewable energy, notable geothermal energy.

The future evolution of energy productivity is uncertain and could move in different directions. Improvements in energy efficiency and efficiencies linked to electrification could improve productivity. How-

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[8] Ireland's GDP figures are affected by the large role of multinational firms in the country, which tend to inflate GDP and will therefore also considerably inflate its level of energy productivity.

ever, the transition to abundant and possibly very cheap renewable energy could also contribute to increased demand for energy through the so-called "rebound" effect, with improvements in energy efficiency leading to an increase in energy consumption (Dimitropoulos, 2007), with potential impacts for climate change. For example, in the transport sector, growing energy efficiency is counteracted by growing demand for larger cars, notably SUVs (Brugger *et al.* 2021). At the same time, new societal trends, such as the sharing economy, might help reduce energy demand (Brugger *et al.* 2021).

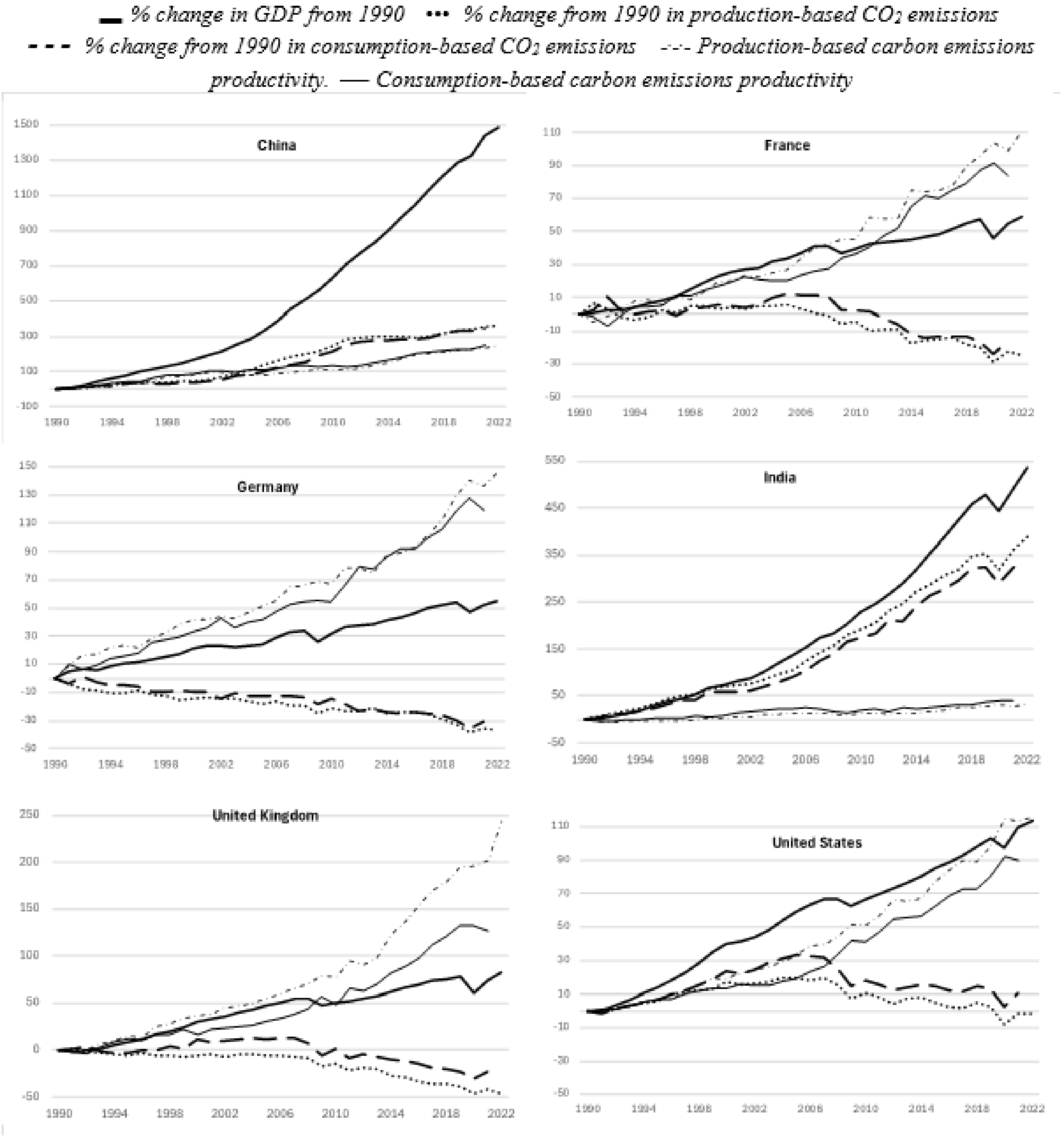
The "Productivity" of Carbon Emissions

Although carbon emissions are a byproduct of resource use and not a typical material or resource, like raw materials or energy, "productivity" indicators related to carbon emissions are the most closely associated with climate change of the three types of indicators discussed in this section. They can be derived in several ways and reflect either emissions linked to domestic production of CO2 or to the CO2 emissions linked to satisfying domestic demand, thus adjusting for emissions generated abroad to satisfy domestic consumption (OECD, 2017). Chart 3 shows these two key indicators of carbon emissions productivity levels for six key G20 countries for the period 1990-2022.

