Centre for Economic Transition Expertise

Research and Policy at LSE

Emissions-adjusted total factor productivity

CETEx Working Paper No. 2

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September 2026

Global School of Sustainability

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This paper was first published in September 2026 by CETEx at the London School of Economics and Political Science.

Suggested citation: De Ridder M and Rachel L (2026) *Emissions-adjusted total factor productivity.* CETEx Working Paper 2. London: Centre for Economic Transition Expertise, London School of Economics and Political Science.

DOI: 10.21953/researchonline.lse.ac.uk.00140962

Emissions-Adjusted Total Factor Productivity*

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This version: 8 September 2026

Abstract

In many economies, the recent productivity slowdown coincided with declines in carbon dioxide emissions. Productivity statistics ignore this progress, even though lower emissions raise future consumption. We propose emissions-adjusted total factor productivity (TFPE), a forward-looking, welfare-relevant productivity measure. TFPE requires few assumptions, relying on the social cost of carbon as a sufficient statistic. At recent consensus estimates of the social cost of carbon, U.S. TFPE could grow twice as fast as TFP during a transition to net zero by 2050. At these costs of carbon, historical productivity adjustments are modest; at higher values, the post-2005 U.S. productivity slowdown disappears. In other countries, TFPE growth significantly exceeds TFP growth during the 1990s.

Keywords: Total Factor Productivity, Growth Accounting, National Accounts, Climate Damages

*First version: March 2025. We gratefully acknowledge financial support from the Structural Transformation and Growth (STEG) research initiative and from the Centre for Economic Transition Expertise (CETEx). Jasper Bechtold, Corentin Laffitte, and Ed Manuel provided excellent research assistance. We thank Philippe Aghion, Daniel Albuquerque, Clare Balboni, Adrien Bilal, Robin Burgess, Corina Boar, Francesco Caselli, Eduardo Davila, Wouter Den Haan, Lukas Freund, Joe Hazell, David Hemous, Ethan Ilzetzki, Chad Jones, Diego Känzig, Danial Lashkari, Ben Moll, Virgiliu Midrigan, Michael Peters, Hugo Reichardt, Pascual Restrepo, Aysegul Sahin, Isabel Schnabel, Chris Tonetti, Laura Veldkamp and Chris Wolf for useful comments and discussion.

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1. Introduction

The growth of total factor productivity is the main driver of long-run increases in living standards in advanced economies (Jones 2016). The fact that productivity growth has been sluggish for the past two decades has therefore been a primary concern of economists and policymakers alike (Goldin et al. 2024, Fernald et al. 2025). U.S. annual growth, for example, has averaged only 0.6% since 2005, well below the historical 1.5% mean (Figure 1a). The slowdown is even more pronounced in Europe, where several countries have experienced outright productivity declines (Draghi 2024).

But do these statistics truly capture the extent to which the economy is getting better at generating welfare from its inputs? Weitzman (1976) taught us that measures of economic activity are informative about welfare only if they account for all the changes to future consumption that arise as a result of today's production. Yet productivity statistics do not adjust for all such effects. One of the most salient omissions is the effect of carbon dioxide emissions, which negatively affect both the climate and future output (e.g., Nordhaus 1977, Nath et al. 2024, Bilal and Känzig 2026).

