Climate Change and Productivity: Exploring the Links

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Abstract

- With climate change advancing, questions about its impacts on economy and society are becoming more urgent. While many studies have explored the economy-wide impacts of climate change on growth and productivity, there has been less focus on the impacts of climate change on a range of other productivity measures.
- This paper disentangles these impacts by providing a conceptual overview of the different measures of productivity that are relevant to climate change, complemented by data and evidence to illustrate these measures. It also explores whether addressing climate change is compatible with productivity and economic growth and how policies can best address climate change while also strengthening productivity growth.
- The paper finds that the discussion on climate change and productivity urgently needs broadening. While much of the debate on productivity and climate change has focused on the economic dimensions of productivity, notably labour productivity growth, improving productivity in the use of materials and natural capital is crucial to achieving net zero and requires much greater emphasis in measuring and analysing productivity.
- Inadequate measurement, in particular, needs to be addressed. While good alternatives to standard productivity measurement are available, these have not yet become mainstream in the analysis of climate change. Particularly important are the development of natural capital accounts and their integration in the policy making process; the use of environmentally-adjusted measures of productivity that incorporate shadow prices; extension of climate-related and productivity analysis to a wider range of productivity measures, such as materials productivity; and a focus on wellbeing, rather than GDP.
- The current rate of productivity growth with respect to materials use is much below what is required to achieving net zero. While 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. To limit the volume of emissions, the acceleration will need to be greater still.
- It is essential to distinguish between the impacts on productivity of climate change itself, and the impacts on productivity of policies to address climate change. Mainstream economic studies have 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 policy action to address climate change on growth and productivity, in underestimating the potential dynamic effects of global policy action on innovation and in comparing the impacts of policy action with an unrealistic counterfactual. The real challenge is how to design climate change policies to meet the global objective of net zero – where it is essential to meet this goal within the shortest possible timeframe – while also supporting productivity and wellbeing.

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1. Introduction

Climate change is already having impacts on economic performance, including on GDP, labour and multi-factor productivity (MFP), and will have even greater impacts in the future. But while many studies have explored the aggregate impacts of climate change on economic growth, there has been less focus on the nature and size of the various – current and future – impacts of climate change on other measures of productivity. Mainstream economic modelling studies have long suggested that the long-term impacts of climate change on growth and productivity would be relatively small (e.g., Tol, 2018; Nordhaus, 2019). However, 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; Pörtner, et al, 2023), including impacts linked to the risk of the climate passing so-called “tipping points” (OECD, 2022; Lenton et al., 2023).

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 limited warming to 1.5°C (Dietz et al., 2021). Other, more recent, studies find much smaller impacts of policy action, however, in particular in the long term (OECD, 2023a; NGFS, 2023). Measurement is a challenge, however (Dietz, et al, 2021) and some studies note that many mainstream modelling studies are based on a range of flawed assumptions and that studies pointing to the high cost of policy action don’t consider the appropriate counterfactual (Stern and Stiglitz, 2023). Moreover, 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).[1]

The discussion on climate change and productivity is further complicated as labour and multi-factor productivity – the standard tools for productivity analysis – aren’t 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. This includes 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 wellbeing and other measures that go beyond GDP.

This paper aims to disentangle some of the issues related to the impacts of climate change on productivity. It not only explores labour and multi-factor productivity, as the core indicators of productivity analysis, but also the productivity of materials and resources, energy, CO_2 emissions and natural capital, given their high relevance in the debate on climate change, as well as measures of productivity that adjust for environmental externalities.

Previous work by The Productivity Institute (TPI) already recognizes that climate change is leading to a deep transition in the global economy with wide-ranging impacts, including on productivity (e.g., Geels et al., 2021; Agarwala and Martin, 2022; Martin and Riley, 2023).

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[1] Stern and Romani (2023) set out a narrative for a new growth story for the 21st century, building on investment and innovation in green technologies and artificial intelligence. See also Zenghelis et al (2024) for the UK.

This paper complements the existing TPI and wider research on the low-carbon transition and productivity in a number of ways.

First, the paper provides a brief *conceptualisation* of the different measures of productivity that are relevant to climate change, notably labour productivity, capital productivity (including the productivity of natural capital), multi-factor productivity, materials (or resource) productivity, energy productivity, emissions productivity (e.g., CO2 emissions relative to GDP) and environmentally-adjusted productivity, based on an exploration of the available methodologies and literature on productivity measurement (section 2). This seeks to clarify and, where necessary, disentangle the discussion on climate change and productivity by a conceptual framing of the various relationships and the relevant indicators, including in distinguishing between the impacts of climate change itself, and the impacts of policies to address and mitigate climate change.

Second, the paper presents a range of *data and evidence* to illustrate the various indicators of productivity and their relevance to the debate on climate change (section 3). Where possible, it presents international comparisons of productivity on some of the key indicators to assess benchmarks and country gaps in performance, that might point to scope for future productivity growth. Presenting some of the available data is also intended to illustrate and clarify the interpretation of the various productivity measures set out in section 2 of the paper.

Third, the paper explores the *current and future evolution* of the different indicators of productivity, building on available empirical studies and scenarios for the transition to net zero (such as the IEA's net-zero scenario, see IEA, 2021a and 2023a) (section 4). This points to changes in productivity that are already occurring, that might be expected in the future (e.g., in aggregate labour productivity) or required (e.g., in emissions productivity) for the transition to net-zero. This section illustrates the challenge ahead for productivity-enhancing policies.

Fourth, the paper explores whether *addressing climate change is compatible with economic growth* (section 5), e.g., in the context of so-called "green growth" (e.g., OECD, 2011), or whether "degrowth" is the way forward (e.g. Hickel et al., 2022).

Fifth, the paper briefly explores how policies can best *address climate change while also strengthening productivity growth* (section 6). The key question in this section is how climate change policies can be designed to meet the global objective of net zero – where it will be essential to meet this goal within the shortest possible timeframe to reduce the cumulative volume of emissions – while also supporting productivity growth.

The final section (section 7) draws some conclusions.

2. Climate change and productivity: concepts and framing

To start exploring the links between climate change and productivity, this section provides some key concepts and seeks to frame the discussion. The next sub-section explores standard measures of productivity and how they may relate to climate change. Section 2.2 focuses on productivity measures that adjust for the environment and the role of natural capital, whereas section 2.3 looks at the potential impacts of climate change and related policies on productivity.

2.1. 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 conceptualising the relationship therefore lies in reviewing the main productivity measures that might potentially be affected by climate change (Table 1).

Table 1 draws on the OECD's Productivity Manual in showing the measures of labour, capital and multi-factor productivity that are commonly used for the analysis of productivity (OECD, 2001). It includes an additional column on measures of materials (or resource) productivity, as climate change is closely associated with materials and energy use, implying that relevant indicators of resource, materials and energy productivity will be important to consider. It also emphasises natural capital as a capital input requiring greater attention.

Table 1: Overview of key Productivity Measures relevant to Climate Change

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.*

The various measures in Table 1 all have their own relevance to the debate on climate change. Notably (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. These indicators show how productively labour is used to generate output or value added. 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, wages 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 productivity 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. As discussed in the next section, 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 and should also focus specifically on the productivity of natural 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).

Recent analysis suggests that intangible assets continue to provide an important contribution to capital deepening, in particular in European countries (Van Ark et al., 2022).

- *Multi-factor productivity (MFP) and climate change*. Indicators of multi-factor productivity relate a measure of output (gross output or value added) to a measure of the combined input of labour and capital and sometimes also to intermediate inputs (energy, materials and services). Measures of multi-factor productivity measure the overall change in the productivity of multiple factor inputs (labour, capital, intermediate inputs, etc.) linked to climate change. 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. Recent analysis for G20 countries shows that this transition to stronger MFP growth is not yet happening, with the bulk of recent GDP growth in G20 countries due to capital deepening, rather than MFP growth (Van Ark et al., 2023).
- *Materials productivity and climate change*. Measures of materials (or resource) productivity measure the efficiency of resource use, e.g., of energy or materials, but can also be related to CO_2 or total greenhouse gas (GHG) emissions. Addressing climate change will require large improvements in the efficiency of resource use, notably in the use of materials contributing to greenhouse gas emissions, i.e., fossil fuels, as well as certain materials contributing to such emissions linked to agriculture, industry and construction (OECD, 2015; 2019). Moreover, increasing materials productivity is important as growing materials use is accompanied by a range of negative side effects on the environment, including biodiversity (OECD, 2019). Measures of materials productivity may simply relate monetary measures of output or value added (e.g., GDP) to physical measures of materials or energy use. However, they can also be integrated in standard productivity measurement by putting a price on the physical measures of materials use and integrating them in a production function with capital, labour and intermediate inputs, as is the case with so-called KLEMS (Capital, Labour, Energy, Materials and Services) measures of productivity (Inklaar and Timmer, 2007).

Sections 3 and 4 of this paper will explore the available evidence on the evolution of some of these indicators and their relevance to the debate on climate change and will also explore their future evolution in the context of the global objective of net zero emissions by 2050.

2.2.Productivity measures adjusted for the environment

The measures set out in the previous section provide a first step in measuring the links between climate change and productivity. A second step involves adjusting the measures of output and factor inputs in Table 1 for environment 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 – which refers to 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) – in total capital input will help demonstrate its contribution to economic growth and productivity and can also help indicate how such capital is eroding as a result of resource extraction and exploitation.

Complementing the measures shown in Table 1 with others that, for example, incorporate environmental goods and bads in the analysis (Brandt et al., 2014; Cárdenas Rodríguez et al., 2016, 2018; Agarwala and Martin, 2022) is therefore important. Potentially, there are several such measures that could be developed as adjustments for environmental externalities can be made on both the output and input side. Not all potential measures are equally important or meaningful, however, and Table 2 shows some of the most prevalent measures in the literature.

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
4. Multifactor productivity measures adjusted for investment in a broader range of natural capital assets, measured at social costs	Output / Factor inputs (including a wider range of natural capital assets valued, measured at **social costs**)	The services of natural capital, valued at **social costs**, are **added** as a capital input

Source: Modified from Agarwala and Martin (2022).

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., 2014). As noted by Agarwala et al. (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. Several studies have already estimated the impact of adjustments for bad environmental outputs on GDP and productivity (Brandt et al., 2014; Cárdenas Rodríguez et al., 2016, 2018; Agarwala and Martin, 2022); these will be discussed in the next section of this paper.

A second potential measure (No. 2 in Table 2) involves *adjusting GDP and productivity measures for unmeasured environmental protection output*. This involves an adjustment for an environmental “good” rather than an environmental “bad”, i.e., a positive externality. Official statistics already provide some data on environmental protection, drawing on statistics on the Environmental Goods and Services Sector (EGSS) and the Environmental Protection

Expenditure Accounts (EPEA) (UN, 2014). For example, EU data shows that, in 2020, expenditure on environmental protection and resource management activities accounted for 2.5% of total EU gross value added (Eurostat, 2023). However, much of such expenditure is not included in GDP, following official national accounts' guidelines, but a case can be made for its inclusion (Agarwala and Martin, 2022), as discussed further in the next section.

A third approach (No. 3 in Table 2) 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., 2014; 2017; Cárdenas Rodríguez et al., 2016, 2018). Standard productivity measures typically include labour input and measures of (produced) fixed and intangible capital, but do not include natural capital, such as subsoil 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 will demonstrate the contribution of natural capital to aggregate economic growth. Available measures show that natural capital typically declines as a share of a nation's total wealth and capital as a country builds other forms of produced capital, notably human, fixed and intangible capital (Brandon et al., 2021).[2]

An alternative to the approach to measuring natural capital used by Brandt et al (2014) and Cárdenas Rodríguez et al. (2016, 2018) is Gross Ecosystem Product (GEP), an indicator that measures the value of services provided by the ecosystem (Ouyang et al., 2020). GEP measurement has thus far mainly been applied to the Chinese province of Qinghai. GEP incorporates material services (the contribution of nature to the provision of food, water supply, etc.), regulating services (the contribution of nature to carbon sequestration, flood regulation, soil retention, sandstorm prevention, etc.) and nonmaterial services (the contribution of nature to ecotourism, mental health, etc.). GEP – like GDP – uses accounting measures, i.e., private costs, rather than measures of economic welfare, however. Moreover, GEP measures flows, rather than stocks and is therefore not the same as measuring natural capital. Another relevant approach is recent work by the UK's Office of National Statistics on the measurement of "inclusive income", which includes the services associated with a wider set of natural (and human) assets than are included in the 2008 System of National Accounts (Taylor, 2022).

The work by Brandt, et al (2014) and Cárdenas Rodríguez et al. (2016, 2018) focuses on a relatively narrow range of natural capital assets (mainly subsoil assets) and uses *private user costs* to value natural capital, as is the standard approach for productivity measurement (OECD, 2001).[3] To inform analysis of the link between climate change and productivity, this has some important limitations. This is first because this measure of nature capital excludes several key assets, such as freshwaters, land, oceans, the atmosphere, etc. that provide important ecosystem services. Secondly, measuring the services of these assets by private costs will not necessarily reflect the *social costs* of using natural capital, 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 environmental systems. 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.

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

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

To address the limitations of the narrow coverage of natural capital and use of private user costs for valuing natural capital, a more elaborate approach (No. 4 in Table 2) would be to incorporate natural capital in productivity measurement with *a wider range of natural capital assets and – to the extent possible - valuing these at social costs*.[4]

A first challenge here is to expand the range of nature capital assets beyond sub-soil assets for which market prices are available, and include assets such as land, but also forests, aquatic and freshwater resources, etc. 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 to incorporate them in productivity analysis. A second challenge is their valuation, which should reflect the net present value of future benefits flowing 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 goes into this direction, however, 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. They 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.[5] By including natural capital in the concept of inclusive wealth and adjusting for the social value of natural capital, measures of "inclusive wealth" provide a broader perspective on the role of natural capital for growth and development.

For example, Kurniawan and Managi (2019) find that in countries that experienced a decline in natural capital from 1990 to 2014 (e.g., Denmark, the Netherlands and the United Kingdom), growth in multifactor productivity will tend to be overestimated with conventional measurement, whereas in countries that experience an improvement in natural capital (e.g., Singapore and South Africa), growth in multifactor productivity will be underestimated with conventional measurement. The Dasgupta review on biodiversity (Dasgupta, 2021) also recognised the concept of inclusive wealth and explicitly recognised the dependency of human existence and economic activity on nature.

Work on the measurement of natural capital is currently underway in many countries and is clearly important for productivity analysis. Section 3.3 of this paper will discuss the findings of work on natural capital, including work on inclusive wealth, further.

While the four potential productivity measures discussed in this section provide important extensions beyond the standard measures discussed in section 2.1, 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 wellbeing. As noted by Stern and Stiglitz (2023), GDP is not a good measure of wellbeing, 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 wellbeing, e.g., as set out by Stiglitz et al. (2009) and OECD (2020). As this paper is mainly focused on productivity, and

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[4] There are many other approaches to measuring natural capital, e.g., measures of footprint and biocapacity; planetary boundaries; material flows; carbon footprint, etc. These are not considered here as they are further removed from productivity concepts. See e.g., Brandon et al. (2021) for an overview of several such measures.

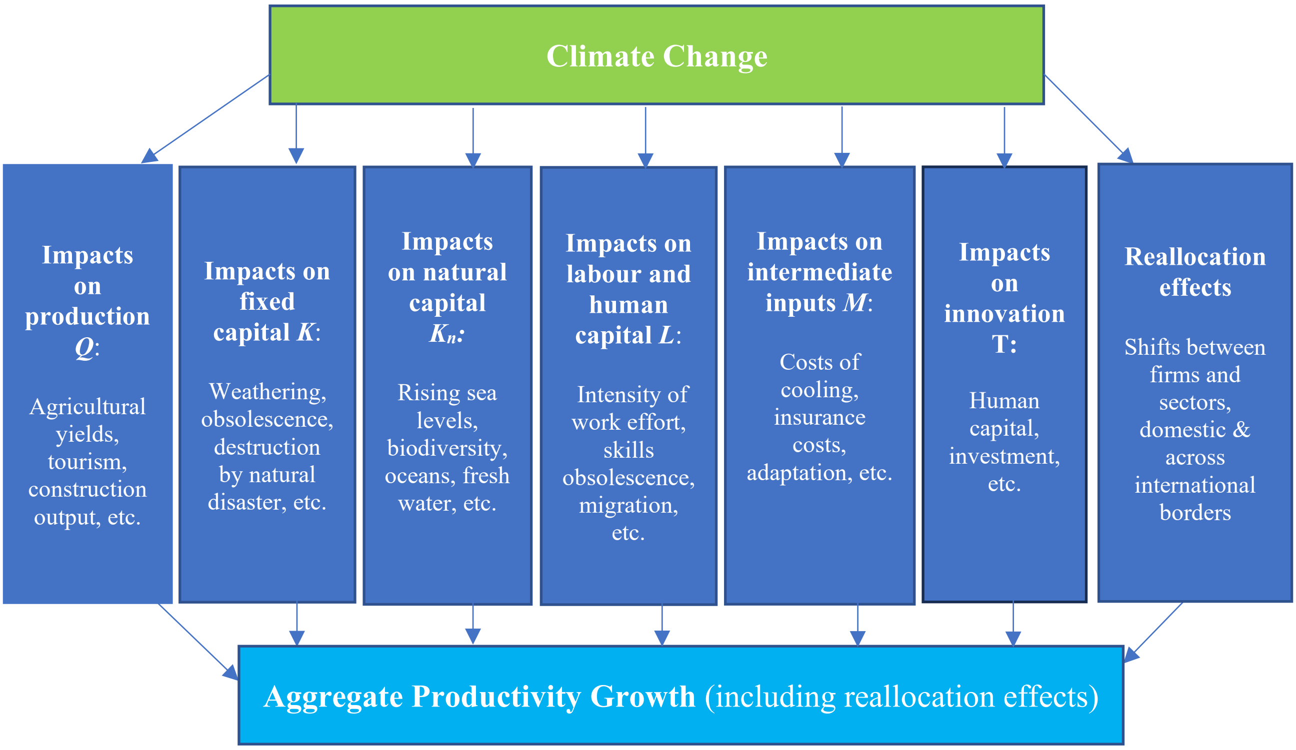
[5] This approach was echoed in the Dasgupta review on the economics of biodiversity (Dasgupta, 2021).

given space constraints, it will not explore these wellbeing aspects in detail. However, section 5 will briefly return to this issue.