The graphs illustrate several features of carbon emissions productivity. First, as with other indicators of materials and resource productivity, there has been considerable improvement in carbon productivity in several countries over the past decades. Most advanced countries have experienced a relative decoupling between GDP growth and emissions, with GDP growing faster than emissions (OECD, 2017; Pilat, 2024). Some – e.g. France, Germany and the United Kingdom in Chart 3 – even experienced an absolute decoupling of GDP growth and emissions, with GDP growing and emissions falling (OECD, 2017; Pilat, 2024). Analysis by the IEA attributes most of the decoupling to four factors; a) rapid growth in clean energy investment; b) growing electrification; c) improvements in energy efficiency; d) a transition away from coal (Singh, 2024). In China and India, GDP growth and CO2 emissions have not decoupled yet, however, and emissions have been rising, in particular in China.

Second, there are considerable differences between the production-based and consumption-based indicators of carbon productivity. The production-based indicators cover CO2 produced in a country without accounting for trade flows, whereas the consumption-based perspective considers emissions from the perspective of final demand, including trade flows (OECD, 2017; Yamano and Guilhoto, 2020). Countries may be able to reduce their emissions from a production perspective by shifting polluting industries abroad or by importing carbon intensive products from abroad. Increasing demand-based carbon productivity is therefore more difficult than increasing production-based carbon productivity and far fewer countries were able to achieve an absolute decoupling between GDP growth and growth in carbon emissions on the demand side than on the production side (OECD, 2017). Moreover, the

Chart 3: The Relationship Between GDP and CO2 Emissions and Carbon Emissions Productivity, Selected G20 Countries, 1990-2022



Source: Our World in Data (2024), https://ourworldindata.org/co2-and-greenhouse-gas-emissions, drawing on World Bank and Global Carbon Budget.

rate of decoupling is considerably lower on the demand-side than on the production side (Pilat, 2024).

The available data also point to large cross-country differences in carbon emissions productivity, linked to the carbon intensity of different economies and their respective use of fossil fuels. China, as several other BRIICS economies, i.e. India, Russia and Saudi Arabia, have particularly low levels of carbon emissions productivity, together with some OECD countries, such as the United States, but also Australia, Canada, Korea and Poland (Pilat, 2024). Countries in Western Europe, e.g. France, and South America tend to have the highest levels of carbon emissions productivity. In principle, these large differences could point to scope for productivity growth. However, there is no evidence that countries with low levels of carbon emissions productivity have experienced more rapid growth in carbon emissions productivity than those with high levels (Pilat, 2024).

Achieving zero global emissions of CO2 (or of all greenhouse gases - GHGs) by 2050 would require a rapid acceleration in carbon emissions productivity growth. The two countries with the highest level of production-based carbon emissions productivity in the OECD – Switzerland and Sweden – had a corresponding low carbon intensity of some 60 grammes of CO2 for every USD of GDP in 2021 (Pilat, 2024) and had experienced an annual average decline in carbon intensity over the previous 30 years of around 2-3 per cent. Bringing emissions down to 10 grammes of CO2 for every USD of GDP in 2050, i.e. close to zero grammes, would require doubling that rate of decline to about 6 per cent annually. For the OECD as a whole, with production-based carbon emissions intensity in 2021 at only 180 grammes of CO2 for every USD of GDP, the annual average average rate of decline in carbon intensity would need to increase from just over 2 per cent from 1990 to 2021, to 9.5 per cent from 2021 to 2050 to achieve 10 grammes of CO2. The current pace of decoupling is thus far below what is needed.

Resource and Materials Productivity in a KLEMS Framework

The indicators in this section presented thus far all relate measures of material use to GDP. However, measures of resource, materials and energy productivity can also be derived in a KLEMS accounting framework, thus relating material use to gross output. For example, Inklaar and Timmer (2007) provide evidence on relative levels of output, inputs (including energy, materials and services) and productivity at the industry level for seven countries. They derive comparisons of output and input levels by deflating data from input-output tables by a set of relative prices developed for industry-level productivity comparisons. The article finds that European countries use much less energy in production than the United States, and that Canadian production is the most energy intensive. On the other hand, the United States (and Canada to a lesser extent) uses far fewer materials in production than European countries.

Mulder and Groot (2012) use the EU-KLEMS database (O'Mahony and Timmer, 2009) combined with IEA data on physical energy to explore the development of energy intensity across 18 OECD countries and 50 sectors over the period 1970-2005. They find declining levels of energy intensity – i.e. improvements in energy productivity – in most manufacturing sectors, but a much slower decline in services sectors, with greater variation across subsectors. They also find that changes in the sectoral composition of economies explain a considerable and growing part of the changes in aggregate energy intensity.

Productivity Measures Adjusted for the Environment

The measures set out in the previous two sections can provide a first step in measuring the links between climate change and productivity. Another step involves adjusting the measures of output and factor inputs in Table 1 for environmental externalities (negative and positive) and by explicitly including natural capital in aggregate capital input. As greenhouse gas emissions and other forms of pollution are not priced by the market, the costs and damages linked to such pollution are not reflected in the output and input measures that are used for productivity measurement. The standard productivity measures shown in Table 1 will therefore provide a biased perspective of productivity growth (Pittman, 1993). Moreover, including natural capital in total capital input will help demonstrate its contribution to economic growth and productivity and can also help indicate how such capital is evolving as a result of resource extraction and exploitation. Potentially, there are several such measures that could be developed. Not all potential measures are equally important or meaningful, however, and Table 2 shows some of the most prevalent measures in the literature.