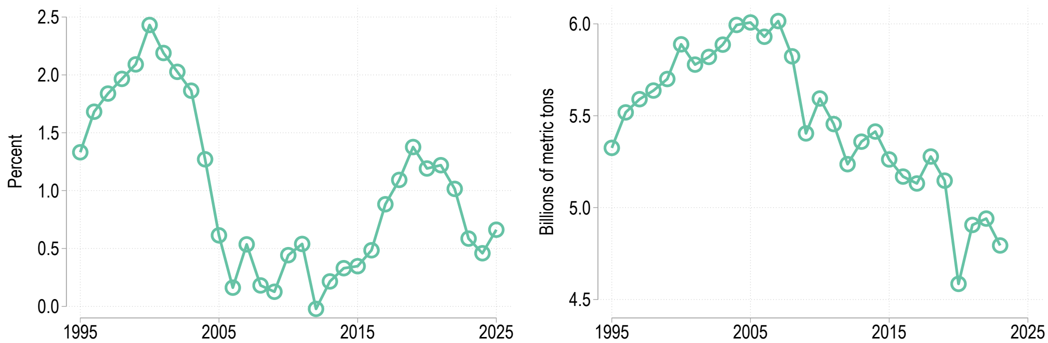
Carbon dioxide emissions have been *falling* in many advanced economies: U.S. emissions are now 23% below their peak, and the ratio of emissions to GDP has fallen by 40% since 2005 (Figure 1b; see also Aghion et al. 2025). These reductions matter for productivity because they limit climate-related damages and thereby expand future consumption possibilities. A welfare-relevant productivity index therefore rises when emissions fall.

This paper asks whether the path of productivity growth changes once we account for how declining emissions affect future consumption. To do so, we quantify the welfare-relevant productivity index in an economy with emissions. This emissions-adjusted total factor productivity measure (TFPE) equals the marginal effect of an increase in the economy's use of inputs on the present value of consumption, taking into account the future damages generated by the emissions associated with production. Measuring efficiency with TFPE restores the link between welfare and productivity in a general framework that nests canonical integrated assessment models (e.g., Nordhaus 1992, Golosov et al. 2014, Hassler et al. 2016). It also coincides exactly with the Solow residual of Green GDP, a central concept in the literature on green national accounts, although TFPE remains a welfare-relevant efficiency measure under weaker assumptions than those required for Green GDP itself (e.g., Dasgupta 2009, Muller et al. 2011).

It may seem unconventional to define productivity as a forward-looking variable that measures the effect of today's production on future consumption. That feature, however, is already present in indices such as the Solow residual, because part of output is used for investment. Weitzman (1976) shows that when investment goods are competitively priced, net investment encodes the present value of the future consumption it generates. Productivity statistics capturing how inputs generate net output are thus forward looking: they capture the effect of inputs on future consumption.[1] TFPE thus generalizes TFP and coincides with it in the absence of emissions.

[1] In practice, productivity is measured as the rate at which input bundles produce gross rather than net output, and Weitzman (1976) imposes additional assumptions on technology and interest rates. Generalizations of the original Weitzman result are provided in Weitzman and Löfgren (1997) and Weitzman (1998).

Figure 1. Trends in U.S. Total Factor Productivity Growth and Carbon Emissions



(a) Productivity Growth (b) Carbon Emissions

Notes: Left: the 5-year moving average of utilization-adjusted productivity growth (Fernald 2014). Right: carbon dioxide emissions.

Our main theoretical result is that this welfare-relevant productivity measure requires little knowledge of the structure of the economy: TFPE can be calculated using only data on carbon dioxide emissions, output, and standard TFP, together with an estimate of the *social cost of carbon*—the marginal effect of emissions on the present value of consumption, a frequently estimated object that coincides with the optimal Pigouvian carbon tax (Hassler and Krusell 2018, Barrage 2020).

The social cost of carbon plays the role of a sufficient statistic in the sense of Chetty (2009): it condenses into a single number all assumptions about the channels through which emissions affect the path of consumption, how long these damages persist, and how future consumption is discounted. Measuring TFPE therefore requires no estimation of production functions and none of the structural apparatus of integrated assessment models: no specification of the damage function, and no assumptions on the carbon cycle. Any such structure is already embedded in the social cost of carbon, as is the extent, if any, to which society internalizes global damages from its emissions.