2.3.The Impacts of Climate Change on Productivity

Apart from considering the potential impacts of climate change on various indicators of productivity from a conceptual point of view, it is also important to explore conceptually what kind of impacts on productivity are already occurring or can be expected in the future. Climate change and actions to mitigate or adapt to climate change can have a variety of impacts on productivity. These can be divided into two main areas.

Figure 1: Direct impacts of climate change on growth and productivity



Source: Author's illustration.

First, the *direct impacts of climate change on productivity*, through the impacts of the changing climate on the different components of a standard production function with output Q, capital K (including natural capital K_n), labour L and intermediate inputs M (Figure 1). For example, climate change is already having important impacts on agricultural yields that are expected to differ between different regions of the world (Pörtner et al., 2022). 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 as firms and governments would 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 so-called "tipping points" would be exceeded. The latter category of impacts has often been ignored in the economics literature but is now regarded as possibly the most important and most dangerous, significantly increasing the magnitude of previously estimated economic impacts (OECD, 2022). As shown in the work of IPCC Working Group II, some of these impacts are already highly certain, while others are still somewhat uncertain (Pörtner et al., 2023). What is clear is that they will all grow in magnitude with the extent of global warming, in particular if climate change would pass key "tipping points".[6] Recent research suggests that such tipping points might be passed sooner than previously expected (Willcock et al., 2023).[7]

These various impacts would affect productivity in specific firms and industries, and also 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.

A second set of impacts linked to climate change than can be distinguished are more *indirect as they result from the policies and actions aimed at reducing the direct impacts of climate change* and achieving the transition to net zero that 130 countries in the world have now committed to. 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).[8]

In principle, economic policies should be designed to meet the overarching target of net zero in the most efficient way, with the least possible costs to productivity and income. At the same time, there is growing evidence that 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. This implies that economic efficiency is not the only – and perhaps not the most important – criterion for policies to address climate challenge. A challenge for climate change policies is that the transition to be net zero will be deeply transformational, as it will have to play out over a very short period compared to previous periods of deep structural change, and as it will affect every individual, country, industry and firm.

Several impacts of climate-related policies on productivity can be distinguished (see, e.g., Kozluk and Zipperer, 2015; Stern and Stiglitz, 2023), notably (Figure 2):

- *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

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[6] 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 (see OECD, 2022).

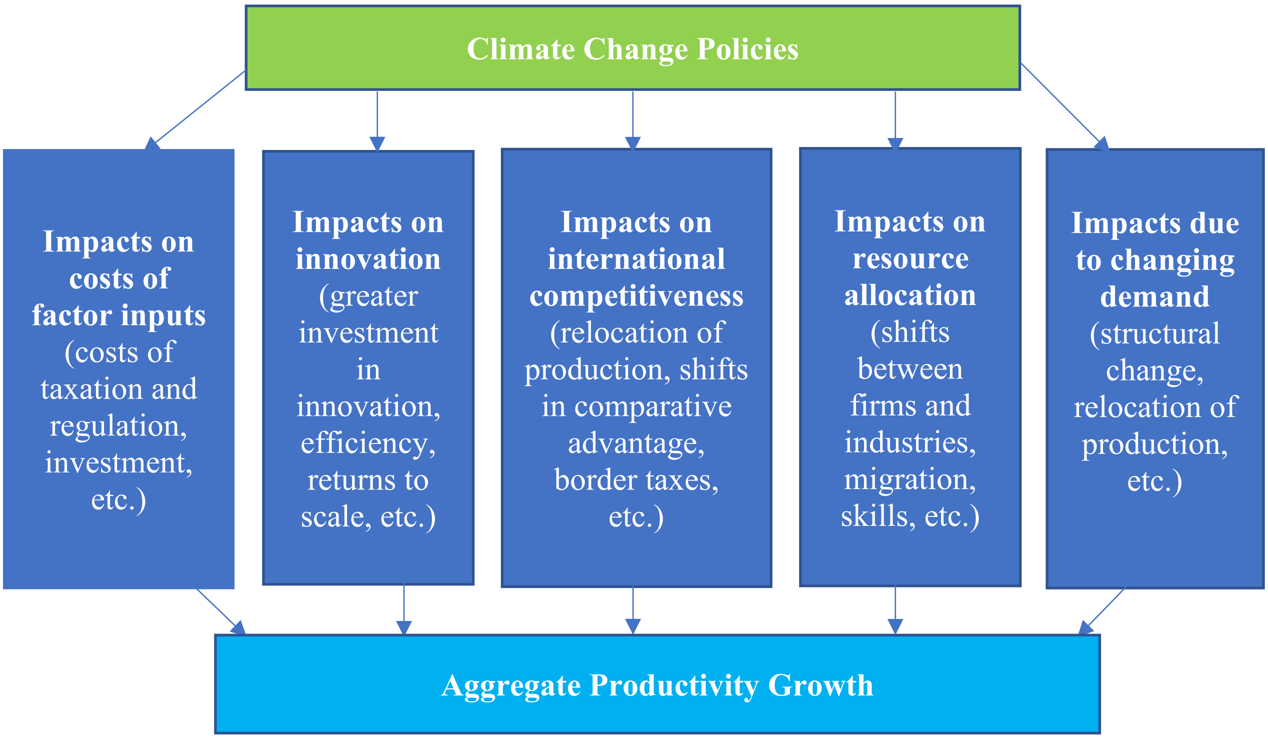
[7] Successive IPCC reports provide further detail on what the impacts of climate change might entail (IPCC, 2023).

[8] See Pörtner et al., 2023 for an overview of the observed and projected impacts of climate change according to Working Group II of the IPCC.

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*. Another perspective, building on 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 performance and competitiveness; and a "narrow" one suggesting that only certain types of environmental regulation will increase innovation and firm performance. Building on this argument, Stern and Stiglitz (2023) point to several factors that may help strengthen growth and 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.

Figure 2: Impacts of climate change policies on productivity



Source: Author's illustration.

- *Impacts on productivity linked to policy-induced shifts in trade and competitiveness*. In a globalised economy, and in case countries take unilateral policy action, 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; Carbone and Rivers, 2017). 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 engaging earlier with environmental challenges might benefit from first-mover advantages that could help firms move towards the technological frontier and allow them to benefit from emerging markets abroad for low-carbon products and technologies, with potentially beneficial effects on competitiveness and productivity.

- *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 for their products. 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. Such structural change will also have large impacts on workers and on the demand for skills in the economy, requiring policy support to facilitate reallocation and ensure a fair and just transition.
- *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; Winkelmann et al., 2022). 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 localisation of production or shifts between and within industries (e.g., from individual to public transport).

The measures of productivity shown in Table 1, including measures of materials productivity, will be affected in different ways by the direct impacts of climate change and the more indirect impacts linked to policies to address climate change. The aggregate effect of these various impacts is uncertain, although some studies have explored some of its dimensions at different levels of analysis (i.e., firm, industry or economy-wide). The next sections will return to this by presenting some of the available evidence and by exploring how productivity might be expected to change because of these different factors. The various impacts are related and will interact, however, and empirical studies will not always be able to distinguish them very clearly, if at all.

3. What do we know about the links – some evidence

To explore the links further, this section builds on the conceptual discussion in the previous section to explore some of the available evidence and indicators on the links between climate change and productivity. This evidence is quite extensive in some areas, but relatively limited in others. The next sub-section will focus on the direct economic impacts of climate change, notably on GDP, labour and multifactor productivity. Section 3.2 will focus on resource and materials productivity, while section 3.3 will look at evidence from environmentally-adjusted indicators of productivity, including the role of natural capital.

3.1.The Impacts of Climate Change on Growth and Productivity

A first area where a considerable amount of work is available concerns the direct impacts of climate change on GDP, productivity and per capita incomes. 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. 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.[9] 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 of studies on the impact of climate change and address a number of problems with previous studies, such as those summarised by Tol (2018), that they consider having created a significant downward bias in the literature. Their preferred estimate points to non-catastrophic damages of climate change on GDP of between 7 and 8% of GDP, and between 9 and 10% when factoring in catastrophic risks, considerably higher than the studies summarised by Tol (2018) and some three times higher than the average from previous studies.

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.

Aligishiev et al. (2022) provide a more recent overview of (some 40) studies on the macroeconomic 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% of global GDP in 2100 with global warming between 1.5° and 2.5°C, and a median loss of 3.3% of global GDP in 2100 with global warming between 2.9° and 4.3°C. The paper notes, 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, including the risk of passing certain tipping points, 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 summarised above have increasingly been criticised over the past decade in being founded on a range of flawed assumptions (Dietz and Stern, 2015; Stern et al., 2022). 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 have been ignored thus far and may lead to biased results.[10] Moreover, the IA models have also been criticised in ignoring the possibility of large-scale events due to climate change, or "tipping points", and in their inability to connect sufficiently to physical science

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[9] Modelling studies typically focus on impacts of GDP instead of productivity, but often include assumptions about an exogenous pace of technological progress, that is driving MFP growth, and about capital deepening. Moreover, with declining growth in labour input in many countries (Van Ark et al., 2023), GDP growth is a close approximation of labour productivity growth.

[10] Dietz et al. (2007), in reflecting on the 2007 Stern Review, already caution against a literal interpretation of estimates of the damages of climate change and note that the arguments for climate stabilization are built on broader foundations than cost-benefit analysis alone. Dietz and Stern (2008) argue that the economics literature "has failed to *simultaneously* assign the necessary importance to issues of *risk* and *ethics*." (ibid, page 94).

modelling of climate change (OECD, 2022).[11] 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 to economy and society.

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.[12] First, they note that many studies get the counterfactual wrong by underestimating the growing scale of damages resulting from climate change.[13] Second, they argue that GDP is not an appropriate measure to study the impacts of climate change, as it ignores certain important impacts, e.g., on health, and as GDP will go up by spending more on repairing the damages caused by climate change. Third, they note that most studies, as well as markets, are underestimating the risks of climate change, and do not account for the systemic nature of that risk. Fourth, they note that the standard argument overlooks many other market failures that reduce efficiency, and affect investment, innovation and growth. Fifth, 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 poor people and poor countries, instead emphasizing efficiency.

Economic analysis that incorporates the risk of one or more tipping points in their analysis of economic costs of climate change find significantly higher costs and impacts on GDP (Dietz et al. 2021), often with magnitudes that are 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 sufficiently covered in the literature.

Stern and Stiglitz (2023) note that, in underestimating the costs of climate change, 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. A recent OECD study presents a Net-Zero Ambition scenario that reaches net-zero emissions before 2060, with global average temperatures peaking just above 1.5°C in the second half of the century. It finds that this scenario would reduce global GDP

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[11] Economic modelling linked to climate change is increasingly also being criticized in other areas. For example, a recent report by the Institute and Faculty of Actuaries (Trust et al., 2023) finds that commonly used climate models in the financial services industry are underestimating risks, noting that carbon budgets may be smaller than anticipated and that risks may develop more quickly. They also note that regulatory scenarios introduce consistency but also the risk of group think, with scenario analysis being taken too literally and out of context.

[12] Keen (2021) also provides an extensive critique of economic modelling related to climate change.

[13] Newman and Noy (2023), for example, use data on extreme weather events and find that the socio-economic costs of such events are considerably higher than the frequently cited economic costs emerging from Integrated Assessment Models.

growth by 0.3% annually over the 2019-2050 period compared to a baseline scenario that would see a 13% increase in CO2 emissions by 2050 and global warming between 2.8 and 4.6°C in 2100 (OECD, 2023a). Section 4 of this paper will return to the impacts of policy action.[14]

Modelling is not the only way to estimate the impacts of climate change on growth and productivity. Several studies estimate the impacts of climate change using weather observations.[15] For example, Kahn et al. (2021) use a panel data set for 174 countries over the period 1960 to 2014 and find that per capita income is adversely affected by deviations of temperature and precipitation from their long-term historical norms, due to impacts of changing weather on agricultural yields, but also on long-term investment and productivity. They find that these effects vary significantly across countries depending on the pace of increases in temperature and variability in climate conditions. They estimate that a persistent increase by 0.04°C per year would reduce the world's real GDP by more than 7 per cent by 2100. Abiding by the Paris agreement, which would limit the increase to 0.01°C a year, would reduce this loss to about 1 percent. Burke et al. (2015) estimate long-term relationships between temperature and productivity and find that productivity is sharply declining at higher temperatures. They conclude that unmitigated global warming would reshape the global economy by reducing average global incomes by about 23% by 2100, while widening global income inequality. Kalkuhl and Wenz (2020) also explore the relationship between temperatures and productivity using data for more than 1500 regions in 77 countries. They find that an increase in the mean global surface temperature by about 3.5°C until the end of the 21st century would reduce global output by between 7 and 14 percent, with higher damages in tropical and poor regions. Kumar and Maiti (2023) estimate the impact of rising temperatures on TFP and find that this reduces labour and capital productivity and damages ecosystem services. They also find that such impacts are higher in extreme climatic zones and less developed economies.

As discussed already above, the potentially large macroeconomic impacts of climate change are accompanied by large variations across countries, regions, sectors, firms and social groups. For space reasons, this paper will not review the extensive sectoral literature on climate change, which includes work on such diverse sectors as agriculture (e.g., Malhi et al., 2021); fisheries (e.g., Cheung et al., 2023), tourism (e.g., Scott et al., 2019), construction (e.g., Gallego-Schmid, 2020) and housing markets (e.g., Cascarano and Natoli, 2023). For the same reason, it will also not explore the extensive discussion on country-specific and regional impacts.

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. Measures of GDP and productivity that would adjust for environmental externalities would be considerably lower than standard measures in the presence of ongoing emissions of greenhouse gases, whereas reducing these emissions, e.g. in the context of policy action, would lead to higher estimates. Stern and Stiglitz (2023) note that assuming that current growth rates can be sustained without stronger climate action is a misleading counterfactual.

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[14] Dietz et al. (2018) explore the costs and benefits of keeping climate change to 1.5°C and point to a range of uncertainties in measuring both costs and benefits.

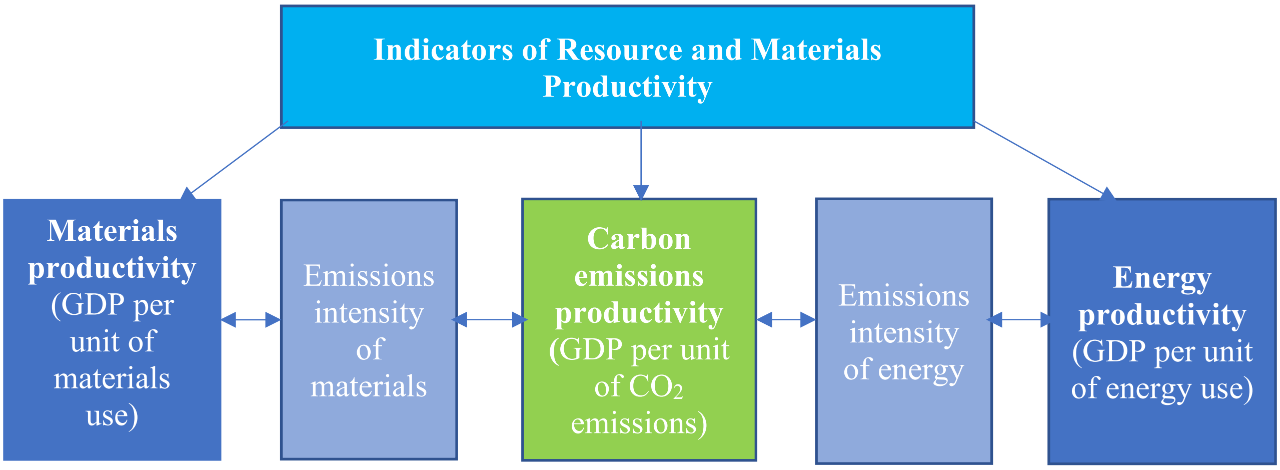
[15] Dell et al. (2014) and Kolstad and Moore (2020) review this literature and the different approaches to estimate these impacts econometrically. Heal and Park (2016) also review much of this literature.

3.2. Resource and Materials Productivity

The mainstream productivity literature generally does not devote much attention to resource and materials productivity, as they are not considered central to the analysis of economic and productivity performance at the firm, industry or economy-wide level. However, indicators of resource and materials productivity are extensively used in environmental policy and energy policy analysis and have a good foundation in methodology and data. They are also highly relevant to climate change and therefore need to be considered in a paper on climate change and productivity. This section explores some of the key indicators and evidence, including recent trends, where available.

Figure 3 illustrates that the three indicators explored in this section – materials productivity, CO_2 emissions productivity and energy productivity, are related to each other through simple relationships.[16] Changes in emissions productivity, i.e., GDP per unit of CO_2 emissions, reflect changes in materials productivity, i.e., GDP per unit of materials use, and in the emission intensity of materials use. Likewise, changes in emissions productivity reflect changes in energy productivity, i.e., GDP per unit of energy use, and changes in the emissions intensity of energy use. The following sections will return to these relationships.

Figure 3: Links between key indicators of resource and materials productivity



Source: Author's illustration.