Adjusting for Bad Outputs

A first measure (No. 1) involves *adjusting output and productivity measures for the environmental damages (outputs) created by by-products of the production process*, e.g. carbon or other greenhouse gas emissions, or other pollutants affecting the environment and human health (Brandt *et al.* 2017). As noted by Agarwala and Martin (2022), “one problem is that the standard approach to measuring productivity adopts a private goods perspective, permitting by assumption the ‘free disposal’ of bad outputs.” Not including these negative environmental externalities in the calculation of GDP and productivity may lead to an overly positive assessment of productivity for countries that use heavily polluting technologies in the production process. On the other hand, GDP and productivity may be underestimated in countries that invest in cleaner production processes, as these investments may not directly increase GDP but will help to reduce the negative externalities linked to pollution.

Cárdenas Rodríguez *et al.* (2023) estimated this adjustment for the period 1996-2018 for all OECD and G20 economies, with pollution being represented by greenhouse gases such as CO2 and nitrous oxide, and several other air pollutants. They found positive (though often small) adjustments to GDP growth in 33 countries, with particularly high adjustments in France, Germany, Italy, the United Kingdom and

Table 2: Selected Environmentally Adjusted Productivity Measures

Measures	Definition	Adjustments
A. Adjustments to output – environmental externalities		
1. Labour productivity adjusted for bad outputs	Output adjusted for bad outputs / Hours worked	The value of bad outputs (e.g., GHG emissions or air pollution) is deducted from output
2. Labour productivity adjusted for unmeasured environmental protection output	Output adjusted for unmeasured environmental protection output / Hours worked	The value of unmeasured environmental protection is added to output
B. Adjustments to capital input – natural capital		
3. Multifactor productivity measures adjusted for investment in selected natural capital assets measured at private costs	Output / Factor inputs (including selected natural capital assets valued at private costs)	The services of natural capital, valued at private costs, are added as a capital input

Source: Modified from Agarwala and Martin (2022).

Sweden, reflecting the effect of pollution abatement in these countries. They also found and negative adjustments in 19 countries, with particularly high adjustments in Brazil, China, Korea, India, Indonesia and Turkey, reflecting the pollution-intensive nature of growth in these countries.

Hua and Wang (2023) also provide estimates of environmentally adjusted MFP growth (EAMFP) for 51 OECD and G20 countries over the period from 1990 to 2020 that includes natural capital and bad outputs. They find that EAMFP growth is below MFP growth in 40 out of 51 countries, i.e. with bad outputs having a negative impact on MFP growth. They note that the gap between MFP and EAMFP growth is largest in lower-middle income economies, such as India and Indonesia, where growth was accompanied by high emissions of pollutants.

Some studies have criticized EAMFP measures. For example, Guarini (2023) suggests that the underlying assumptions of constant returns to scale, perfect competition and perfect input substitutability are unrealistic in the context of environmental policy and innovation.

Adjusting for Good Outputs

A second potential measure involves *adjusting GDP and productivity measures for unmeasured environmental protection output.* This involves an adjustment for an environmental "good" rather than an environmental "bad". For example, EU data shows that, in 2020, expenditure on environmental protection and resource management activities accounted for 2.5 per cent of total EU gross value added (Eurostat, 2022). However, much of such expenditure is currently considered as intermediate consumption and thus not included in GDP (UN, 2014). A case can be made for its inclusion, however (Agarwala and Martin, 2022).

Agarwala and Martin (2022) argue that the available data may still underestimate total expenditure on environmental protection. They note that in the United Kingdom, available statistics underestimate the overall output of all firms in the economy on environmental protection activities, as they only cover the four industries most likely to engage in environmental protection (mining, manufacturing, energy and water supply). Moreover, the recorded output may also be underestimated, as much of firms' expenditure is own-account (and therefore not recorded in GDP) and non-market (as firms incur costs that are not included in output or prices). Estimating these expenditures and including them in GDP as an "environmental good" will tend to increase the level of GDP and thus change the rate of labour productivity growth.

Agarwala and Martin (2022) measure the time spent on "green tasks", using detailed occupation data and a list of occupation-specific tasks, including "green tasks" and apply this to measure total output of environmental protection activities in the United Kingdom. As a result of their approach, that included various adjustment to avoid double counting, they find that unmeasured environmental protection would add some 6-7 per cent to the level of UK GDP. Moreover, as a result of the adjustment, they also find that UK labour productivity grew slightly faster between 1997 and 2019 than with standard productivity measurements. Making such adjustments for a wider set of countries would be valuable in establishing a broader understanding of the likely size of such investments.

Natural Capital as a Capital Input

A third approach to adjusting standard productivity measures for the environment involves *including natural capital in the measure of capital stock* that is used for productivity analysis (Brandt *et al.* 2017; Cárdenas Rodríguez *et al.* 2023). Standard productivity measures typically include labour input and measures of (produced) fixed and intangible capital, but do not include natural capital, such as sub-soil assets and other productive capital, as well as non-agricultural land, forests and protected areas, even though the use and extraction of such assets may contribute to GDP. Including natural capital as an asset will have an impact on measured productivity growth and demonstrate the contribution of natural capital to GDP growth.[9]

Recently, Cárdenas Rodríguez *et al.* (2023) estimated the contribution of a range of natural capital assets to GDP growth over the period 1996-2018 and found sizeable positive effects for Saudi Arabia, Russia, Australia, Chile, China and Brazil. However, even in these countries, natural capital accounted for less than 10 per cent of output growth. Denmark, Mexico, Norway and the United Kingdom were among the countries with a negative contribution of natural capital to output growth, implying that they relied less on the extraction of natural capital (e.g. oil in the case of Norway) than before (Cárdenas Rodríguez *et al.* 2023).