The literature has by no means converged on a definitive social cost of carbon. Most estimates of the global damages range from $50 to $300 per metric ton of carbon dioxide in 2017 dollars. At the top end of the range, Bilal and Känzig (2026) derive a social cost of carbon of $938 in 2017 dollars from a time-series regression of global temperature shocks on global output. In a meta-analysis that allows for broader damages beyond economic activity, Moore et al. (2024) find an average of $252. U.S. policy assumed a $48 cost of carbon in 2021, which rose to $180 by 2023 (Carleton and Greenstone 2022). Domestic-only carbon damages are, in all but the largest economies, at least an order of magnitude smaller than the global cost of carbon. U.S. policy adopted an exclusive focus on domestic costs between 2017 and 2021, for example, so that emissions were evaluated at a cost of less than $8 per ton (Voosen 2021). Domestic costs of carbon emissions may even be negative in colder economies that benefit from rising temperatures, such as Canada (Nath et al. 2024).

We take an agnostic approach and calculate TFPE for a range of values: $50, $250, and $900.[2] This range encompasses much of the variation in existing estimates, reflecting differences in both

[2]These values are for the social cost of carbon in 2017, measured in 2017 dollars. We allow these costs to grow at 2.1% per year. Section 3 elaborates.

the scope of damages considered (domestic, global) and their magnitude. Taken together, they allow us to assess comprehensively whether emissions meaningfully alter productivity dynamics.

We find that recent TFPE growth exceeds TFP growth in most advanced economies, although the difference is only economically meaningful at the top end of the estimates for the social cost of carbon. At a cost of $50 per metric ton or less, TFPE is hard to distinguish from TFP. In this case, adjusting productivity for emissions lowers its level by less than 1%, so the effect on productivity growth is near zero. This has a natural interpretation: at these costs of carbon, the benefits from avoiding climate damages are small relative to modest improvements in traditional TFP growth. Policymakers relying on such costs of carbon in cost–benefit analyses would struggle to justify prioritizing climate over conventional growth-enhancing policies.

At the top end of carbon cost estimates, TFPE and TFP growth rates are meaningfully different. If the social cost of carbon exceeds $812, for example, TFPE growth in the U.S. has *increased* — rather than slowed — over the past two decades. Thus, adjusting for emissions can materially affect the dynamics of recent productivity growth, but only at social costs of carbon near the very upper end of the literature, such as those in Bilal and Känzig (2026).

We then use TFPE to quantify the productivity-equivalent gains from future decarbonization in the United States. The purpose of the exercise is to show how a given emissions path can be translated into the same units as conventional productivity growth. We start from the Congressional Budget Office's productivity forecast and compare the path of TFPE under two Network for Greening the Financial System (NGFS) scenarios: *Current Policies*, which holds currently implemented policies fixed, and *Net Zero 2050*, in which U.S. emissions decline to approximately zero by 2050.

We find that prospective emissions reductions can have large effects on TFPE, even under consensus social costs of carbon. At $250, reaching net zero by 2050 nearly doubles U.S. emissions-adjusted productivity growth over 2025–2035 relative to standard TFP. At a cost of $900, the gains are even larger: TFPE growth peaks at 2.3% during the first decade of the transition, compared with less than 1% under current policies and 0.6% when no adjustment for emissions is made. The broader implication is that TFPE is useful not only for revisiting historical productivity trends, but also for comparing climate scenarios in units that are directly interpretable as productivity growth.

Related Literature. This paper is most closely related to the literature on adjusting national accounts for environmental externalities. The "green national accounts" literature builds on the insight in Weitzman (1976) that, under particular conditions, aggregate output net of capital depreciation is proportional to the present value of consumption.[3] If future consumption is affected by carbon in the atmosphere, carbon emissions amount to a depreciation of natural capital, and those damages should be subtracted from gross domestic output in order to measure welfare. Nordhaus (2021) summarizes this idea, labeling output net of environmental depreciation "green national income." This is part of a long literature with early contributions including Solow (1986), Hartwick

[3]Formally, Weitzman shows that a constant consumption path equal to the current net national output delivers the same welfare as the equilibrium consumption path (see Appendix A).