Resources and Materials Productivity

Measures of resources or materials productivity relate gross output, GDP or value added to the total volume of resources or materials used to produce that output. For example, OECD measures of material resources cover the amount of biomass (mainly linked to agriculture and forestry), fossil fuels, metals and non-metallic minerals (with the bulk linked to material use by 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 of

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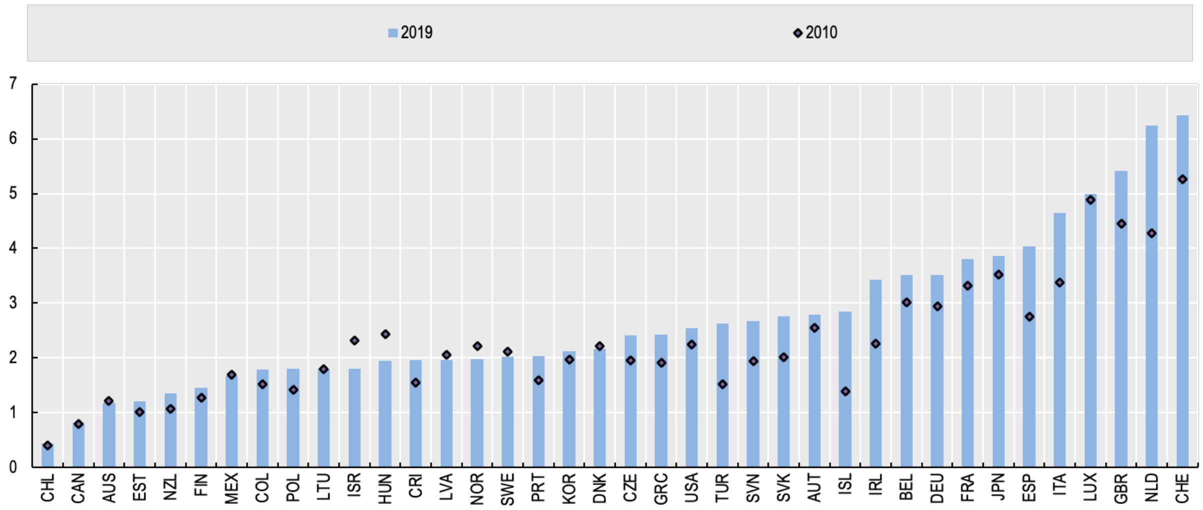
[16] CO_2 emissions are not a resource or material as such, but the result of materials and energy use in the production process. However, increasing emissions productivity is key to addressing climate change, which is why CO_2 emissions productivity is considered as a separate productivity indicator in this section.

materials used (in terms of domestic material consumption or DMC, typically expressed in tonnes) (OECD, 2017).[17]

Such measures of materials productivity (Figure 4) show that OECD countries – on average – generated some 2700 US$ of value added per tonne of materials in 2019, compared with less than US$ 2300 in 2010 (and only 1700 US$ in 2000, OECD, 2018), pointing to a 2.5% annual average growth of materials productivity between 2000 and 2019. At the same time, Figure 4 shows very large differences between OECD countries, with a range from less than 500 US$ of value added per tonne in Chile in 2019, to over 5000 US$ per tonne in Switzerland, the Netherlands and the United Kingdom. These differences mainly reflect structural factors, such as the relative importance of extractive sectors such as mining in different countries (e.g., in Australia, Canada and Chile); 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.

However, despite the large structural differences between countries, the cross-country differences also suggest there is likely scope for further productivity growth. Between 2010 and 2019, some countries (e.g., Iceland, the Netherlands, Spain and Turkey) significantly improved materials productivity. Others (e.g., Australia, Mexico, Israel, Hungary, Norway and Denmark), however, experienced negative productivity growth. Over the long term, materials productivity in OECD countries has increased considerably, and in 2015 OECD countries generated 50% more value added per unit of material resources than in 1990 (OECD, 2015).[18]

Figure 4: Materials Productivity in OECD countries, 2010 and 2019
(GDP per domestic material consumption, in US$ per kg, 2015 PPPs)



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

The OECD's indicators on materials productivity discussed thus far have been criticised in several studies. Giljum et al. (2014) note that improvements in materials productivity in the preceding three decades were much too slow to achieve an absolute reduction in materials use. Moreover, they note that indicators based on DMC do not include the indirect material flows

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[17] This indicator is complemented by data on the domestic extraction of materials used in the economy. The OECD has published indicators of materials productivity covering biomass, fossil fuels, metals, and non-metallic minerals (OECD, 2019), and indicators excluding fossil fuels (OECD, 2017). This paper includes materials use linked to fossil fuels, as the transition to net zero should have the largest impacts on resource use in this area.

[18] Figure 4 and several figures in this section show productivity levels for two or more years. These productivity levels don't fluctuate much from year to year and are mainly shown for illustration.

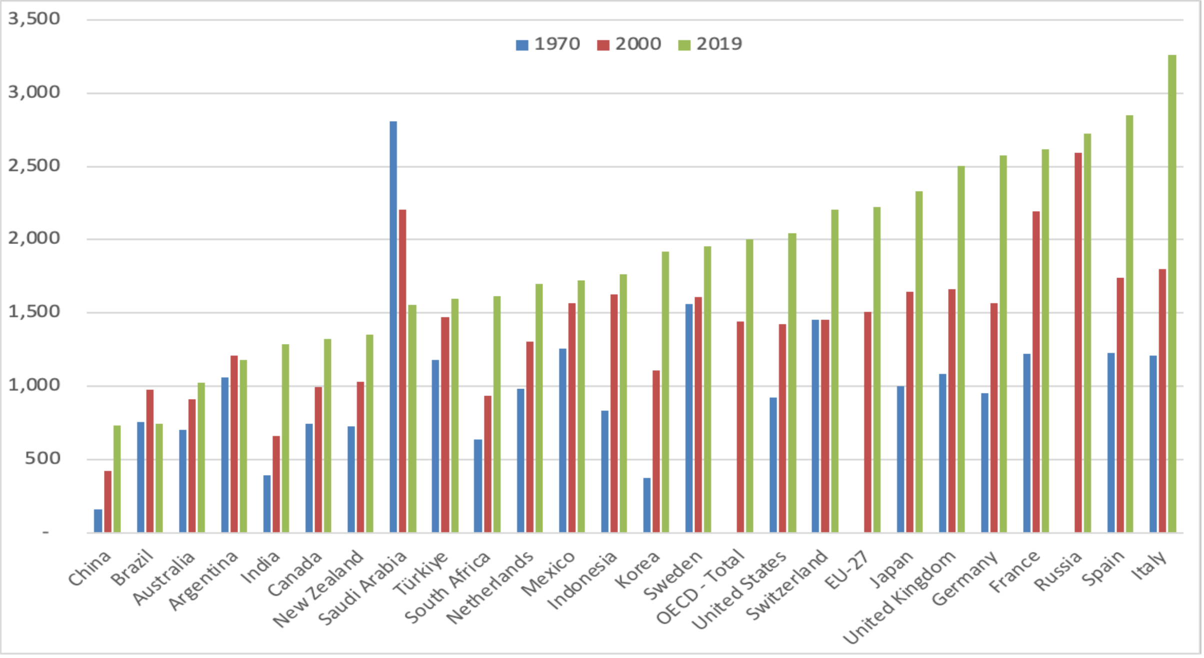
associated with internationally traded products. They also note that an absolute decoupling of materials use and GDP only occurred in countries with relatively low economic growth. Wiedmann et al. (2015) examine indicators of material footprint that extend domestic material consumption by including material flows associated with global production and consumption networks. They find that – in contrast with the evidence for OECD economies presented before – achievements in the decoupling of materials use from GDP in advanced economies are much smaller than reported or even non-existent.

Figure 5 therefore shows an alternative indicator of materials productivity, measured as GDP over a country's material footprint, for the period 1970-2019. It points to some improvement in materials productivity for most countries, but at a slower rate of growth than measured by DMC. For example, the OECD average annual growth rate of materials productivity with the materials footprint indicator is 1.7% from 2000 to 2019, compared to 2.5% for the DMC indicator. Moreover, the levels of productivity in 2019 measured by material footprint are considerably lower than measured by DMC. For example, the UK produced 2500 US$ of GDP in 2019 per tonne of material footprint, compared with 5419 US$ per tonne relative to DMC.

Another global study of materials and resource productivity for the period from 1970 to 2010 (Schandl et al., 2017) also paints a gloomier picture about global materials productivity. It 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. The study also 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.

Figure 5: Materials Productivity in selected OECD and G20 countries, 1970-2019

(GDP per material footprint, in US$ per tonne, 2015 PPPs)



Source: OECD.Stat, accessed 19 October 2023.

Steinberger and Krausmann (2011) have questioned the usefulness of indicators of materials and resource productivity for sustainability analysis, however, by demonstrating that different types of materials and energy consumption exhibit fundamentally different behaviours relative to incomes and economic activity. Biomass, as it is necessary for the most basic subsistence, has a very low-income elasticity (below 0.1), whereas the consumption of fossil fuels is almost proportional to incomes, with an elasticity above 0.8. Other materials, e.g., construction materials, have an income elasticity between these two extremes (between 0.49 and 0.7) in the estimates by Steinberger and Krausmann (2023). They therefore caution against cross-country comparisons of resource productivity, as the inclusion of inelastic biomass will appear to make low-income countries seem inefficient compared to high-income economies. They suggest alternative measures, e.g., by correcting productivity measures for income levels.

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 stylised 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 have a negative impact on resource productivity.

Indicators of materials productivity are highly relevant to climate change, as emissions linked to material use (notably fossil fuels, but also material use linked to agriculture, industrial processes and construction) account for about two-thirds of all GHG emissions (OECD, 2019). Addressing climate change and reducing these emissions is strongly linked to improved materials management, notably the phasing out of fossil fuels, as well as improved materials productivity in the use of some other materials. Materials management also includes actions linked to the reduction of waste, resource efficiency and recycling, where there are still large differences across countries. At the same time, the greater use of renewable sources of energy will require greater use of other materials, notably metals.[19] Section 4 of this paper will briefly explore the outlook for materials productivity and examine how it will need to improve to meet net zero goals and other environmental goals.

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 currently typically expressed in tonnes of oil equivalent (OECD, 2017). Energy use will have different impacts on climate change depending on the source 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 in production, consumer goods and services. Available indicators of energy productivity (Figure 6) show large differences across OECD and G20 countries, with large gaps between leading countries such as Ireland[20], Switzerland, Costa Rica, Denmark and the United Kingdom, and countries with low levels of energy productivity such as Korea, Finland, China, Canada, South Africa and Iceland.

The OECD's data suggest that global energy productivity rose by over 50% between 1990 and 2021 (i.e., an annual average growth rate of just over 1.3%), with particularly high productivity growth in several central European countries (e.g., Poland, the Baltic countries and the Czech Republic), as well as in China, Luxembourg and Ireland.[21] Brazil and Iceland experienced

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[19] Several 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. See IEA (2021b), Ritchie (2023) and Nijnens et al. (2023).

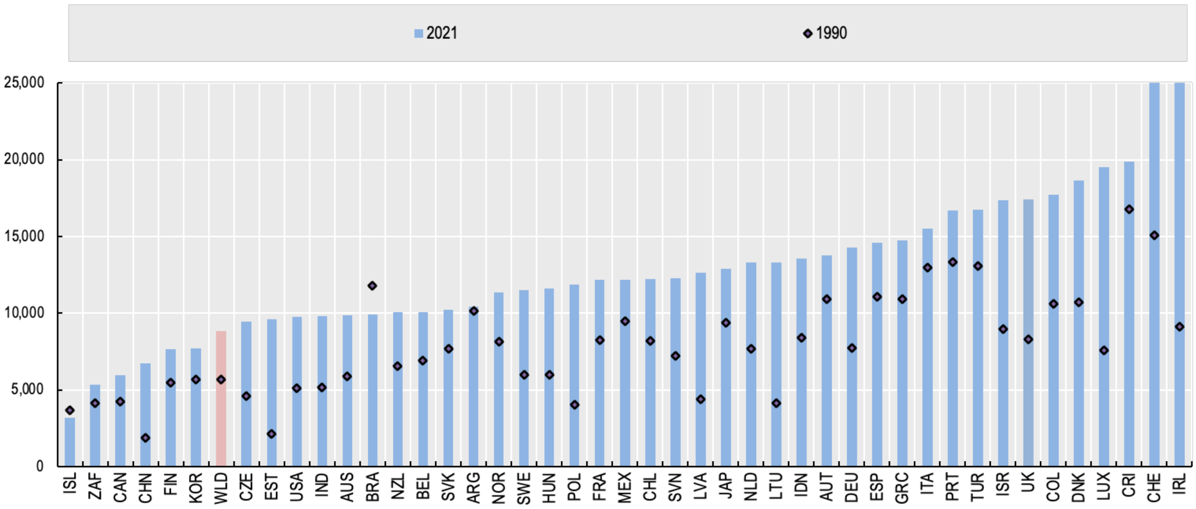
[20] Ireland's GDP figures are affected by the large role of multinational firms in the country, which tend to inflate GDP and will therefore also considerably inflate its level of energy productivity.

[21] Figure 6 shows data for two years in levels, with the 2021 level possibly affected downwards by the COVID crisis. However, most countries continued to have growth in energy productivity between 2019 and 2021.

negative growth in energy productivity over the period, however, and Argentina's energy productivity grew by only 3% over the three decades. The large cross-country differences in energy productivity and high growth rates in several countries suggest significant scope for further improvements in energy productivity, with potential benefits for climate change.

Figure 6: Energy productivity, 1990 and 2021

(US$ per tonne of oil equivalent)



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

Du and Lin (2017) estimate a more complex measure of total-factor productivity energy change for 123 economies worldwide. They find an increase of energy productivity globally of almost 35% between 1990 and 2010, mainly driven by technological progress, with higher productivity growth in the more developed economies and no evidence of convergence in energy productivity between developed and developing economies during the period. In a study for a more limited number of advanced economies, Apergis and Christou (2016) also find no evidence of full convergence and the presence of some convergence "clubs". They do, however, suggest that energy productivity 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.

As shown in Figure 3, energy productivity is linked to 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 energy productivity. Moreover, there is a possibility that abundant low-cost energy from renewable sources could increase future energy use and even reduce energy productivity through the so-called "rebound" effect, with improvements in energy efficiency leading to an increase in energy consumption in the medium to long term (Dimitropoulos, 2007). As discussed by Dimitropoulos (2007), there is no consensus on the size of this effect, due to a lack of a sound theoretical framework that can explain the complex interactions, and due to inconclusive evidence. The paper notes that the importance of a rebound effect, in particularly in the medium to long run, suggests that energy efficiency policies cannot substitute for policies that promote carbon-free energy. Sorell et al. (2009) find that, for household energy services in OECD countries, the direct rebound effect should generally be less than 30%. Moreover, they suggest that this effect would decline in the future as demand saturates and income increases. They also suggest that theoretical considerations and the available empirical evidence suggest that direct rebound effects would be smaller for other energy services. Overall, direct rebound effects should therefore only partially offset the energy savings from efficiency improvements.[22]

Given these considerations, 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 high levels of carbon emissions productivity, linked, amongst others, to its high use of renewable energy, notable geothermal energy. As is visible in Figure 6, countries with very low levels of energy productivity have not experienced faster productivity growth than those with high levels of energy productivity. However, as discussed in the next sub-section, improvements in energy productivity do account for much of the improvement in carbon emissions productivity, including in the UK (Agarwala and Martin, 2022).

Section 4 of this paper will explore the outlook for energy productivity and examine how it will need to improve to meet net zero goals.

Carbon Emissions Productivity

Although carbon emissions may not be considered a typical material or resource, like raw materials or energy, resource 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 or to the emissions to satisfy domestic demand, thus adjusting for emissions generated abroad to satisfy domestic consumption (OECD, 2017). Figure 7 shows two key indicators of carbon emissions productivity levels for OECD and G20 countries for the periods for which they are available from OECD sources, i.e., 1990-2021 for the production-based perspective, and 1995-2018 for the demand- (or consumption-) based perspective.

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 most countries over the past decades, except for Brazil, Indonesia and Saudi Arabia on both indicators, and Argentina on the demand-based indicator. Except for these countries, most countries have experienced a relative decoupling between GDP growth and emissions, with GDP growing faster than emissions. Some countries even experienced an absolute decoupling of GDP growth and emissions, with GDP growing and emissions falling (OECD, 2017; Figure 8). Analysis by the IEA attributes most of the decoupling to four factors, i.e. a) rapid growth in clean energy investment; b) growing electrification; c) improvements in energy efficiency; d) a transition away from coal (Singh, 2024).