The work by Brandt *et al.* (2017) and Cárdenas Rodríguez *et al.* (2023) focuses on a subset of natural capital assets and

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[9] Including natural resources – or natural capital – also helps in explaining productivity differences across countries. Freeman et al. (2021) show that including natural resources in cross-country productivity comparisons explains most of the productivity advantage of resource-intensive countries such as Qatar and Saudi Arabia.

[10] A variant of this approach, better suited to cross-country comparisons, involves the use of producer reservation prices, where natural resources are valued by world-market resource prices (Freeman *et al.* 2022).

uses *private user costs* to value natural capital, as is the standard approach for productivity measurement (OECD, 2001).[10] To inform analysis of the link between climate change and productivity, this has some limitations. First, this measure of natural capital excludes several key assets, such as soil and freshwater resources, oceans, and biodiversity. that provide important ecosystem services. Second, measuring the services of these assets by private costs will not necessarily reflect their social costs, which are likely to be much higher than the private costs, e.g. due to the impacts of resource extraction and the use of natural capital on biodiversity and the environmental ecosystem. The use of private user costs does not provide a measure of welfare and does not address the negative environmental externalities linked to the extraction of natural capital.

Going beyond such measures is challenging, however. A first challenge is to expand the range of natural capital assets beyond sub-soil assets for which market prices are available, and include assets such as land, but also aquatic and freshwater resources. Some of these are treated as non-produced assets in the national accounts, with no investment going into their creation (Martin and Riley, 2023). The measurement of these assets raises several problems, which is why little progress has been made in incorporating them into productivity analysis. A second challenge is their valuation, which should reflect the net present value of future benefits flowing to the natural capital over its lifetime (Martin and Riley, 2023). A question here is whether those benefits should include environmental and social benefits of natural capital, and how these can be valued. Few studies are available at this stage that apply this broader approach to natural capital to productivity measurement.

An empirical application that starts to go into this direction is the work by Managi and Kumar (2018) and Kurniawan and Managi (2019), who measured what they called "inclusive wealth" over the period 1990 to 2014 for 140 countries. These studies defined inclusive wealth as the combination of human, produced and natural capital, with accounting prices measuring the social value of goods and services rather than private user costs. Drawing on this work on inclusive wealth, Managi and Kumar (2018) and Dasgupta *et al.* (2022) show that globally, the per capita stock of produced capital doubled between 1990 and 2014, whereas the per capita stock of human capital increased by some 13 per cent and the value of the per capital stock of natural capital declined by 40 per cent.

Sato *et al.* (2018) estimated TFP growth for 43 countries, both based on the concept of inclusive wealth (and thus including natural capital) and unadjusted for natural capital, as a way of assessing the sustainability of growth in different countries. The study found significant differences in the respective TFP growth rates for certain countries, with some – such as Australia, Canada, China, Japan, Mexico, the United Kingdom and the United States having significantly higher TFP growth when adjusted for natural capital. On the other hand, several other countries had significantly lower – and often negative – TFP growth rates when adjusted for natural capital, including Bolivia, India, Kenya, Senegal and Turkey.. This suggests that natural capital grew faster than other capital inputs in these countries, potentially reflecting high rates of depletion. Jumbri and Managi (2019) used a similar approach, covering 140 countries and find similar results, with significant differences between TFP measures based on inclusive wealth – i.e. including natural capital – and those not based on that concept.

These studies, and others like it, demonstrate the relevance of measures of natural capital to work on productivity. Drawing on natural capital in the process of economic development is not necessarily a problem, as long as the natural capital is converted into other capital, i.e. fixed, intangible or human capital. Van Krevel (2021) finds that many countries were able to turn their depleted natural capital into produced (i.e. fixed or intangible) and human capital, thus supporting economic development.

Such studies cannot assess whether the rate of resource depletion is ecologically sustainable, however, and whether the deprecation of natural capital may promote economic wealth at the cost of ecological health (Van Krevel, 2021). Scenario studies suggest that development paths that combine income growth with a much-reduced reliance on natural resources provide the most sustainable way towards increasing inclusive wealth and also to mitigating and adapting to climate change (Kurniawan and Managi, 2021).

While the potential productivity measures discussed in this section provide important extensions beyond the standard measures discussed in the previous section, there is a question whether they go far enough, and whether GDP – even when adjusted for environmental externalities - is sufficient to capture the range of economic and social impacts of climate change, including impacts on well-being. As noted by Stern and Stiglitz (2023), GDP is not a good measure of well-being, in particular in the context of climate change. They note that what is relevant is not growth in GDP, but growth in a multidimensional measure of well-being, e.g. as suggested by Stiglitz *et al.* (2009). As this article is mainly focused on productivity, it will not explore the link between climate change and well-being any further.

Addressing Climate Change While Supporting Productivity and Well-being

The Impacts of Climate Change Policies on Productivity

The article has thus far mainly explored the direct impacts of climate change on productivity. A second set of impacts linked to climate change are indirect as they result from the policies and actions aimed at reducing the direct impacts of climate change. These actions will have their own – positive and negative – impacts on productivity and economic performance. However, these impacts should be considered in the context of the large social and economic costs that would occur if action were not taken and climate change would be allowed to run its course without restraint (Stern and Stiglitz, 2023).