Second, as with other indicators of resource and materials productivity, the graphs point to large cross-country differences in emissions productivity, linked to the carbon intensity of different economies and their respective use of fossil fuels. Several BRIICS economies, i.e., China, India, Russia and Saudi Arabia, have particularly low levels of carbon productivity, together with some OECD countries, notably Australia, Canada, Korea, Poland and the United States. Countries in Western Europe (Switzerland, Sweden, Ireland, Iceland and France) and

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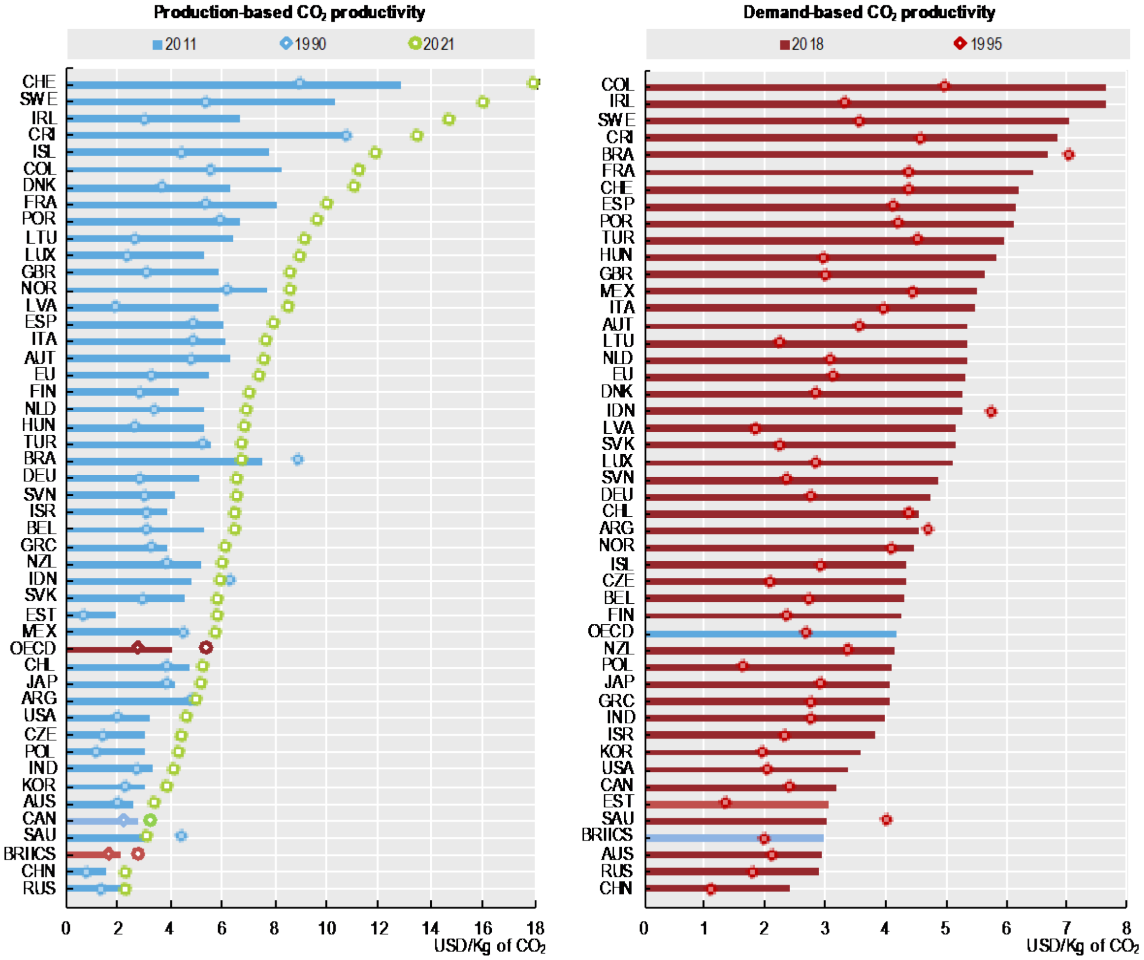
[22] Sorell et al. (2009) also note that there exists considerable scope to improve estimates of the direct rebound effects for different energy services and note the need for better data. See also Turner (2013) for a thoughtful discussion of the rebound effect and the need for greater clarity on the various mechanisms involved.

South America (Brazil, Colombia and Costa Rica) tend to have the highest levels of carbon productivity.

Figure 7: CO_2 Productivity: Production and Demand Perspectives (US$ per kg of CO_2)



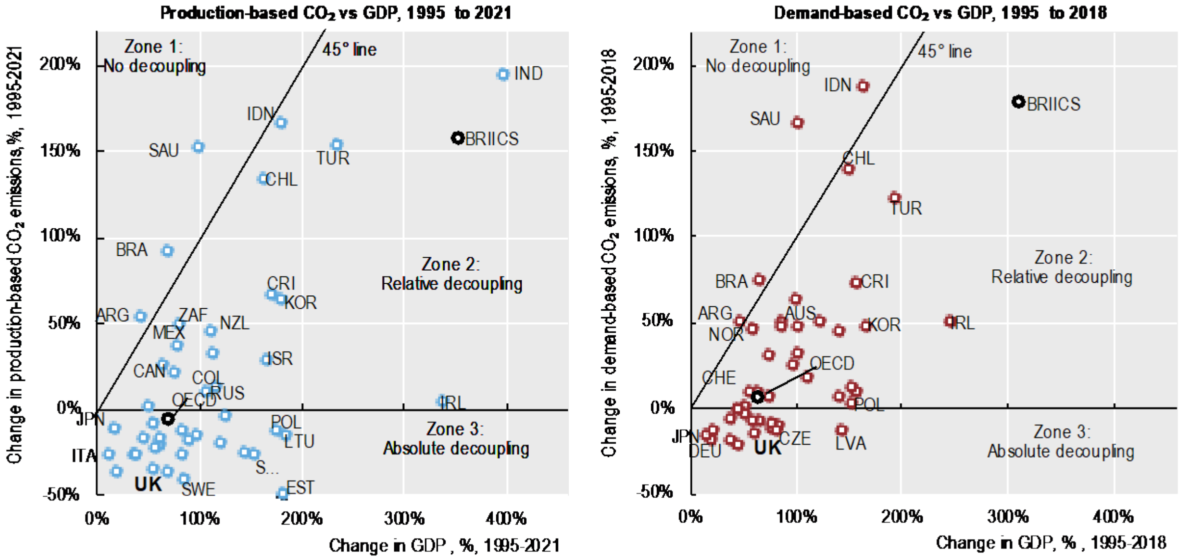
Source: OECD, Green Growth Database, accessed on 28 March 2023.

In principle, these large differences could point to scope for productivity growth, where countries with very low levels of emissions productivity might be expected to have scope for faster growth of productivity. However, for the period 2011-2021 there is no evidence that countries with the lowest productivity levels grew faster than those with high levels, Estonia being the only clear exception (Figure 7).

Third, there are considerable differences in ranking and productivity levels between the production- and consumption-based indicators of carbon productivity. The production-based indicators cover CO_2 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; Figure 8). Moreover, the rate of absolute decoupling was considerably lower on the demand-side than on the production side.

Figure 8: CO_2 Emissions and GDP growth

OECD and G20 countries



Note: The graphs exclude China for the production-based perspective, with 760% GDP growth between 1995 and 2021 and a 248% growth in CO_2 emissions; and China (637% GDP growth between 1995 and 2018 and 245% growth in CO_2 emissions) and India (374% GDP growth between 1995 and 2018, and 230% growth in CO_2 emissions) from the demand-based perspective.

Source: OECD, Green Growth Database (accessed 29 March 2023).

A more elaborate approach to the measurement of emissions productivity was taken by Agarwala and Martin (2022) in their work for the UK. They consider all greenhouse gas (GHG) emissions, not just CO2, expressed in tonnes of CO2 equivalent, relative to real GDP. They find that GHG emissions fell by over 40% between 1990 and 2019, while GDP grew nearly 75% over the same period. They note this implies an improvement in GHG emissions productivity by nearly 150% over the period, reflecting growth in energy productivity, and a greening of energy sources, as discussed further below.[23]

An extension of the analysis of emissions productivity is to examine the relationship between emissions productivity and energy productivity. Changes in emissions productivity are equivalent to changes in energy productivity plus changes in the carbon intensity of energy. Figure 9 shows the contribution of the annual average change in emissions intensity from 1990 to 2021 for different countries broken down in the contribution of the growth in energy productivity and the contribution of the declining carbon intensity of energy. Over this period, the bulk of the improvement in emissions productivity has resulted from improvements in energy productivity, i.e., more GDP being produced with a given amount of energy use. However, improvements in the CO2 emissions intensity of energy made large contributions in several countries and accounted for the bulk of the improvement in emissions productivity in Finland and Italy (Figure 9).

Figure 10 shows a similar breakdown for carbon emissions productivity with materials productivity and the carbon intensity of materials. It shows that materials productivity has been the main source of improvements in carbon productivity, although it declined in some countries, such as Brazil and Saudi Arabia. A decline in the carbon intensity of materials contributed to carbon productivity in most countries, although it made a negative contribution

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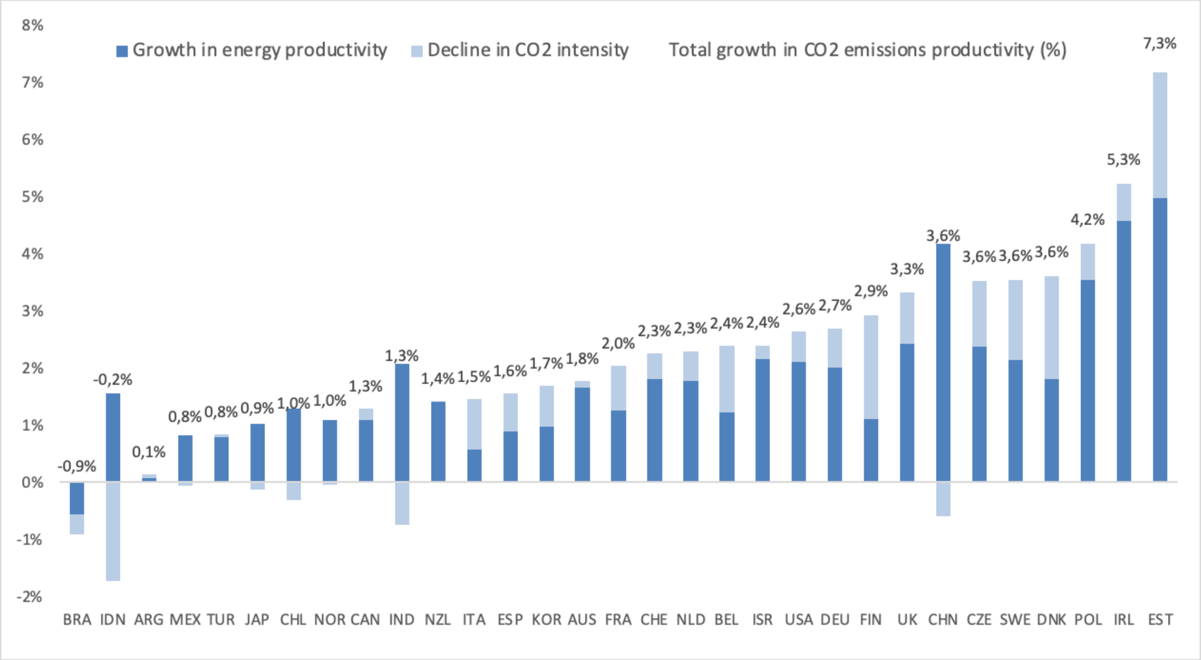
[23] Recent OECD work has extended the estimation of greenhouse gases by country and industry from CO_2 to all greenhouse gases, which will allow the work presented in this section to be extended to all emissions.

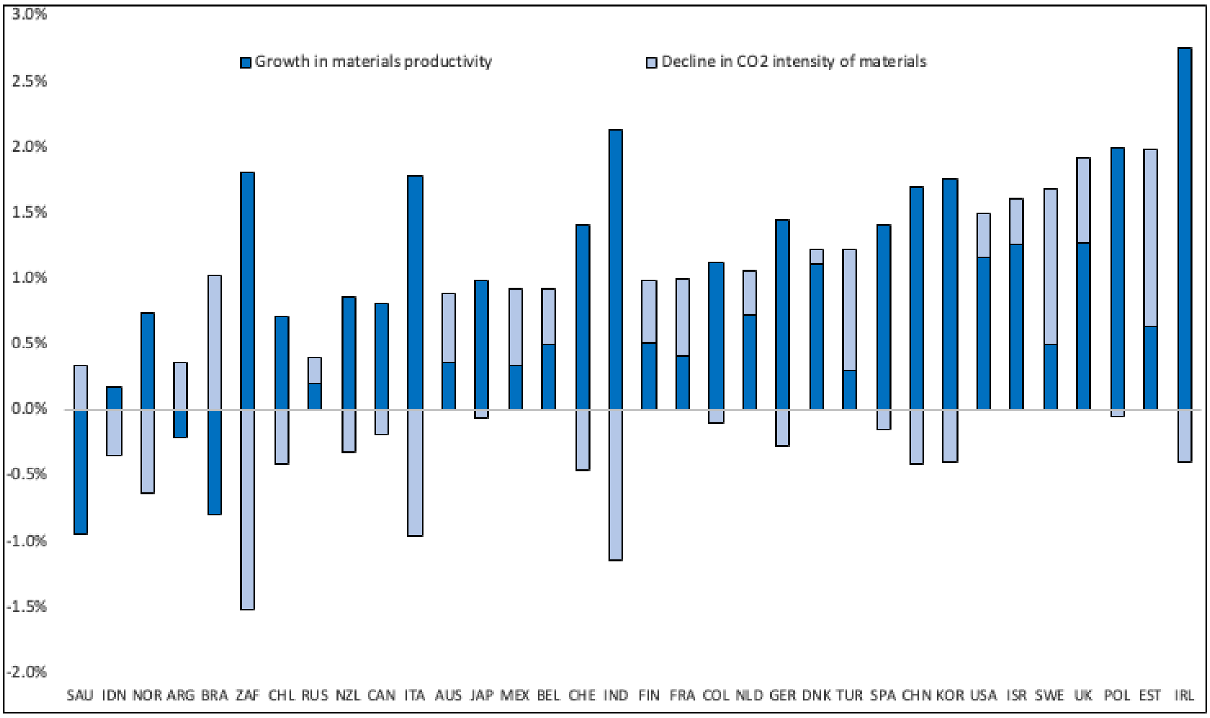
in some, including India, Italy, Norway and South Africa. Section 4 of this paper will explore the outlook for carbon emissions productivity and examine how it will need to improve to meet net zero goals.

Figure 9: Contribution of Changes in Energy Productivity and Carbon Intensity of Energy to Changes in CO2 Emissions Productivity
Annual averages, in percentage points, 1990-2021



Source: OECD, Green Growth Indicators Database (accessed 29 March 2023).

Figure 10: Contribution of Changes in Materials Productivity and Carbon Intensity of Materials to Changes in CO2 Emissions Productivity
Annual averages, in percentage points, 2000-2018



Source: OECD, Green Growth Indicators Database (accessed 27 November 2023).

Resource and Materials Productivity in a KLEMS framework

Measures of resource, materials and energy productivity can also be derived in a KLEMS accounting framework. 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.

One of the key findings of their paper is the large variation in the use of intermediate inputs (energy, materials and services) across countries (Inklaar and Timmer, 2007). The paper finds that European countries use much less energy in production than the United States, with Canadian production the most energy intensive. On the other hand, the United States (and Canada to a lesser extent) use far fewer materials in production than European countries.

Mulder and Groot (2012) use KLEMS data (i.e., the EU-KLEMS database, see: 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 found 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 sub-sectors. They also found that changes in the sectoral composition of economies explain a considerable and growing part of the changes in aggregate energy intensity.[24]

3.3. Environmentally Adjusted Productivity Measures

All the indicators presented in sections 3.1 and 3.2 are based on existing monetary or physical variables and do not include any adjustment for environment or climate-related externalities, either positive or negative, as discussed in section 2.2. This section therefore explores some key productivity measures that adjust for environmental externalities and inputs.[25]

Natural capital as a capital input

A first approach to adjusting for the environment involves taking account of the services provided by natural capital in productivity analysis (Brandt et al., 2014; Cárdenas Rodríguez et al., 2016, 2018). As noted in section 2.2, this involves including natural capital among the assets considered as providing capital services. If this adjustment only considers the private costs of natural capital, it will be positive when countries extract more value from domestic natural resources over time.

For example, Cárdenas Rodríguez et al. (2016, 2018) estimate the contribution of a selected range of natural capital assets – i.e. non-renewable subsoil assets – to GDP growth over the period 1991-2013 and finds sizeable positive effects for Russia, Saudi Arabia, Chile, Israel, China, Australia and Colombia (Figure 11). In the case of Russia, these assets accounted for

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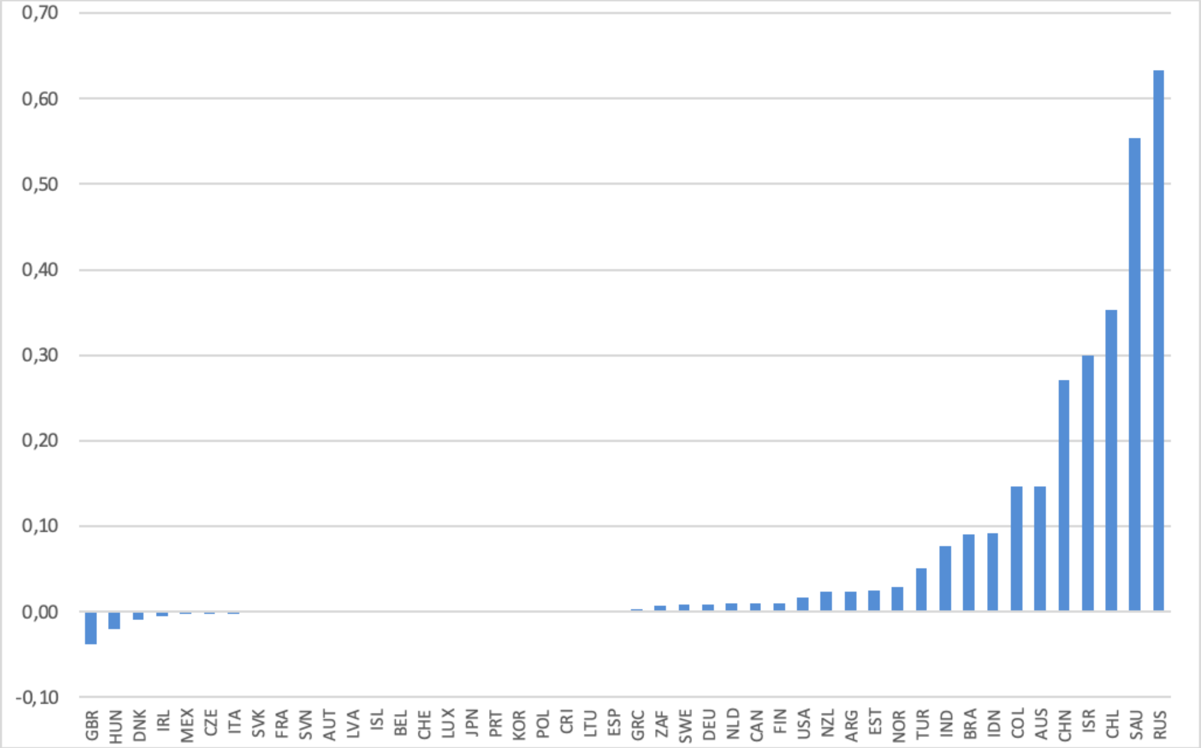
[24] Several other studies have used KLEMS or KLEMS-associated data, such as the World-Input Output Database to examine developments in energy productivity and energy intensity, e.g., Mulder (2015), Atalla and Bean (2017). Agarwala and Martin (2022) explored the impact of structural change on UK energy intensity from 1990-2019 and found it had little impact, possibly as much as the structural change of the UK economy – i.e. the decline of manufacturing – had happened before.