Several impacts of climate-related policies on productivity can be distinguished (e.g. Kozluk and Zipperer, 2015; Stern and

Stiglitz, 2023), notably:

- *Impacts on productivity and factor inputs linked to the costs of regulation and environmental policies aimed at addressing climate change.* Many studies of environmental policy suggest that policies and regulations to improve the environment (and address climate change) are a cost and burden to firms, distorting markets and diverting resources from more productive uses, thus reducing productivity.
- *Impacts on productivity linked to policy-induced innovation and technological change.* The so-called "Porter Hypothesis" argues that well-designed environmental policies and regulations will encourage firms to innovate, which could help increase productivity (Porter, 1991). The hypothesis involves several variants (Kozluk and Zipperer, 2015), with the "weak" one suggesting that more environmental regulation will encourage more environmental innovation; the "strong" one suggesting that environmental policies can improve firm's overall competitiveness; and a "narrow" one suggesting that only certain types of environmental regulation will increase innovation and firm performance.
- *Impacts on productivity linked to policy-induced shifts in trade and competitiveness.* When countries take unilateral climate policy action in a globalized economy, firms might move their activities to countries with fewer environmental restrictions, leading to "pollution havens". Such relocation could have impacts on productivity in the countries affected (Aldy and Pizer, 2015). Trade policy actions to limit the reallocation of production, e.g. by taxing imports of carbon-intensive products, might also influence productivity and competitiveness. On the other hand, in line with the Porter hypothesis, countries addressing environmental challenges earlier might benefit from first-mover advantages that could allow them to benefit from markets for low-carbon products abroad.
- *Impacts on productivity linked to policy-induced structural change and reallocation.* Policies to address climate change are likely to have impacts within and across sectors of the economy, with some firms and sectors gaining from growing demand for low-carbon products and technologies, and others faced with declining demand. Moreover, firms successfully engaged in low-carbon innovation may gain market share over firms that are not able to adjust to changing conditions. This will lead to reallocation across the economy, both within and across firms and sectors, with uncertain impacts on aggregate productivity.
- *Impacts on productivity linked to policy-induced shifts in demand.* Policies for net zero may also have impacts on aggregate demand, e.g. linked to changing consumption patterns and new social norms (Stern and Stiglitz, 2023). These could lead to new opportunities and markets and also affect productivity, e.g. through new areas of innovation to meet emerging demand, and through changes in the localization of production or shifts between and within industries (e.g. from individual to public transport).

The measures of productivity shown in Table 1 will be affected in different ways by the direct impacts and indirect impacts of climate change. The aggregate effect of these various impacts is uncertain, although studies have explored some of its dimensions at different levels of analysis (i.e.

firm, industry or economy-wide). The various impacts are related and will interact, and empirical studies will not always be able to distinguish them very clearly, if at all.

Some of the likely impacts of policy action, such as costs linked to taxation and regulation, are widely expected to be negative, whereas others, such as impacts linked to innovation and technological change, may well be positive. Stern and Stiglitz (2023) point to several factors that may help strengthen productivity in response to climate policies, including improved resource efficiency; increasing returns to scale; stronger "system" productivity, e.g. in energy and transport systems as well as in cities; a faster move to the knowledge frontier due to increased social priorities; higher global investment; as well as increased global cooperation and coordination.

Stern and Stiglitz (2023) also note that, in underestimating the costs of climate change, as discussed before, and overestimating the costs of policy action, mainstream studies suggest that policy action will necessarily require a "sacrifice in growth". To the extent that such a sacrifice exists, it appears to be relatively modest. For example, estimates of the costs of the transition for the United Kingdom by the Climate Change Committee have fallen over time, as the result of rapid technological progress and economies of scale in the production and diffusion of low-carbon technologies (Stern, 2022). A recent IEA report finds that clean, energy-efficient technologies are now often the most affordable, in particular in terms of lifetime cost (IEA, 2024). Arkolakis and Walsh (2024) find that moving to clean power in the United States would reduce power prices, enable an aggregate wage gain of 2-3 per cent and free up resources that could support productivity growth.

Assessing the current and future sources of productivity growth in the context of net zero policies can also provide some insights in the links between climate change and productivity. Recent measures of productivity do not yet demonstrate a transition to more sustainable growth. MFP growth – the combined efficiency of factors inputs – has been falling at the global level (Van Ark *et al.* 2023). More sustainable growth could include increased MFP growth, i.e. more output with the same inputs or the same output with less input. Moreover, global growth has relied heavily on investment in fixed (tangible) capital – buildings, structures, machinery and equipment – all of which are dependent on scarce natural resources, and not as much on intangible capital, such as R&D, data and software. Investment in intangibles – that rely mainly on knowledge and human ingenuity – has grown in many countries over the past decades, however (Van Ark *et al.* 2024). As there is no real limit to new knowledge, a shift to intangibles could be a step towards more sustainable growth. On the other hand, materials use in global production continues to rise , as do the environmental impacts associated with that use, although materials productivity is also rising. Growth today thus continues to rely heavily on tangible resources and is not yet becoming "weightless" (Quah, 1999).

Recent analysis for France suggests several potential changes in these sources of growth in the context of net zero policies.

First, the economy's capital-output ratio will likely increase due to net zero policies, linked to the higher (fixed) capital intensity of many low-carbon technologies relative to existing fossil fuel technologies (Pisani-Ferry and Mahfouz, 2023). Second, the pace and direction of technological progress will be affected, with a greater focus on low-carbon innovation. While such technological progress deviates from that driven by the market, it could be highly productive and cost-reducing, as shown by rapid progress in many key areas, such as renewables, battery technologies, electric vehicles and heat pumps, for example. Third, some of the existing stock of capital – both fixed and intangible – would become obsolete as the structure of the economy shifts. The overall impact of these changes on productivity growth is unclear and depends, for example, on whether investments in low-carbon technologies are additional to other investments or replace them, and how productive investment in low-carbon technologies is relative to existing investments.

Modelling studies can provide some further insights. Recent OECD modelling finds a relatively small cost in terms of GDP – and productivity – of policies aimed at the net zero transition (Fouré *et al.* 2023). The study finds a decline from its baseline global GDP growth of 2.3 per cent between 2019 and 2030 to 2.0 per cent, and from 2.1 per cent between 2030 and 2050 to 1.9 per cent. It notes that these macroeconomic costs should be put in context, as they do not adjust for avoided climate damages, particularly the reduced risks of climate tipping points that could not be quantified, as well as co-benefits from emissions reductions, e.g. on health (Fouré *et al.* 2023).

Scenarios developed by the Network for Greening the Financial System, a group of 127 central banks and financial supervisors, provide an additional perspective (NGFS, 2023). They point to the – relatively modest – negative cost of policy action, but also shows that policy action would have positive effects on GDP relative to a baseline of no policy action by avoiding a range of acute and chronic damages linked to climate change.

The negative impacts of climate policies on aggregate growth and productivity may therefore be relatively modest, and there may be circumstances under which the impact might even be slightly positive, e.g. when firm or countries are able to seize the opportunities associated with rapid carbonization. Moreover, most of the studies discussed above do not adjust their estimates of impacts on GDP and productivity for environmental externalities or avoided damages.

However, most of the evidence on the costs related to climate policy suggests that there are winners and losers, as is typically the case with structural reform. In the case of climate policy, productivity in highly polluting industries is more likely to be affected negatively than that in other industries. Moreover, large firms may be better able to adjust to climate policy than small firms, given their greater access to finance, and the availability of complementary factors that can help adopt new technology, such as skills, management or organizational factors.

OECD (2021) finds that environmental policies mainly entail costs for high-pollution industries and low-productivity firms, including through the detrimental effects of policy changes on laggard firms. On the other hand, more stringent environmental policies may have positive effects in improving the productivity of frontrunner firms and industries. It also concludes that the negative effects seem transitory and that environmental policies may mainly trigger a reallocation from high to low-emission industries. The study does not account for the potential beneficial effects of policies on the environment and human health, however.

Concerns in policy circles about the potential costs of policy action may also have other reasons, however. Dechezleprêtre and Sato (2017) note that firms affected by regulation may have an incentive to overstate the potential impacts on competitiveness as a strategic tool to lobby against such policies, which could allow them to take unpopular decisions to offshore or cut down on production, rather than address the underlying competitiveness problems. Moreover, as is typically the case with structural reform, the negative impacts on productivity are highly concentrated, whereas the positive impacts are more diffuse.

All of this does not imply that the transition to net zero will not be challenging for many firms, and in particular for those in industries relying heavily on fossil-fuel technologies. However, the aggregate impacts of policy actions to drive the transition on productivity may be relatively small and could be minimized by complementary policy action to address the challenge of transition, e.g. as regards access to finance, technology, skills or know-how, as discussed in the next section of this article. Crucially, policy action will require global coordination, as a large part of the positive effects of policy action in terms of avoided acute and chronic damages will depend on the global effort to reduce greenhouse gas emissions.

Climate Change Policies

Policy action to address climate change is now being taken across the world with 130 countries accounting for over 90 per cent of global GDP now publicly committed to achieving net zero.[11] Progress in reducing emissions is being made in many countries, especially through greater use of renewable energy, notably solar and wind; the phasing out of fossil fuels, notably coal; and improvements in energy efficiency combined with growing electrification. Several studies have explored how the world can achieve net zero and limit global warming. For example, the IEA's net-zero scenario provides a detailed account of the technologies that are needed to help reduce carbon emissions and achieve the goal of net zero by 2050 (IEA, 2021; 2023a).

While the global goal of net zero can be achieved in different ways, economists are broadly in agreement on the best approaches to be used (e.g. Blanchard *et*

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[11] Many advanced countries aim for net zero by 2050. Some emerging and developing economies have later target dates. See: https://zerotracker.net for details

[12] This does not imply that there are not significant differences in view on approaches to the economics of climate change. See Stern *et al.* (2022) and Stern and Stiglitz (2023) for a discussion.

al. 2023; OECD, 2023).[12] This is because there is already considerable experience across the world in implementing climate policies and strategies, which implies that several of the key policy tools for climate action are well understood, with a significant relationship between stronger climate policy action and greater emissions reductions (Nachtigall *et al.* 2024; Stechemesser *et al.* 2024).

A first element of climate strategies are policies to level or rebalance the playing field for low-carbon products and technologies relative to incumbent, fossil-fuel based ones, by "getting prices right". Such policies seek to adjust for the negative impacts of carbon emissions on the economy by adjusting prices for the negative environmental externalities related to carbon emissions, for example, through carbon taxes, tradeable permits such as Europe's Emission Trading System and the removal of fossil fuel subsidies. Empirical evidence suggests that such policies have a strong impact on carbon emissions (Stechemesser *et al.* 2024). However, while some economists have argued that carbon pricing and the removal of fossil fuels subsidies are enough to address climate change, they are clearly insufficient on their own. There are many other market failures and barriers that affect emissions, thus requiring a broader perspective and a much wider range of policies (Stern, 2022; Sterner *et al.* 2023: Grubb *et al.* 2023).