[25] See Lovell (2022) for an extensive overview of the measurement of productivity in the presence of environmental externalities.

almost 25% of total output growth, and in Saudi Arabia more than 15% of output growth was linked to increased extraction of sub-soil assets, notably oil. Hungary and the United Kingdom were the two countries with the largest negative contribution of natural capital to output growth, implying that they relied less on the extraction of subsoil assets (oil in the case of the UK) than before (Cárdenas Rodríguez et al., 2018).

Figure 11: Contribution of natural capital (subsoil assets) to GDP growth, OECD and G20 countries

Long-term average (circa 1991-2013), in percentage points



Source: OECD (2016), "Environmentally adjusted multifactor productivity", OECD Environment Statistics Database, based on Cárdenas Rodríguez et al. (2016).

As discussed in section 2.2., measuring only non-renewable natural assets and valuing natural capital only at private costs does not account for the environmental and social value of natural capital, including its role for biodiversity or the environmental system in general. Adjusting for a wider range of assets and adjusting for the social value of natural capital provides a different perspective on the role of natural capital in growth and development. Managi and Kumar (2018) and Kurniawan and Managi (2019) measured natural capital at social costs in their work on inclusive wealth over the period 1990 to 2014 for 140 countries, which included a focus on produced, human and natural capital as the key components of inclusive wealth.

Managi and Kumar (2018) and Dasgupta et al. (2022) show that globally, the stock of produced capital doubled between 1990 and 2014, whereas the stock of human capital increased by some 13% and the value of the stock of natural capital declined by 40%. Combined with a number of other adjustments, the studies find that global GDP per capita grew by about 80% over the period, but that global inclusive wealth per capita only increased by 10% over the period, with only 84 out of 140 countries experiencing an increase in inclusive wealth over the period.

Based on the same data, Kurniawan and Managi (2019) find that in countries that experienced a decline in natural capital inputs (e.g., Denmark, the Netherlands and the United Kingdom), growth in multifactor productivity will tend to be underestimated with conventional measures as aggregate factor input is overestimated. Conversely, in countries that experience an increase in natural capital inputs (e.g., Singapore, Canada and South Africa), growth in multifactor productivity will be overestimated with conventional measures.

Sato et al. (2018) used the concept of inclusive wealth to estimate TFP growth for 43 countries, both based on the concept of inclusive wealth 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 – notably Australia, Belgium, Canada, China, Japan, Mexico, Thailand, the UK and the USA having significantly higher TFP growth when adjusted for inclusive wealth. On the other hand, several other countries had significantly lower – and often negative – TFP growth rates when adjusted for inclusive wealth, including Benin, Bolivia, Botswana, Ghana, Honduras, India, Kenya, Morocco, Senegal and Turkey. 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 and those not based on that concept.

Measures of inclusive wealth have also been used to examine the relationship between environmental quality – proxied by natural capital – and economic growth. Kurniawan et al. (2021) find the relationship between natural capital and economic growth is not linear, consistent with an environmental "Kuznets curve" (Kuznets, 1955), that suggests that energy use and pollution per capita first rise with per capita income and then fall when economic development proceeds. Kurniawan et al. (2021) find that increasing GDP per capita initially leads to greater extraction of natural capital until a turning point is reached and natural capital is no longer degraded and may be restored. However, the study also finds evidence of a second turning point at higher levels of GDP per capita, with once greater extraction of natural capital, possibly linked to pressure from growing population density.

In a similar vein, Sugiawan and Managi (2019) explore the relationship between energy consumption and inclusive wealth, and also make projections of the growth of inclusive wealth for the next three decades. They find that a negative and significant impact of energy consumption on inclusive wealth, suggesting an unsustainable pattern of world energy consumption. The study suggests that increasing the efficiency of energy consumption will lead to higher growth of inclusive wealth per capita and also notes that a shift to renewable energy is a precondition for sustainable development.

These studies, and many others like it, demonstrate the importance and relevance of measures of natural capital in the context of work on productivity, even apart from its key role for studies on sustainability more general.[26] Section 4 of this paper will return to the relationship between natural capital and productivity and examine how this may evolve in meeting net zero goals.

Adjusting for bad outputs

A second approach to adjusting for the environment involves accounting for the economic damage caused by pollution, e.g., carbon emissions or other pollutants (Brandt et al., 2014; Cárdenas Rodríguez et al., 2016, 2018; Agarwala and Martin, 2022). This adjustment to GDP (and to labour productivity growth) will tend to be positive in countries where pollution has

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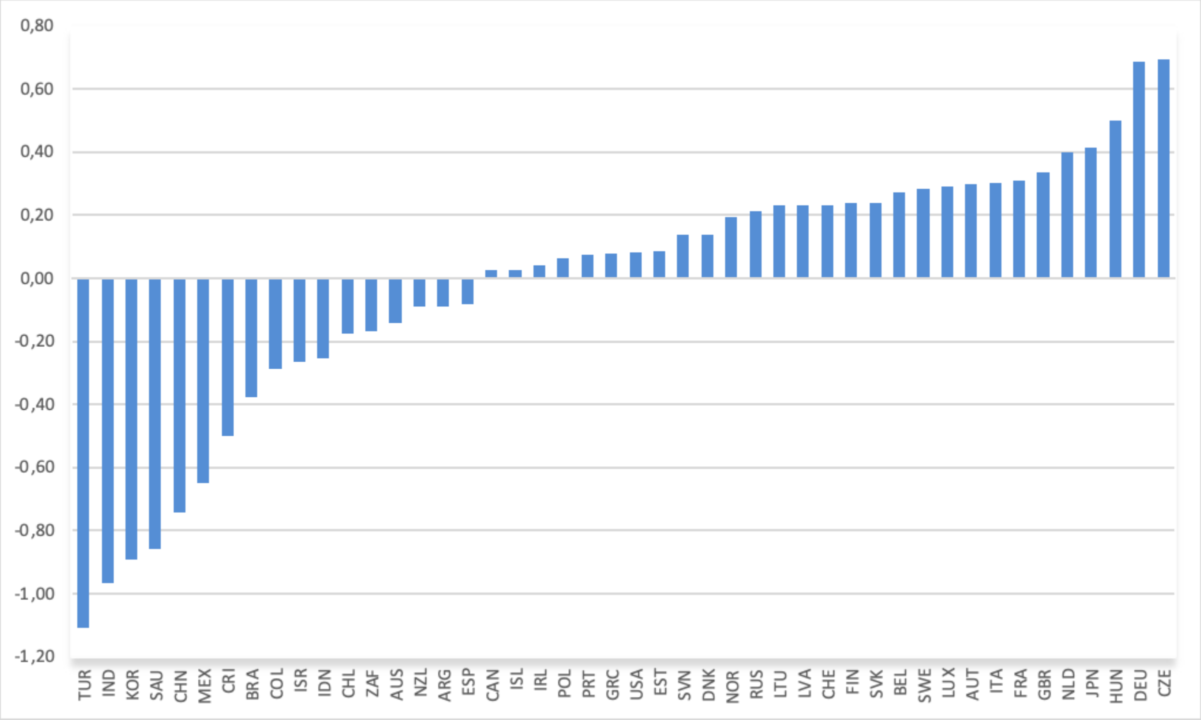
[26] The measurement and analysis of natural capital is still evolving and further work is required. Agarwala et al. (2023) and Polasky and Daily (2021) provide useful overviews of the discussion. The indicators of inclusive wealth discussed in this section are not fully aligned with standard productivity analysis, suggesting that further work is also required to integrate natural capital fully into productivity analysis.

decreased, and negative in countries where it has increased. It therefore provides an indication of the extent to which growth has been achieved at the expense of environmental degradation.

Cárdenas Rodríguez et al. (2016, 2018) estimated this adjustment for the period 1991-2013 for all OECD and BRIICS economies, with pollution being represented by greenhouse gas emissions and air pollutants. They found positive adjustments to GDP growth in 29 countries, with particularly high adjustments in the Czech Republic, Germany, Hungary, Japan, the Netherlands and the United Kingdom; and negative adjustments in 17 countries, with particularly high adjustments in Turkey, India, Korea, Saudi Arabia, China and Mexico (Figure 12). In some countries, notably Germany, Japan, Italy and Hungary, the positive adjustments accounted for over 20% of total output growth over the period (OECD, 2017).

Figure 12: Growth adjustment for pollution abatement, OECD and G20 countries

Long-term average (circa 1991-2013), in percentage points



Source: OECD (2016), “Environmentally adjusted multifactor productivity”, OECD Environment Statistics Database, based on Cárdenas Rodríguez et al. (2016).

Hua and Wang (2023) 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., that bad outputs have a negative impact on MFP growth in the bulk of countries. They find that the gap between MFP growth and EAMFP growth is largest in lower-middle income economies, such as India and Indonesia, where growth is achieved at the cost of high emissions of pollutants. However, some middle- and high-income countries also have a large down-ward gap between the two measures, such as Argentina, Brazil, Canada, Chile, China, Iceland, Israel, Latvia, Sweden, Turkey and the United States. Some countries have large positive gaps between the two measures, pointing to growth being achieved while lowering pollution emissions, e.g., in Bulgaria, Denmark, Germany, Hungary, Lithuania and Slovakia.

The OECD work shows that the UK is among the countries with a sizeable positive adjustment to output growth. Agarwala and Martin (2022) derive adjustments for the UK over a more recent period (1990-2020), using a slightly different set of pollutants than the OECD study. For the period 1997-2020, they find an average annual growth rate of environmentally adjusted labour productivity of 1.8%, compared to 1.1% without the adjustment, i.e., broadly consistent with the OECD work.

Some studies have criticised 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 notably in the context of environmental innovation. Herman et al. (2023) discuss EAMFP measures in the context of a broader review of measures linked to green growth and suggest it should be regarded as an indicator connecting policy inputs and environmental and economic performance.

Adjusting for good outputs

As discussed already in section 2 of this paper, another approach to adjusting for the environment in the context of productivity measurement is accounting for the investments that countries are making to protect the environment, by incorporating all expenditures for environmental protection as an investment in the national accounts, rather than as an intermediate expenditure. As noted by Agarwala and Martin (2022), most output related to environmental protection is currently not included in GDP, following agreed international national accounting rules (UN, 2014).

Data on some of this expenditure is, however, available for several countries in the Environmental Protection Expenditure Accounts. This shows expenditure on both environmental protection activities (or EPA, i.e., economic activities aimed at preventing, reducing and eliminating pollution of the environment) and resource management activities (RMA, i.e., economic activities aimed at preserving and enhancing the stock of natural resources). For EU countries, data for 2020 show that this expenditure accounted for over 6% of GDP in Finland, about 2.5% for the EU, but for only 1.0% in Ireland (Eurostat, 2023).

Available data on EPA and RMA may still underestimate total expenditure on environmental protection. Agarwala and Martin (2022) note that in the UK, 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 (and therefore not valued at market prices).[27] 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.[28]

Agarwala and Martin (2022) use a method set out by Martin and Monahan (2022a) and applied by Martin and Monahan (2022b) to measure the time spent on "green tasks" and apply this to measure total output of environmental protection activities in the UK. As a result of their

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[27] According to Eurostat, EU data for the Environmental Goods and Services Sector do include market and non-market output, as well as output for final use and for ancillary use, where output for own final use is to be valued at basic prices of similar products sold on the market or by the total costs of production and non-market output is to be estimated by the total costs of production. However, Eurostat acknowledges that EGSS data are relatively new, and that the completeness of datasets differs across countries. Moreover, it acknowledges that (voluntary) data on non-market production, ancillary use and own final use are less complete than other data. See: https://ec.europa.eu/eurostat/cache/metadata/en/env_egs_esms.htm

[28] Even though some data are available, environmental protection output is currently not included in GDP, following international guidance on national accounts (Agarwala and Martin, 2022).

approach, they find that unmeasured environmental protection adds some 6-7% to the level of UK GDP between 1997 and 2019. Moreover, as a result of the adjustment, they 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.

4. What will climate change policies imply for productivity growth?

Policy action to address climate change is now being taken across the world with 130 countries accounting for over 90% of global GDP and many global firms now publicly committed to achieving net zero.[29] 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 through improvements in energy efficiency. Several scenario studies and models have explored how the world can achieve net zero and limit global warming as much as possible, ideally keeping warming below 1.5°C. For example, the IEA's net-zero scenario provides a detailed account of the technologies that need to be introduced in different sectors of the economy to help reduce carbon emissions and achieve the goal of net zero by 2050 (IEA, 2021a; 2023a).

This section explores what policies to achieve net zero by 2050 might imply for different measures of productivity. This will aim to show some of the changes in productivity expected (e.g., of labour productivity) or required (e.g., carbon emissions productivity) for net-zero and also show the challenge ahead for productivity-enhancing policy actions such as those advocated by Geels et al. (2022), Stern and Stiglitz (2023) or Cervantes et al. (2023). The next section briefly returns to the policies to address climate change and explores to what extent they are compatible with productivity growth.

4.1.Net zero, labour and multi-factor productivity growth

As noted already in section 2, the impacts on productivity of climate change policies aimed at achieving net zero are uncertain. 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 rapid technological change, may well be positive. For example, estimates of the costs of the transition for the UK by the Climate Change Committee have been reduced over time, as the result of rapid technological progress and economies of scale in the production and diffusion of low-carbon technologies (Stern, 2022). The impacts of other factors discussed in section 2, such as those linked to international competitiveness, resource allocation and changing demand, are also uncertain, even as regards their likely sign.

Assessing the likely future sources of productivity growth in the context of net zero policies can be a first source of evidence. Recent analysis for France suggests several potential changes in the sources of growth in the context of net zero policies. First, the 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; Epaulard et al., 2023). Second, the pace and direction of technological progress would be affected, with a greater focus on low-carbon innovation. While such technological progress would deviate 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

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[29] See: https://zerotracker.net

technologies 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 new, low-carbon technologies is relative to existing investments in technology.

These potential changes in the sources of growth should be seen in the context of the current situation. Standard measures of productivity do not yet demonstrate a transition to more sustainable growth, as multi-factor productivity – the combined efficiency of factors inputs – has been falling at the global level (Van Ark et al., 2023), and as the transition to net zero will likely require considerable investment in fixed capital, and not just in intangible or human capital. In addition, materials use in the process of economic growth continues to rise, as discussed in the previous section. Growth therefore continues to rely heavily on tangible inputs and resources and is not yet becoming "weightless" (Quah, 1999).

Formal modelling studies are another source of evidence. 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 slight decline from its baseline global GDP growth of 2.3% between 2019 and 2030 to 2.0%, and from 2.1% between 2030 and 2050 to 1.9%. The study notes that these macroeconomic costs should be put in context, as they exclude avoided climate damages, particularly the reduced risks of climate tipping points that could not be quantified, as well as co-benefits from emissions reductions such as on health (Fouré et al., 2023).

Another source of evidence on likely impacts on productivity are studies that have explored the so-called Porter hypothesis (Porter, 1991), about the impact of environmental regulation on economic performance. Kozluk and Zipperer (2015) survey 37 empirical studies from 1983 and 2013.[30] They find that the results of many studies are ambiguous, as many of the studies are considered fragile and context-specific, making it difficult to draw overarching conclusions. They point to relatively broad support for the weak version of the Porter hypothesis, however, and a more ambiguous effect on productivity.

Albrizio et al. (2014) explore the impact of environmental policies on productivity at the macro, industry and firm level using the OECD's environmental policy stringency (EPS) index. At the macroeconomic level, they find that productivity is boosted following an initial fall in productivity prior to the implementation of more stringent policies. At the industry level, they find a positive impact on productivity of a tightening of environmental policies for the most technology advanced country-industry pairs. This effect diminishes with the distance to the global technology frontier and vanishes for the least productive country-industry pairs. At the firm level, only one tenth of all firms are able to reap some productivity gains following a tightening of environmental policies, while the least productive one-third of firms face a negative effect on productivity in the short run.

Rubashkina et al. (2015) find that environmental regulation in the manufacturing sectors of 17 European countries between 1997 and 2009 had a positive impact on innovation activity, as proxied by patents. However, they found no evidence of impacts on productivity, thus confirming the "weak" variant of the Porter hypothesis, but not the "strong" variant. De Santis et al. (2015) find that environmental policies generate positive productivity returns in a study

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[30] Studies of the Porter hypothesis may use aggregate, industry, or firm-level data, but typically include an assessment of the aggregate impacts on productivity.

for 18 OECD countries over the period 1990-2015, with both market and non-market policies playing a role.

Dechezleprêtre and Sato (2017) also review the literature on the impacts of environmental regulation on firm performance. They find that the cost burden of environmental policies is often very small, also compared to other factors affecting firm competitiveness. Moreover, the effects tend to be concentrated in a subset of sectors where environmental and energy costs are high, such as a number of basic industrial sectors, where the risk of pollution leakage is also high. They also find that environmental regulations induce innovation activity in cleaner technologies, thus supporting the "weak" version of the Porter hypothesis. However, they find that the positive impacts of such innovation do not outweigh the negative impact of regulation.

Hille and Möbius (2018) examine a cross-country dataset of 28 OECD countries and 14 manufacturing sectors between 1995 and 2009. They initially find positive impacts of environmental regulation on productivity growth, but these become mostly insignificant and partly negative when adjusted for simultaneity. They confirm the weak version of the Porter hypothesis, however, with positive impacts of environmental regulation on innovation. However, these positive impacts on productivity are counterbalanced by the costs of complying with more stringent environmental policies.

Cohen and Tubb (2018) review 103 studies on the Porter hypothesis and find considerable heterogeneity in both the sign and significance of the estimated effects, with a positive effect more likely at the state, region or country level, compared to the facility, firm or industry level. They note that these findings are consistent with the strong version of the Porter hypothesis where strict but flexible environmental regulations induce innovation and increase competitiveness.

Wang et al. (2019) explore the impact of environmental regulation on productivity for a panel of OECD countries from 2004 to 2010. They use environmentally adjusted measures of productivity incorporating greenhouse gas emissions as a bad output and find that both current and lagged measures of environmental regulation are positively correlated with green productivity. However, this relationship turns into a negative one when the stringency is above a certain level, suggesting that modest regulation may induce innovation that offset the regulatory costs, whereas the regulatory costs outweigh innovation at more stringent regulation. They conclude that well-crafted environmental regulations do not erode competitiveness and may have additional benefits beyond productivity, such as environmental benefits, safety and quality of life.

Dechezleprêtre and Kruse (2022) examine the economic impacts of climate policy stringency on regulated and indirectly on supply chains, based on data for 19 countries over the period 1990 to 2015. They confirm the weak version of the Porter hypothesis, with climate policies inducing innovation in regulated sectors, although they find no evidence of impacts on innovation along the supply chain. They find no evidence that climate policies either harm or improve productivity or value added in regulated firms, suggesting that impacts on innovation may compensate for the potential costs of climate policies.

Trinks and Hille (2023) evaluate the impact of carbon costs on a range of economic performance indicators, including productivity, based on analysis of microdata for 3.1 million firms in 32 countries over the period 2000-2019. They find little evidence of adverse effects on performance, except for modest reductions in employment, but point to the large heterogeneity of outcomes, with the largest impacts in carbon leakage sectors and EU countries. The study estimated improvements in productivity in nearly all subgroups, but only found significant impacts on productivity in small firms in leakage sectors.

Benatti et al. (2023) explore evidence for the Porter hypothesis based on data covering three million firms in six euro area countries over the period 2003 to 2019. They find that policy tightening has a negative impact on productivity in high-polluting firms, and stronger than in less-polluting firms. They also find that larger high-polluting firms experience positive impacts on MFP growth, linked to easier access to finance and stronger innovation. Firms that have better access to financial resources and experience with R&D cope better with policy tightening. They conclude that while environmental regulation does have a cost, the impacts on MFP growth are limited and can be minimised by adopting suitable policies.

Dechezleprêtre et al. (2023) explore the impact of the European Union emissions trading system (EU ETS) and show that it has had no significant impacts on profits and employment of the regulated firms and led to an increase in their revenues and assets. They also find that the EU ETS induced regulated companies to increase R&D in carbon-saving technologies, which is compatible with the Porter hypothesis.[31] Metcalf and Stock (2023) explore the macroeconomic impacts of carbon taxes for fifteen European countries over the period 1990 to 2018. They find no evidence for a negative impact on employment of GDP growth of carbon taxes, but rather a small positive impact.

A recent study of Germany and several countries in South, Central and Eastern Europe finds more mixed effects of the impacts of environmental policy on innovation (Makrevska Disoska et al., 2023). The study found that environmental regulation in Germany did induce firms to invest in innovation, with positive impacts on productivity. In the other countries, environmental policies appeared to have more limited impacts on innovation and had a negative impact on productivity. The study concludes that the maturity of an innovation system, e.g. as regards knowledge diffusion, may influence to what extent policy has positive impacts on innovation and productivity.

Several country-specific studies have also examined the Porter hypothesis. Van Leeuwen and Mohnen (2021) examine firm-level data for manufacturing in the Netherlands from 2000 to 2008. They find strong support for the weak version of the Porter hypothesis with environmental regulation have a direct and indirect – via investment – impact on innovation. They find that resource-saving eco-innovation, e.g., process-integrated innovations, have a positive impact on MFP, whereas pollution-reducing eco-innovations, e.g., end-of-pipe innovation, tend to reduce MFP. They suggest that environmental regulations properly aimed at process-integrated innovation could thus help strengthen productivity growth. Lena et al. (2022) examine evidence for Italian manufacturing industries between 1995 and 2017 and find that environmental regulation has no negative effect in most of the sample industries considered. For China, Lee et al. (2022) find that innovation capabilities and environmental regulations have a positive effect on green total factor productivity, with environmental regulations supporting productivity growth through their impact on innovation capabilities. For Korea, Lee and Lee (2022) find that environmental protection expenditure has a negative correlation with TFP, suggesting that the Porter hypothesis is not applicable to Korea.

The overview of studies in this section suggests that the negative impacts of climate policy on aggregate productivity may be relatively modest, and that there are circumstances under which the impact might even be slightly positive, e.g. when firm or countries are able to seize the market opportunities associated with rapid carbonisation. Concerns about the potential negative impacts of climate policies on productivity may therefore be exaggerated. Moreover, most of the studies discussed above do not adjust their estimates of impacts on GDP and productivity for environmental externalities. If policy action to address climate change would

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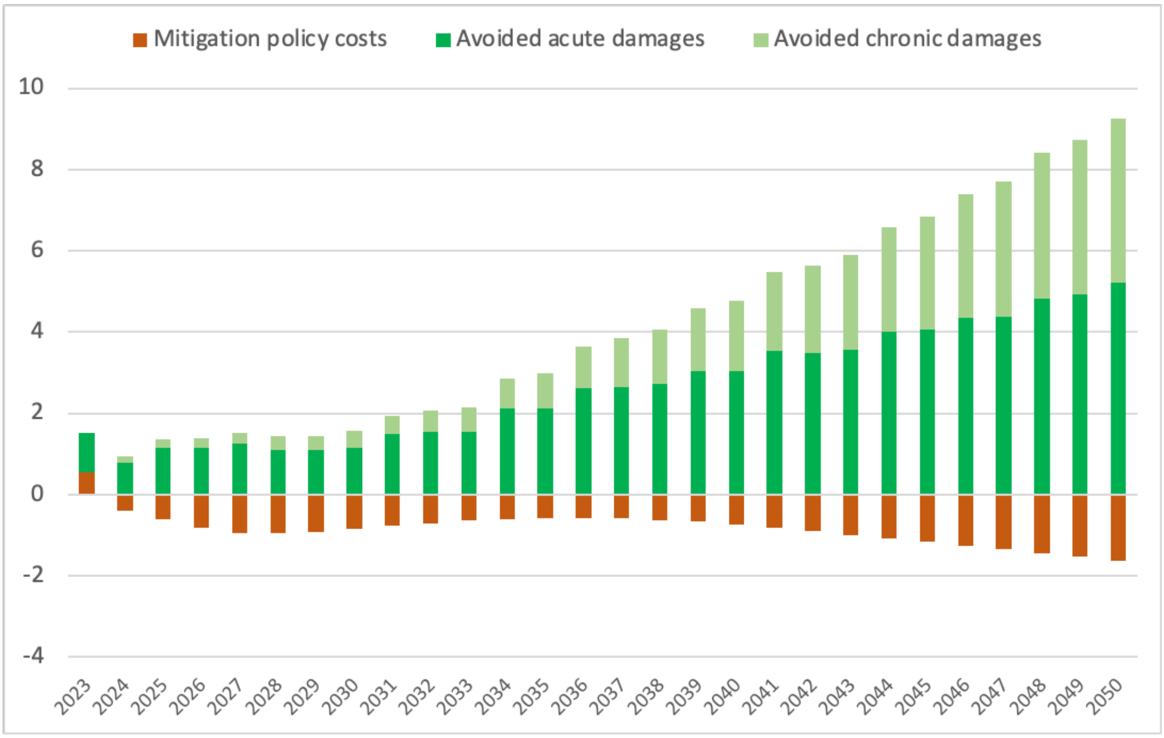
[31] Another factor contributing to the overall positive impact of the EU ETS scheme on regulated firms is their ability to pass costs of carbon prices through (Dechezleprêtre et al., 2023).

reduce greenhouse gas emissions and pollution more generally, GDP and productivity adjusted for environmental externalities would increase more than unadjusted measures.

An example of the latter perspective is a recent IMF blog (Mehrhoff, 2023), drawing on scenarios developed by the Network for Greening the Financial System, a group of 127 central banks and financial supervisors (NGFS, 2023). The scenario points 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 overall scenario shows a positive effect on GDP from policies to address climate change (Figure 13).

Figure 13: Potential benefit to world GDP under net zero carbon emissions by 2050

(percent deviation from reference scenario)



Source: IMF (2023), based on NGSF (2023). The reference scenario is the Current Policies scenario with to transition but physical risk.

However, most of the evidence on the costs related to climate policy action 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 environmental regulation and climate policy than small firms, given their greater access to finance, and the likely greater availability of complementary factors that can help adjust to new technology, such as skills, management or organisational factors. OECD (2021) summarises the evidence and find 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. The OECD work also concludes that the small negative effects seem transitory and that environmental policies may mainly trigger a reallocation from high to low-emission industries. As is often the case, the study does not account for the potential beneficial effects of policies on the environment and human health.

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 difficult for many firms, and in particular for those in industries relying heavily on fossil-fuel technologies, with no competitive alternative available yet. However, the aggregate impacts of policy actions to drive the transition on productivity may be relatively small and could be minimised 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 later sections of this paper. 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.

4.2.Net zero, resource and materials productivity

Carbon emissions productivity

The future impacts of achieving net zero on indicators of materials productivity are somewhat more easily to predict than the impacts on labour or MFP growth. If global emissions of CO_2 (or of all greenhouse gases) would move to zero than indicators of carbon or GHG emissions productivity would move to infinity (and become meaningless), as the global economy would not only achieve an absolute decoupling between GDP and GHG emissions (i.e., where GDP grows and emissions decline), but a full decoupling (i.e., with emissions moving to zero). Indicators of carbon and GHG emissions productivity will therefore need to see very strong growth over the coming decades if the world is to achieve net zero.[32]

The required acceleration in productivity growth is not trivial. The two countries with the highest carbon productivity in the OECD – Switzerland and Sweden – produced some 60 grammes of CO_2 for every US$ of GDP in 2021 (Figure 7) and had experienced annual average growth in carbon productivity over the previous 30 years of around 2-3%. Bringing emissions down to 10 grammes of CO_2 for every US$ of GDP in 2050, i.e., close to zero grammes, would require doubling that growth rate to about 6% annually. For the OECD as a whole, with carbon productivity in 2021 at only 180 grammes of CO_2 for every US$ of GDP, annual average productivity growth would need to increase from just over 2% from 1990 to 2021, to 9.5% from 2021 to 2050 to achieve 10 grammes of CO_2 in 2050. For the UK, which produced 120 grammes of CO_2 per US$ of GDP in 2021, annual average productivity growth would have to increase from just over 3% from 1990-2021, to just over 8% from 2021-2050, to achieve 10 grammes of CO_2 per US$ of GDP by 2050. Emissions productivity will therefore need to accelerate considerably from current growth rates to achieve net zero by 2050.

As discussed in section 3.2, indicators of demand-based CO_2 productivity tend to change more slowly than indicators of production-based CO_2 productivity as this requires changing the emissions intensity of demand, including imports, which may be harder to achieve for any

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[32] The ongoing decoupling of GDP, resource use and CO2 emissions in several advanced countries is certainly a positive factor, as suggested by some (McAfee, 2019), but will not be sufficient at its current rate to address climate change.

national government than changing the emissions intensity of national production, including exports. The most productive countries in the OECD in this perspective, Colombia, Ireland and Sweden, consumed some 130 to 140 grammes of CO_2 per US$ of GDP in 2018, and had achieved annual productivity growth ranging from 2 to 3.5% over the period from 1995 to 2018 (Figure 7). Achieving 10 grammes of CO_2 per US$ of GDP in 2050 would require annual average growth rates of almost 8% for these countries. For the OECD as a whole, with demand-side carbon productivity in 2018 at only 240 grammes of CO_2 for every US$ of GDP, annual average productivity growth would need to increase from just under 2% from 1995 to 2018, to 9.4% from 2018 to 2050 to achieve 10 grammes of CO_2 in 2050.

For the UK, with 180 grammes of CO_2 consumed per US$ of GDP in 2018, annual average productivity growth would have to increase from 2.7% from 1995-2018 to 8.6% from 2018 to 2050 to achieve 10 grammes of CO_2 per US$ of GDP by 2050. Overshooting the net zero target of 0 grammes of CO_2 even more, e.g., by aiming at 50 grammes of CO_2 per US$ of GDP by 2050, would require a lower productivity growth rate of 3.9% annually, but would involve failure of the UK's 2050 net zero target.

Vogel and Hickel (2023) point to the need for even more rapid reductions in CO_2 emissions if advanced countries that have already achieved an absolute decoupling of GDP and CO2 emissions would not only aim to achieving net zero by 2050 but would do so in a way that is compatible with their equity commitments under the Paris agreement. This commitment would leave advanced countries with a very small remaining carbon budget until 2050, thus requiring a very rapid decline in carbon emissions. Accelerating carbon emissions productivity is therefore a particularly important and urgent task.

Materials productivity

The likely impacts of moving to net zero on materials and energy productivity are less certain and are likely to be much more limited.[33] The materials productivity of certain materials, such as fossil fuels, should in principle move to infinity as they are phased out to achieve net zero, but the scope for productivity improvements in the use of other materials is less certain.

The OECD's Materials Outlook (OECD, 2019) provided a global assessment of materials use. It projected a doubling of global material use from 2017 to 2060, with the strongest growth occurring in emerging and developing economies. This was accompanied by a decline in materials intensity (i.e. an improvement in materials productivity) driven by a global shift to services, technological developments and the waning of China's construction boom. It also projected increased competitiveness of the recycling sector compared to primary materials. Under the OECD's baseline scenario, fossil fuel emissions would continue to increase and materials management activities (including fossil fuels, but also the use of iron and steel and concrete) would account for almost two-thirds of all greenhouse gas emissions, making improvements in materials productivity essential for policies to address climate change.

Studies are now emerging on the potential of improvements in materials productivity for addressing climate change. Scott et al. (2019) used an input-output framework, combined with econometric analysis and case study evidence for six manufactured products to examine the contribution of improvements in materials productivity for the UK emissions gap. They estimated that a range of policies to improve materials productivity could complement existing

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[33] This section includes the materials and resources needed for energy production, notably fossil fuels, in total materials use and the measurement of materials and resource productivity, thus demonstrating the overall scale of resource use and the impact of the phasing out of fossil fuels. KLEMS studies of productivity treat materials (M) and energy (E) separately.

UK climate change policies and significantly reduce UK emissions. Such policies could focus on the redesign of products, so they 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 have a positive and causal impact on the microeconomic competitiveness of firms. The study concludes that increasing materials productivity can help reconcile competitiveness and climate change objectives for certain firms, sectors and countries. However, Flachenecker (2018) finds that the focus on microeconomic competitiveness has limitations for the understanding of competitiveness at the macroeconomic level, and notes that the endogeneity of materials productivity is not sufficiently considered in empirical studies. He finds no evidence that increases in materials productivity affect competitiveness in a negative way and argues for policies that channel the gains from improvements in materials productivity to improve productivity and enhance environmental pressures.

Haas et al. (2015) examine material flows, waste production and recycling in the EU and globally. They find a very low degree of circularity of only 6% of all materials processed, as 44% of processed materials are used to produce energy and thus not available for recycling, and as societal stocks produced by materials (e.g., buildings and infrastructure) are still growing. To improve circularity – and thus improve resource productivity – they emphasize a shift to renewable energy, a reduction in the growth of societal stocks, and a significant increase in circularity of all products, resulting from better eco-design.

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 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). Other materials also have a wide range of potential environmental impacts, not all related to climate change, but also to issues such as biodiversity (e.g. due to changing land use or the extraction of construction materials). Improving materials productivity and reducing materials use is therefore not only important for climate change, but for the state of the environment and natural capital more generally.

Energy productivity

The future evolution of energy productivity is also uncertain and could move in different directions. Section 3 already noted the scope for further growth in energy productivity, linked in particular to improvements in energy efficiency, including the efficiencies linked to electrification of key energy-using systems. However, the transition to abundant and possibly very cheap renewable energy could also contribute to increased demand for energy, which could potentially lower energy productivity. As discussed already in section 3, abundant low-cost energy from renewable sources could increase future energy use and even reduce energy productivity through the so-called "rebound" effect, with improvements in energy efficiency leading to an increase in energy consumption in the medium to long term (Dimitropoulos, 2007). For example, in the transport sector, growing energy efficiency is counteracted by growing demand for private and larger cars, notably SUVs, while growing efficiency in data centres is only just able to keep up with growing demand (Brugger et al., 2021).

At the same time, new societal trends might help reduce energy demand. Brugger et al. (2021) find that in the European case, societal trends such as digitalisation (e.g., the shift towards smart products and services); new social and economic models (e.g., the sharing economy, growing consumer awareness); and a greater focus on quality of life (e.g., a greater focus on health, but also urbanisation and regionalisation) could substantially reduce energy demand.

4.3.Natural capital and productivity

Section 3 already discussed some recent studies on the relationship between natural capital and productivity, with some taking a relatively narrow perspective focused on non-renewable sub-soil assets, and others taking a broader perspective including renewable natural capital, including forests, freshwater resources, oceans, etc. The most recent UN assessment of natural capital, which takes the broader perspective, shows that the world's natural capital declined by more than 28 percent between 1990 and 2019 (UNEP, 2023). It also points to large differences across regions, with five countries in Latin America (Barbados, Chile, Ecuador, Peru and Trinidad and Tobago losing more than half of their natural capital since 1990. Japan was found to have the largest loss of natural capital, of 70 percent since 1990, due to overexploitation of fisheries and forests.