A second element of climate policy, also strongly supported in empirical studies (Stechemesser *et al.* 2024) are actions to *strengthen and shape markets for low-carbon products and technologies* through supportive regulation, technological standards or innovative public procurement. Implementing new products and technologies can be complicated by existing rules and regulations and lack of supportive technical standards. For example, inefficient planning and permitting procedures are currently slowing down investments in wind and solar energy in many countries. Supportive regulatory policies are also key in giving clear and strong market signals (Stern, 2022), e.g. for the phasing out of carbon-intensive technologies, e.g. internal combustion engine (ICE) vehicles, or in changing consumer behaviour. Technological standards that support low-carbon innovation, for example building codes, standards for heating systems and the like, are also important.

A third important element are policies that *foster low-carbon innovation.* These policies are important to reduce the costs of the climate transition and make carbon-free technologies competitive with their high-carbon alternatives (Cervantes *et al.* 2023). Acemoglu *et al.* (2016) have shown that the complementarity of carbon taxes and innovation policies allows for much lower carbon taxes, thus reducing the costs of policy action.

The economic literature points to several barriers and market failures that discourage low-carbon innovation, and therefore finds strong economic justifications for policies that seek to overcome these barriers.[13] Such policies may focus on im-

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[13] See Cervantes *et al.* (2023) for an overview and discussion.

proving the business environment for innovation, e.g. through competition or skills policies. They may also include more specific innovation policies such as investment in public R&D or tax incentives and grants to investment in business R&D. Detailed empirical analysis for 22 OECD countries shows that innovation policies such as R&D tax credits and direct support (e.g. grants) have a positive impact, with one extra unit of R&D support translating into 1.4 extra units of R&D (Appelt *et al.* 2023). These impacts are expected to be higher for low-carbon innovation as empirical studies have estimated that knowledge spillovers for low-carbon technologies are 60 per cent higher than for high-carbon technologies, given their relative novelty (Dechezleprêtre, Martin and Mohnen, 2014).

A fourth key element are policies that *mobilize investment and finance* for low-carbon activities and technologies. Establishing ambitious and stringent long-term climate policy frameworks is important to send a strong signal to investors and financial markets about the future of low-carbon assets (OECD, 2023). Policies to reduce investor risk, e.g. by risk insurance and guarantees, are important to, as are policies to reduce regulatory barriers to investment.

A fifth key element are policies that *support and facilitate the necessary structural change and resource allocation* and allow for a smooth and fair transition for displaced workers. This requires labour markets that facilitate the transition for workers and investment in new "green" skills, including advanced technical skills to help develop new technologies, but also skills to use and service new technologies, and use them across society. Investing in such skills will not only support innovation but will also help people make the transition in the labour market, helping them move from declining industries – such as fossil fuel-based ones – to emerging and growing industries such as renewable energy, recycling and environmental services.

Policies in support of structural change will also need to consider the distributional impacts of policy action, as there is a risk that the poorest households, communities and countries will be hit hardest without supporting policy action. Integrating these concerns in key policies, such as the design of carbon taxes, the removal of fossil-fuel subsidies, support programmes, or education and training, will be key to ensuring a transition that is perceived as fair. An important challenge in this context is that structural change will have to play out over a very short period compared to previous periods of deep structural change, and affect every individual, country, industry and firm.

A final, but crucial, element are policies that address the *global dimensions of climate change*, including supportive trade policies, international science and technology cooperation and policies that support investment in low-income economies and help them adjust to climate change. One challenging aspect are carbon border adjustment measures where jurisdictions apply import fees based on the carbon content of imported goods, reflecting the difference in carbon pricing between that jurisdiction and the exporting country (Clausing and Wolfram, 2023). Such measures are intended to address carbon leakage, i.e. emissions increasing in foreign jurisdictions because of stringent domestic climate policies.

Global action is also central to achieving positive impacts on GDP and well-being at the national level. While individual countries have good reasons to take actions at the national level and should see positive returns from that as regards innovation, adaptation and resilience, the greatest benefits from policy action occur when all countries reduce emissions, thus limiting damages and creating an environment that encourages innovation and structural change.

Productivity Policies and Climate Change

The question is how these climate change policies align with the policies that are generally considered to support productivity growth. As explored by Van Ark, de Vries and Pilat (2023), pro-productivity policies typically include actions to: a) support investment and factor accumulation; b) foster innovation and structural change; c) make markets work and encourage resource allocation; d) facilitate internationalisation; as well as e) foundational policies.

Addressing climate change in the context of pro-productivity policies does not necessarily change the policy tools that governments use to strengthen productivity growth but changes what tools are being applied and how they are being applied, and what complementary tools are being used to address climate change. For example, as discussed already, the overarching objective of addressing climate change and reaching net zero will require much greater emphasis on policies that improve the functioning of markets by getting "prices right" and adjusting for the negative externalities related to fossil fuels. It will also require much greater directionality of the innovation process to encourage low-carbon innovation (Cervantes *et al.* 2023), foster new firms and industries, promote investment in specific areas (e.g. renewable energy, infrastructure, clean transport) and support specific skills. Other elements that will require greater emphasis included the management and restoration of natural capital; ensuring the resilience of existing infrastructure; and access to capital, amongst others (Bowen *et al.* 2012). Sector-specific policies will also be required, e.g. to strengthen resilience in agriculture, and aimed at adaptation to climate change.

The policies required for the transition to net zero deviate in several ways from the standard framework for pro-productivity policies, as they are intended to guide the (global) economy towards a specific goal, i.e. net zero emissions. In principle, these deviations should lead to lower productivity growth than the default set of pro-productivity policies. However, it is not clear what such a default or counterfactual implies in practice, as it assumes no impact of climate change on GDP and productivity. The only credible scenarios are policies that address climate change, while supporting productivity and income growth to the best possible extent.