From the perspective of growth and 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) uses the UNEP data on inclusive wealth, including natural capital, and finds that many countries were sufficiently able to turn their depleted natural capital into produced (i.e. fixed or intangible) and human capital, thus supporting economic development and increasing their level of inclusive wealth. However, some developed countries were not as well able to achieve this.

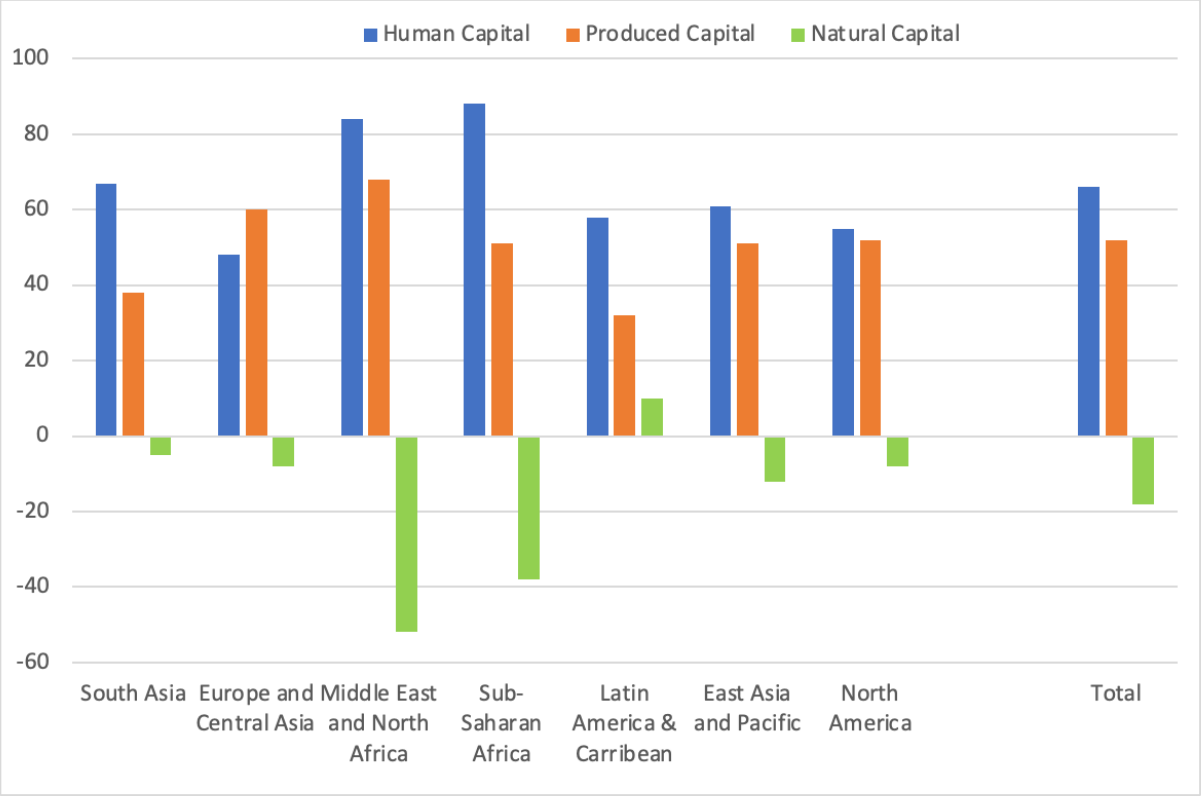
However, such studies do not assess whether the rate of resource depletion is ecologically sustainable and whether the deprecation of natural capital may promote economic wealth at the cost of ecological health (Van Krevel, 2021). Bowen (2016) notes that the exploitation of natural capital has long been a key source of economic development, but also reviews historical evidence where environmental factors have sometimes contributed to societal collapse.

UNEP (2023) also explores the development of natural capital relative to other forms on capital in the process of economic development. It finds large differences between countries and regions (Figure 14). Globally, increases of human capital and produced capital accounted for 66 and 52 percent respectively of the increase in inclusive wealth from 1990 to 2008, with natural capital depletion contributing 18 percent to wealth reduction. The Middle East and North Africa, and sub-Saharan Africa had particularly large negative contributions of natural capital depletion to inclusive wealth.

Going forward, scenario studies suggest that development paths that combine relatively rapid income growth with a much-reduced reliance on natural resources provides the most sustainable way towards increasing inclusive wealth while also providing the best approach to mitigating and adapting to climate change (Kurniawan and Managi, 2021).

The UNEP work concludes that the global community needs to reverse the declining trend in natural capital (UNEP, 2023). It notes that this would require investments in the restoration of natural capital and in clean energy technologies. Mirzabaev and Wuepper (2023) find that investments in ecosystem restoration (i.e. natural capital) have high economic and social returns. However, they point to a large gap between what is required to protect and restore ecosystems and what is currently being invested.

Figure 14: Relative contributions of human, produced and natural capital by regions, 1990-2008



Source: UNEP (2023), Inclusive Wealth Report 2023, Table 5.2.

5. Productivity, green growth and degrowth

An important question that has not yet been addressed in this paper, but which is currently being discussed in some of the literature, is whether addressing climate change is compatible with further GDP and productivity growth, in what is often called "green growth" (OECD, 2011; Bowen and Fankhauser, 2011), or whether addressing climate change requires "degrowth" (Hickel et al., 2022).[34]

Proposals for degrowth claim that advanced economies, in particular, should abandon GDP growth as a policy goal and close down or phase out polluting and less-necessary production (e.g., fossil fuels, meat and dairy, fast fashion, cars and aviation) as well as increase circularity in production more generally. Degrowth proposals also emphasize public services, including health care, education, housing, transport and renewable energy. Moreover, they often include proposals linked to employment and the labour market, including proposals related to working time, and to sustainable development and the role of low- and middle-income countries, intended to share the burden of adjustment from degrowth across countries and different social groups.

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[34] This paper will consider the Hickel et al. (2022) paper as a good summary of the main degrowth argument but notes that there are more extensive elaborations that provide further detail on the underlying research and policy proposals, e.g., Kallis et al., (2018) and Mastini et al. (2021)**.** A review by Fitzpatrick et al. (2022) of the academic literature on degrowth between 2005 and 2020 suggests that its agenda has expanded considerably since 2005, however, making it difficult to define the degrowth agenda with a high degree of precision. Slameršak et al. (2023) focus on post-growth scenarios, possibly suggesting a change in focus of the discussion.

While the proponents of degrowth make several important claims, notably the risk of climate breakdown, the importance of planetary boundaries for economic growth, and the slow rate of decoupling of CO_2 emissions from GDP, as discussed earlier in this paper, their proposals have been heavily criticised.[35] These criticisms are both of an economic and political nature.

The main economic arguments against degrowth are the following. Jakob and Edenhofer (2014) and Van den Bergh (2017) note that while recent periods of negative growth, such as the 2008 economic crisis or the recent COVID crisis did reduce or slow down global emissions, they only did so to a small extent. This is because GDP is only one factor driving emissions, with the carbon intensity of GDP often a much more important factor. Achieving a significant reduction in emissions would therefore require a large drop in GDP, with high risks, including a fall in consumer and investor confidence, macroeconomic instability and high unemployment. Van den Bergh (2017) also notes that degrowth may mix cause and effect. While climate policies may well have an impact on growth, "this does not imply the reserve causality that zero or negative growth will solve the problem of climate change or is even a necessary ingredient of any solution (Van den Bergh, 2017, p.108).

Another economic criticism of degrowth is that, while poverty has fallen considerably across the globe over the past decades, income levels in much of the world are still at very low levels, suggesting a strong need for further income growth in many parts of the world. Degrowth at the global level would thus imply strong growth in GDP in certain regions,[36] such as Sub-Saharan Africa and South Asia, while requiring deep cuts in GDP in advanced economies (Jakob and Edenhofer, 2014). Naude (2023a) notes that most of the current CO_2 emissions come from emerging and developing economies, where GDP growth is expected to continue. Reducing the GDP of advanced economies would therefore have relatively little impact on global emissions. [37]

Naude (2023a) also notes that some of the specific proposals associated with degrowth, e.g., for energy sufficiency or a four-day working week, might be susceptible to rebound effects and stimulate economic growth rather than reduce it. Moreover, redistributing growth to developing countries might stimulate economic growth there, increasing emissions, while reducing GDP in developed economies might reduce incentives for climate mitigation and innovation precisely in the countries that currently drive most of the world's low-carbon innovation.

A related criticism on degrowth comes from the perspective of structural change and was also noted by Van den Bergh (2010; 2017). A key challenge in addressing climate change is how to foster and accelerate the transition from a society based on fossil fuels that is rapidly eroding natural capital and planetary boundaries to one based on renewable energy that restores natural capital and operates within planetary boundaries. Such a shift requires extensive structural change and "creative destruction" within the economy, both on the demand and the supply side, with some sectors and firms growing and others declining, a process that is not the same as "simply" stopping growth in certain areas of economic activity (Stern and Stiglitz, 2023). Halting growth altogether instead risks preserving the existing structures, consumption and production patterns and might therefore not reduce emissions or the concentration of greenhouse gases in the atmosphere.

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[35] A useful perspective on degrowth is the record of a debate between Jason Hickel and Stéphane Hallegatte (2021).

[36] Wollburg et al. (2023) estimate that the global emissions associated with the alleviation of extreme poverty are relatively modest, but that providing sustainable middle-income standards of living would involve higher emissions. Reduced inequality, energy efficiency and energy decarbonization can reduce such emissions further.

[37] A more extensive elaboration of several of these arguments can be found in Naude (2023b; 2023c).

Changing existing structures, consumption and production patterns will require a radically different set of rules and economic incentives (e.g., carbon taxes, the removal of fossil fuel subsidies, supportive regulations and standards, etc.), however, as well as massive investment and innovation in new energy sources and new ways of production, and changes to consumption patterns including greater circularity in production. It will also require extensive support for the resulting structural change, including in supporting workers losing their jobs in sectors heavily linked to fossil fuels and greenhouse gas emissions, or in countries heavily dependent on such activities.

In principle, such supportive rules and incentives would lead to (potentially strong) growth and innovation in some parts of the economy, e.g., the renewable energy sector, but also clean transport; and to a sharp decline (and – in some cases – phasing out) in others, notably in sectors that are directly associated with fossil fuels, e.g., coal mining or oil and gas extraction, or with greenhouse gas emissions more generally, e.g., the meat and dairy industry. The resulting structural change – or creative destruction – should have strong dynamic effects on the economy, as it would facilitate the exit and decline of some firms and industries, and the entry and growth of others.

The point here is that using the dynamic process of innovation and creative destruction – i.e., the entry, growth and exit of firms and industries – may be a more effective and more efficient way of achieving the transition to a low-carbon economy than degrowth, which does not place much emphasis on structural and technological change, or the need for new firm entry and new sources of (clean) growth, or on innovation. Jakob and Edenhofer (2014) find that reductions in carbon emissions of reducing GDP per capita by 10% would be much more costly than even the most expensive technological mitigation options considered in scenario studies. Degrowth also seems to be primarily about command-and-control mechanisms, i.e., government closing down whole industries, rather than about incentives and policy mechanisms that can foster innovation and encourage rapid structural change.

A second set of criticisms of degrowth relate to its implementation and political feasibility. A number of commentators (Westlake, 2023; Naude, 2023a) have argued that the lack of income growth in several countries over the past decade has contributed to growing political tensions. Aiming for degrowth – which would in practice involve a move to a zero-sum society (Naude, 2023b) – would likely exacerbate such tensions further and would therefore be unlikely to receive support in democratic societies.[38] Naude (2023b) also questions whether "... we can indeed decouple innovation, happiness, social progress, tolerance, and 21st century values from the size and dynamics of the economy."

In response to these criticisms, advocates of degrowth suggest a focus on what they call "sustainable degrowth", which would involve scenarios where degrowth would have both socially and environmentally positive effects (Van den Bergh and Kallis, 2012). Slameršak et al. (2023) provide a more detailed perspective of such a scenario, discussed further below.

While the concept of degrowth has received many criticisms, so has that of green growth. Jakob and Edenhofer (2014) and Bowen and Hepburn (2014) point to two different versions of green growth. In the first, 'strong" version of green growth, environmental policies would have positive effects even in the short term. The second, weaker, version suggests that sound environmental policies might be implemented at relatively modest costs, with both future and present benefits. Bowen and Hepburn (2014) note that the weak version is closely aligned with

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[38] Weiss and Cattaneo (2017) in a review of the degrowth literature suggest that the degrowth literature would benefit from more rigid hypothesis testing, including in analysing the potential for non-market value creation and concrete well-being benefits. They suggest this could lead to greater public support.

mainstream economic thinking (as discussed in section 3.1) where climate change policies would have some cost in the short term, to be compensated by stronger economic outcomes in the long run. They note that the strong version requires either a) high investment multipliers, e.g., in a context of low aggregate demand; b) the elimination of market failures that would open up new and larger economic gains; c) benefits to innovation and investment as firms seek to establish a competitive advantage. Bowen and Fankhauser (2011) also emphasize the strategic relevance of green growth, in turning a negative debate about a costly constraint (i.e., emissions) into a narrative about potential opportunities.

According to Jakob and Edenhofer (2014), the empirical foundations for both versions of green growth are relatively weak, however, which is why some have argued that environmental quality can only be guaranteed with drastically reduced growth. Moreover, both versions emphasize growth and GDP as the main objective, rather than focusing also on what that growth would achieve in terms of consumption, environmental impacts, health, wellbeing, etc.

A detailed critique of green growth from the degrowth perspective was provided by Hickel and Kallis (2020). They note that while there has been some relative decoupling of domestic resource use and GDP growth in some advanced economies, as discussed in sections 3 and 4, there is no such decoupling when resource use is adjusted for the materials used in the production and transport of imported goods, and global resource use has been increasing on a steady trajectory. Hickel and Kallis (2020) and Vogel and Hickel (2023) also examine the decoupling of GDP from greenhouse gas emissions. They find some evidence of an absolute decoupling in some regions but note that this is not happening fast enough to achieve net zero and remain within remaining carbon budgets. Naude (2023c) also finds that green growth has not (yet) been able to achieve an absolute decoupling between GDP growth, materials use and carbon emissions.

These criticisms are aligned with the discussion on resource and materials productivity in sections 3 and 4 of this paper. OECD (2019) also shows that global materials use and CO_2 emissions linked to that materials use – fossil fuels, but also emissions linked to agriculture, the production of manufacturing goods, and construction – will increase considerably over the coming decades, although technological change and the structural change from goods-producing industries to services will reduce materials use to some degree.[39] Jackson and Victor (2019) support these arguments and note that ".. decoupling GDP from the flow of emissions is not the same as decoupling economic activity from the stocks of environmental and material resources on which future prosperity depends." The slow decoupling of resource use from GDP is perhaps not surprising, as policies currently provide only limited incentives to do so.

While directly reducing GDP, as suggested by degrowth proponents, is not the right way to address climate change, reducing materials use and ensuring that growth respects planetary boundaries is essential. Policies and approaches that address demand and reduce consumption and waste are therefore clearly of great importance for an overall strategy for climate change (Pisani-Ferry and Mahfouz, 2023). Price signals, regulations, standards and other incentives to influence demand can play an important role here, but so can policies and approaches that seek to change individuals' personal choices.

In response to this debate, Van der Bergh (2010; 2017) proposed a third way that seeks to bridge degrowth and green growth strategies, in what he calls an "agrowth" strategy. His proposed approach is *ex ante* agnostic about GDP growth as it is primarily focused on

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[39] The OECD baseline scenario for materials use suggests an increase from 89 Gt of global materials use in 2017, to 167 Gt in 2060 (OECD, 2019). The corresponding change in global GHG emissions would be from 44 Gt CO_2 equivalent in 2017 to 75 GT in 2060.

increasing social welfare (including human wellbeing, equity and a stable climate). He considers there may be different ways of increasing welfare, including – in certain cases, through either negative or high GDP growth. Jakob and Edenhofer (2014) also question the sole focus on GDP and growth and argue for a focus on social welfare and the various capital stocks that underpin that welfare, including natural capital and public infrastructure, rather than GDP. A related perspective is recent work by Tønnessen (2023) on "wasted GDP", which shows that a considerable part of US GDP is "wasted", leading to ecological pressures that derive from economic activities that do not support human development.

A recent paper by Slameršak, et al. (2023) moves beyond the earlier degrowth literature and discusses options for what is called a "post-growth' transition. It recognizes the challenges with low growth and degrowth and outlines key features of post-growth scenarios, where policies would no longer be aimed at achieving high GDP growth. These features include decent living standards for all; increased public investment for the energy transition; reductions in less-necessary forms of production and consumption, such as fossil fuels, fast fashion, etc.; convergence of material and energy use between advanced and emerging economies; and reduced inequality.

Van der Bergh's (2010; 2017) and Jakob and Edenhofer's (2014) approach is aligned with some of the discussions in this paper, which have already pointed to the limitations of GDP in the presence of large negative environmental externalities, and the need to adjust for those externalities in the measurement of GDP, including in measuring natural capital. However, their work goes further in focusing on wellbeing rather than GDP, which implies also considering a range of aspects of wellbeing that go beyond GDP, such as immaterial wellbeing, health and environmental sustainability.

This reflects the growing interest in wellbeing in the international debate over the past two decades, resulting from, amongst others, the influential Stiglitz-Sen-Fitoussi report (Stiglitz et al., 2009), which made extensive recommendations to improve the measurement of economic performance and social progress. This report has affected measurement in many areas and led to extensive work on the measurement of wellbeing, as reflected, amongst others, in OECD work (OECD, 2020a), and also led to new policy thinking to go beyond GDP, e.g., in the Living Standards Framework developed by New Zealand's Treasury (New Zealand Treasury, 2011; 2021) and equivalent approaches in several other countries (Exton and Shinwell, 2018).