That does not mean there are no trade-offs between climate change policies and pro-productivity policies. However, good policy design can help reduce the potential negative impacts of climate change policies on productivity, e.g. by ensuring that such policies build on well-functioning markets and clear price signals; that competition and trade openness are maintained; by fostering international cooperation and coordination; and by making innovation policies a central component of the policy package, as such policies can help accelerate the transition, reduce the costs of policy action and support productivity (Cervantes *et al.* 2023).

In principle, economic policies should be designed to meet the target of net zero in the most efficient way, with the least possible costs. At the same time, the path for emissions reductions matters, as the economic and social impacts of climate change will increase with the time needed for the transition and the volume of greenhouse gases that is emitted before net zero is reached. This implies that economic efficiency is not the only – and perhaps not always the most important – criterion for policies to address climate change.

Main Findings and Conclusions

This article aimed to help clarify the ongoing debate about the impacts of climate change on productivity. A first finding is that the analysis of climate change requires a wider set of measures than standard productivity analysis, i.e. not just measures of labour and multi-factor productivity. On the one hand, it is important to distinguish between impacts of climate change on productivity measures that are closely associated with economic performance (e.g. labour and multi-factor productivity, either adjusted or not adjusted for environmental externalities). On the other hand, it is crucial to also explore productivity measures that are associated with the physical and natural processes linked to climate change (e.g. materials, energy and carbon emissions productivity, and the role of natural capital and the ecosystem as a whole). While much of the debate on productivity and climate change has focused on economic performance, improving productivity in the use of materials, resources and natural capital is central to achieving net zero and requires much greater emphasis in the debate on climate change and in the measurement and analysis of productivity.

This will require improvements in the current – incomplete and inadequate – state of productivity measurement, and its use in analysis and policy. While credible alternatives and complements to GDP and standard measures of productivity have been available for some time, including measures of environmentally adjusted productivity, as well as measures of natural capital, these have not yet been sufficiently developed and integrated to become the default for work in this area. Particularly important are the development of natural capital accounts (Agarwala *et al.* 2023) and their integration in the policy making process (Guerry *et al.* 2015); the use of environmentally-adjusted measures of productivity that incorporate shadow prices (Brandt *et al.* 2017; Cárdenas Rodríguez *et al.* 2018, 2023; Agarwala and Martin, 2022); greater attention for the full range of productivity measures, including materials, energy and carbon emissions productivity, rather than only measures of labour and multi-factor productivity; more KLEMS productivity studies that include energy and materials; and a greater focus on well-being, rather than just GDP (Van den Bergh, 2017). Some of these areas still require further methodological development. However, not integrating them in the policy debate on climate change risks biased and incomplete evidence for decision makers.

In examining the evidence on productivity growth, the article finds that mainstream economic studies over the past few decades have significantly underestimated the damaging impacts of climate change on GDP and productivity, due to a range of methodological limitations and deficiencies and by ignoring the growing risks of the climate passing tipping points.

The article also finds that while there has been substantial productivity growth in the use of certain natural resources in advanced economies, including energy, materials and carbon emissions, the current pace of decoupling of GDP from the use of these natural resources is much below of what is required to meet net zero climate goals. Productivity growth in countries that have already achieved high productivity levels in the use of natural resources will still need to double or treble compared to growth rates achieved over the past decades, whereas countries with lower productivity levels will need to achieve even higher growth rates in the future. Better understanding the drivers of such productivity growth could benefit from more productivity research focused on resources and materials.

Standard measures of productivity also do not yet demonstrate a transition to more sustainable growth. Multi-factor productivity growth – the combined efficiency of factors inputs – has been falling at the global level, and the transition to net zero will likely require large investments in fixed capital, and not just intangible and human capital. With global material use continuing to grow, growth and productivity are clearly not yet becoming "weightless" or green.

In examining the impacts of climate-related policies on productivity, the article finds that studies today may well overestimate the long-term costs of policy action to address climate change, in ignoring the dynamic effects of global policy action on innovation, economies of scale and learning-by-doing, including the rapidly falling costs of key green technologies, and in comparing outcomes with a wrong counterfactual. If there is no long-term trade-off between growth and climate, economic studies may have held back the case for economically and socially positive policy action to address climate change.

The main policy challenge is how to design climate change policies to meet the global objective of net zero – where it will be essential to meet this goal in the shortest possible timeframe to reduce the overall volume of greenhouse gas emissions – while also supporting productivity and well-being. To meet this challenge, governments will need to shape markets for low-carbon products and services, notably in adjusting for environmental externalities by carbon taxation, emissions trading and the removal of fossil fuel subsidies, and by regulation and standards. They will also need to give direction to technological change to accelerate low-carbon innovation and foster the uptake and diffusion of low-carbon technologies. Innovation policies are particularly important, as they can complement carbon taxation and help bring down the cost of policy action, and support productivity growth. Climate change policies will also need to facilitate the necessary structural change, and provide for a fair transition, both for social groups that may be most affected in the process, and for developing countries that will be most affected by climate change.

A final conclusion is that economists in general, and those working on productivity in particular, should engage much more with the debate on climate change and its links to economic growth, productivity and well-being. Such engagement will require much greater cooperation with other disciplines, including climate science. National productivity commissions and other analysts focusing on productivity growth may also want to broaden their monitoring, reporting and analysis to a wider set of productivity measures.

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