To conclude this discussion, it appears that while degrowth – as conceived in the original proposals – is not the best way to go in addressing climate change, green growth – as originally conceived – also faces important limitations. In the presence of large environmental externalities and the erosion of natural capital, focusing only – or primarily – on (environmentally unadjusted) measures of GDP and productivity in policy discussions related to climate change is clearly no longer appropriate. Moreover, given the many impacts of climate change beyond GDP, a greater focus on wellbeing, instead of just GDP, is clearly crucial to the policy debate. At the same time, more standard measures of productivity will continue to have their place in the debate on climate change and productivity, notably at the firm and sectoral level, as it will be essential to enhance efficiency in the use of all productive resources. Understanding and addressing the global decline in multi-factor productivity growth will therefore also be essential (Van Ark et al., 2023).

The fundamental question is therefore not whether we can have growth or not, but how we can achieve a rapid transition to net zero while also supporting wellbeing and improving productivity in the use of factor inputs and resources, and what policies can achieve such a transition. The next section returns to this question in exploring some of the policy issues related to climate change and productivity.

6. Addressing climate change while supporting productivity and wellbeing

The global goal of net zero can be achieved in different ways. Economists are broadly in agreement on the best approaches to be used (see e.g., Stern, 2008; Blanchard et al., 2023; OECD, 2023a).[40] 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 already well understood, with a significant relationship between stronger climate action and greater emissions reductions (Nachtigall et al., 2024).[41]

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" (see e.g., Stern, 2008). Such policies seek to adjust for the negative impacts of carbon emissions on the economy and society by adjusting prices for the negative environmental externalities related to carbon emissions, for example, through the implementation of carbon taxes, tradeable permits such as Europe's Emission Trading System and the removal of fossil fuel subsidies. Without adjustment for these externalities, low-carbon products and technologies may find it difficult to compete with fossil-fuel based alternatives. Policies to level the playing field may go beyond levelling and could involve positive support for low-carbon activities and technologies beyond that required by an adjustment for environmental externalities alone.

While several countries have implemented policies to level the playing field for low-carbon products and technologies, fossil-fuel based products and technologies continue to have an advantage in many markets today. OECD data for 72 economies accounting for 40 billion tons of GHG emissions show that in 2021 58% of economic activity in these countries was still not subject at all to carbon taxation, and only 7% was taxed by carbon taxes of over 60 US$ per ton of carbon (OECD, 2023b). The World Bank's Carbon Pricing Dashboard shows that in 2022, 47 national jurisdictions had implemented carbon pricing initiatives, accounting for just over 23% of all GHG emissions globally (World Bank, 2023). Carbon price levels are generally low, however, and a recent OECD assessment found that only three countries (Switzerland, Luxembourg and Norway) priced more than 50% of their GHG emissions at over 60 EUR per tonne (OECD, 2023c).

The lack of carbon pricing is one challenge, explicit and implicit subsidies for fossil fuels are another. Explicit fossil fuel subsidies alone amounted to more than 1 trillion US$ globally in 2022, double the levels in 2021, as governments sheltered vulnerable consumers from the energy crisis (IEA, 2023b). Moreover, the negative economic and social impacts of fossil fuels in terms of pollution and their impacts on people's health, nature and society are not reflected in prices, further distorting markets and decision making. Estimates of such implicit subsidies for fossil fuels, that account for environmental costs and other costs related to fossil suggest these amounted to over US$ 7 trillion in 2022, or 7.1% of GDP, an increase of 2 trillion US$ since 2020, reflecting government support linked to surging energy prices (IMF, 2023).[42]

Improving the playing field for low-carbon products and technologies goes beyond taxes, pricing and subsidies. Fossil fuels have underpinned the global economy for a very long time and the industry can be considered as a rent seeking agent that will seek to shape, twist or

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[40] This does not imply that there are not – at the same time – significant differences in view on approaches to the economics of climate change. See e.g., Stern et al. (2022) and Stern and Stiglitz (2023) for criticism of mainstream economic thinking on climate change.

[41] This section only provides a brief overview of some key policies for climate change. See Stern (2022) and OECD (2023a) for more extensive discussions.

[42] See IMF, https://www.imf.org/en/Topics/climate-change/energy-subsidies

preserve relevant policies and regulations and attempt to control or lobby the political process (Høj et al., 2006). Overcoming this advantage of incumbency will be critical for successful climate strategies. Slow adjustment to changing circumstances and markets, or lack of political will tend to slow down implementation, leading the benefits of policy action to emerge only slowly (Hoeller and Louppe, 1994).

While some economists have argued that carbon pricing and the removal of fossil fuels subsidies are enough to address climate change, this perspective is clearly wrong. This is because 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 particularly 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; Meissner et al., 2023; Stern and Valero, 2021). Cervantes et al. (2023) also note that the complementary of carbon taxes and innovation policies, as suggested by Acemoglu et al. (2016), allows for much lower carbon taxes, and thus allows innovation policies to partially substitute for carbon taxes. Moreover, as suggested by many studies supporting the Porter hypothesis, innovation policies can help support productivity growth.

A recent assessment of low-carbon innovation policies suggests that greater emphasis is required for the different stages of research, development and demonstration (RD&D), including for low-carbon technologies that are not yet mature, as opposed to mainly for technology diffusion; greater direct support for business R&D, e.g. through grants, rather than indirect, e.g. through tax credits; greater national and international collaboration in low-carbon innovation; and the close integration of innovation policies in broader climate change strategies (Cervantes et al., 2023).

A third element of climate policy 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. In many EU countries, for example, planning procedures for onshore wind energy take more than five years, considerably above the two years recommended by the European Union (Fox, 2022). 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, as discussed earlier in this paper.

Technological standards that support low-carbon innovation, for example building codes, standards for heating systems and the like, are also key. Given the growing availability of cost-effective solutions for net zero, it is increasingly important that new buildings and heating equipment meet high energy standards and – to the extent possible – are equipped with their own supportive low-carbon energy systems, such as heat pumps or solar panels. Standards can also help with the existing building stock, to encourage building retrofitting and improve efficiency. A recent IEA report urges the global introduction of mandatory zero-carbon-ready building energy codes by 2030 but notes that many countries have long lead times to develop and implement new codes (IEA, 2022). Accelerating the process to set such standards is key. Coordination in international standard-setting will also be important for many technologies to help level the playing field and increase market size and scale.

A fourth key element are policies that *mobilise 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, 2023a). Policies to reduce investor risk, e.g., by risk insurance and guarantees, are important to, as are policies to reduce regulatory barriers to investment, e.g., as regards permitting rules.[43] Investment and finance will need to increase globally, with current estimates of global climate finance at almost 1.3 trillion US$, far below the 8 to 9 trillion US$ estimated to be required by 2030 (Climate Policy Initiative, 2023). The recent Inflation Reduction Act in the United States is an example of a policy that is expected to unlock large volumes of private investment aimed at decarbonisation.

A fifth key element are policies that *support and facilitate the necessary structural change and resource allocation* and allow for a fair and just 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 and just (Pilat, 2022). Moreover, as discussed by Terzi (2020), climate change policies may be more effective when they are made directly relevant to consumers, by highlighting local and regional impacts; reducing the perception that climate change is a problem that is distant in time; emphasizing the personal benefits of action; highlighting concrete actions and their effect; managing uncertainty, and careful targeting.

Policies for the transition also need to ensure that it is resilient to potential bottlenecks that could disrupt the transition, e.g., materials shortages, supply-chain constraints, skills gaps, public financing, technological bottlenecks, etc. (OECD, 2023a).

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 important dimension of global policies that is currently being discussed 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 (OECD, 2020b).

Global action is also central to achieving positive impacts on GDP and wellbeing 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, competitiveness, adaptation and resilience, the greatest benefits from policy action occur when all countries act to reduce emissions, thus limiting both acute and chronic damages and creating a global environment that encourages innovation and structural change.

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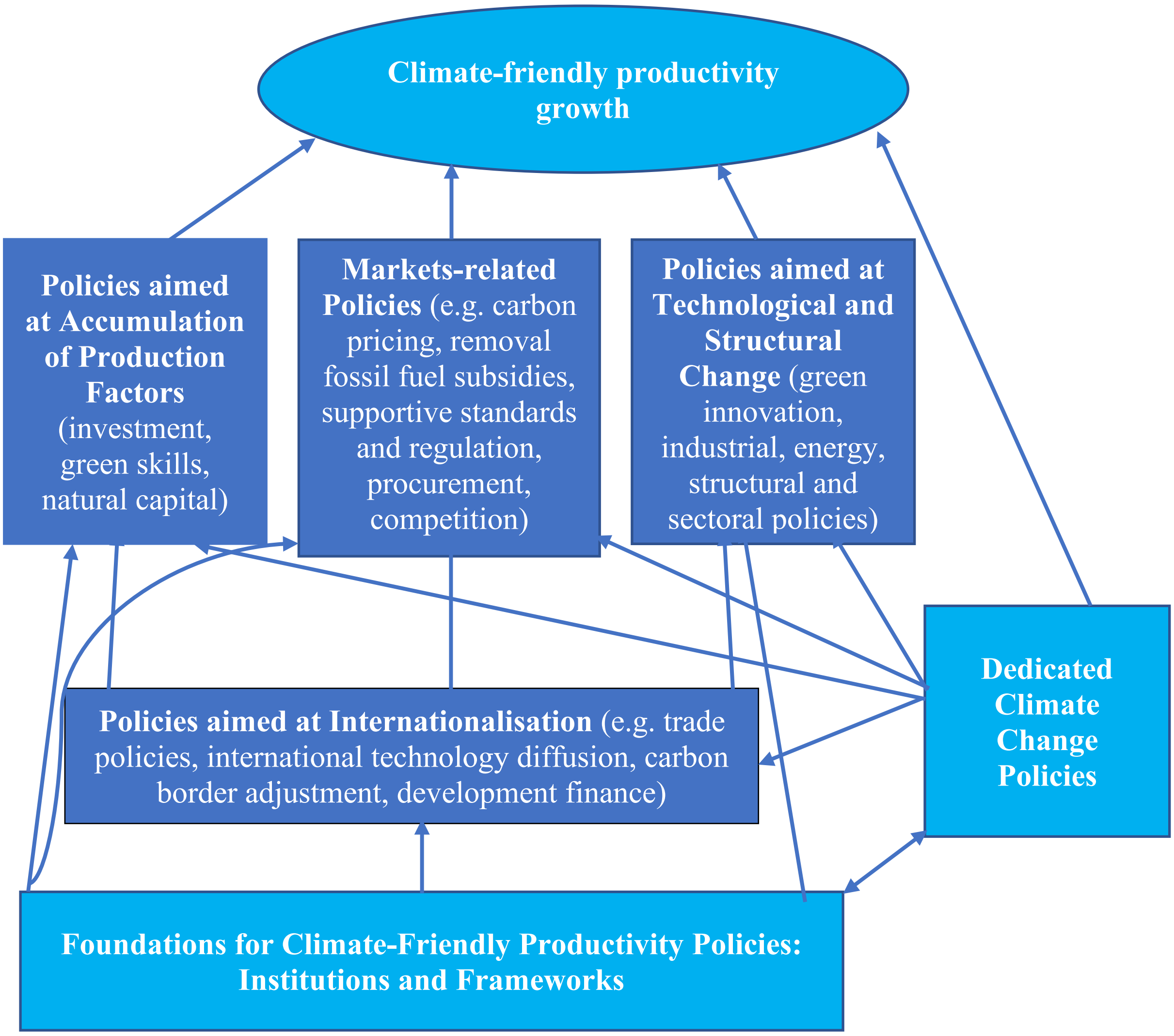
[43] Chapter 9 in OECD (2023a) discusses how to align finance and private sector action with climate goals in further detail.

The question is how these policies to address climate change 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 in a number of areas to: a) support investment and factor accumulation; b) foster innovation and structural change; c) make markets work; d) facilitate internationalisation; as well as e) foundational policies (Figure 15).

Figure 15: Framework for policies to address climate change and support productivity



Source: Author's elaboration, see Van Ark et al. (2023) for the basic framework.

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 and environmental pollution (see e.g., Stern, 2008). 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; investment in low-carbon infrastructure and ensuring the resilience of existing infrastructure; skills and human capital to facilitate the transition; and access to capital, amongst others (Bowen et al., 2012). Sector-specific policies will also be required, e.g., to strengthen resilience and productivity in agriculture, and specific policies aimed at adaptation to climate change. Figure 15 highlights some of the main elements of climate-friendly policies in the context of a pro-productivity policy framework.

The policies required for the transition to net zero and highlighted in Figure 15 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 would be expected to lead to lower productivity growth than the default set of pro-productivity policies. However, as noted previously, it is not clear what such a default or counterfactual implies in practice, as it assumes no impact of climate change and no change in policies from standard pro-productivity policies. The only credible scenarios are policies that address climate change, while supporting productivity and income growth as far as possible.

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).

Policies for net zero also need to be credible. One key element of this is the predictability and stability of policies, that are key to ensuring investor confidence. In addition, Dolphin et al. (2023) argue that policies need to strike a suitable balance between building commitment and achieving cost efficiency. They argue that getting expectations right for private investors – through a credible commitment to a policy pathway – is more important than getting prices right. Their proposed approach to climate policy development, based on “backward induction” explicitly accounts for the need for credibility and differs from current approaches to climate change policies, that are often open-ended and incremental.

7. Main findings and conclusions

This paper 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 productivity of natural capital and of 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 work on productivity, including by national productivity commissions (Pilat, 2023).

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, inclusive wealth and wellbeing, 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; Vardon et al., 2023) and their integration in the policy making process (Guerry et al., 2015; Ruijs et al., 2019); the use of environmentally-adjusted measures of productivity that incorporate shadow prices (Brandt et al., 2014; Cárdenas Rodríguez et al., 2016; Agarwala and Martin, 2022); greater attention for the full range of productivity measures, including materials, energy and CO_2 emissions productivity, rather than only measures of labour and multi-factor productivity; a greater focus on wellbeing, rather than just GDP (Van den Bergh, 2017); and the greater use of non-market based values reflecting the diverse values of nature (Nature, 2023). Some of these areas still require further methodological development. However, not integrating them in the current policy debate on climate change risks biased and incomplete evidence for decision makers.

In examining the evidence on productivity growth, the paper also finds that while there has been substantial productivity growth in the use of certain natural resources in advanced economies, including energy, materials and CO_2 emissions, the current pace of decoupling of GDP from the use of natural resources and CO_2 emissions 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 CO_2 emissions and 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 and greater engagement of productivity analysts in such research. Standard measures of productivity do not yet demonstrate a transition to more sustainable growth, as multi-factor productivity – the combined efficiency of factors inputs – has been falling at the global level, and as the transition to net zero will likely require considerable investment in fixed capital, and not just intangible and human capital. With global material use continuing to grow, growth is clearly not yet becoming "weightless" or green.

Mainstream economic studies over the past few decades have significantly underestimated the damaging impacts of climate change on economy and society, due to a range of methodological limitations and deficiencies and by ignoring the growing risks of the climate passing so-called tipping points. At the same time, studies today may well overestimate the long-term costs of policy action to address climate change on growth and productivity, 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. Statements that climate change policies will have a negative impact on economic productivity measures have little meaning unless they are compared with the counterfactual of no policy action, and the devastating effects on economy and society that would result.

However, it is clear that there are challenges in the timing of long-term benefits versus short-term costs, with some important costs possibly being incurred before the emergence of tangible benefits. Addressing this will require much attention for the distributional impacts of climate policy and a strong focus on ensuring potential short-term benefits for consumers and businesses, e.g. through support for the roll-out of cost-reducing energy technologies, such as renewables, heat pumps, insulation and energy efficient applications. This is also why cost-reducing innovation policies are such a crucial part of the policy mix. Moreover, achieving the benefits of climate policy action will require a global effort to reduce the damages of climate change and maximise the opportunities linked to rapid innovation.

The question is also whether addressing climate change is compatible with further economic growth, e.g., in the context of so-called “green growth” or whether “degrowth” is the way forward. Proposals for degrowth, that suggest a significant reduction in GDP in advanced economies, do not provide an effective or efficient way of dealing with climate change, however. This is because most of the growth in greenhouse gas emissions is occurring in emerging economies and as cuts in GDP are a less efficient way of reducing emissions than already available technologies. However, policies and approaches that address demand and reduce consumption and waste are clearly of great importance in an overall strategy for climate change.

At the same time, continuing to focus economic policies primarily on standard measures of GDP, labour and multifactor productivity growth is no longer appropriate. In the presence of large environmental externalities and the rapid depletion of natural capital, it is essential to pay much more attention to environmentally adjusted measures of GDP and productivity, as well as measures of natural capital and wellbeing, in policy discussions related to climate change and productivity.

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 wellbeing. To meet this challenge, governments will need to shape markets for low-carbon products and services, e.g., through regulation and standards, and 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 help bring down the cost of policy action, and support productivity growth. Climate change policies that use market mechanisms and the forces of competition, where possible, are also important, e.g., in adjusting for environmental externalities by carbon taxation, emissions trading and the removal of fossil fuel subsidies. 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 and that will require further economic development.

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. In 2019, Oswald and Stern (2019) found that only 57 of some 77,000 published articles in top general interest economics journals involved the subject of climate change. Noy (2023) noted that economists are insufficiently engaged with the IPCC, partly because not many economists focus on climate change. Stern (2022) and Sterner et al. (2024) argue that it is time for economics and economists to engage and that economics must change to respond to the challenge of climate change, including in going beyond the basic economic message of carbon pricing (Sterner et al., 2024). Such engagement would 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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