(1990), and Weitzman and Löfgren (1997). Muller et al. (2011) quantify such accounts for the U.S. and show that some industries generate damages that exceed their value added.

Our approach builds on this literature but shifts the focus from GDP to productivity growth, making it both complementary to and distinct from the existing work. At a global level, TFPE is the Solow residual of (GHG emissions) Green GDP. Its usefulness, however, goes beyond this accounting role. TFPE is also the welfare-relevant measure of productive efficiency under weaker assumptions than those required to interpret Green GDP itself. Welfare interpretations of Green GDP require assumptions such as a constant interest rate and the comprehensive inclusion of all forms of capital. By contrast, TFPE follows directly from the envelope condition: because it measures the marginal contribution of productivity to the present value of consumption, its welfare interpretation does not require the stronger assumptions needed to evaluate non-marginal changes in welfare.

More broadly, the paper relates to the macro–climate literature studying the growth effects of climate change and environmental policy (e.g., Nordhaus and Boyer 2003, Golosov et al. 2014), as well as work on the productivity slowdown in advanced economies (e.g., Adler et al. 2017, Fernald et al. 2025). It also connects to a long tradition interpreting productivity growth as a welfare-relevant statistic under appropriate conditions (e.g., Weitzman 1976, Basu and Fernald 2001). Our contribution is to provide a simple, welfare-relevant productivity measure that incorporates environmental damages, thereby connecting these literatures in a way that can be readily implemented in the data.[4] We also relate to the literature that emphasizes interactions between climate change and endogenous growth (Acemoglu et al. 2012, Acemoglu et al. 2016). A detailed review of the literature is provided in Aghion et al. (2019), Hémous and Olsen (2021), and Dechezleprêtre and Hémous (2022).

2. Framework

We examine productivity in an economy with emissions that nests standard integrated assessment models (e.g., Nordhaus 1992, Golosov et al. 2014). We start by considering a global economy and discuss how welfare-relevant productivity differs from TFP. We then turn to the country level, because global emissions affect domestic households and domestic emissions affect households abroad.

2.1. Economic Environment

Consider a global economy for which output Y_t at discrete time t is given by

$$Y_t = A_t F_t(\mathbb{K}_t) D_t(S_t), \tag{1}$$

[4] An alternative literature adjusts productivity by treating environmental services as inputs to production, as in the OECD's environment-adjusted multifactor productivity (Rodríguez et al. 2018) and the U.K. calculations of Agarwala and Martin (2022). These measures ask how productivity growth would have differed had environmental pressures remained unchanged from the previous period. They are therefore period-by-period production-accounting exercises, based on assumed, time-invariant output elasticities with respect to environmental services, rather than measures derived from an intertemporal welfare criterion. TFPE instead values the future consumption losses caused by current emissions, treating emissions as a byproduct of production. This makes TFPE the welfare-relevant productivity index in canonical integrated assessment models. The correlation between growth in TFPE and growth in the OECD measure is 0.38. For a rigorous discussion of the welfare-relevance of productivity indices, see Basu et al. (2022).

where $A_t F_t(\mathbb{K}_t)$ denotes output absent climate damages, $\mathbb{K}_t$ is a vector of production inputs, and $D_t(S_t)$ captures damages from the atmospheric stock of past carbon dioxide emissions S_t. That stock is determined by the full history of emissions, that is, $S_t = L(E^t)$, where $E^t \equiv \{E_0, E_1, .., E_t\}$. The flow of emissions E_t is a byproduct of production and satisfies

$$E_t = \phi_t F_t(\mathbb{K}_t), \tag{2}$$

where ϕ_t captures the emissions intensity of production and may vary over time due to changes in technology, sectoral composition, or input use. Aggregate output as measured in the national accounts equals consumption C_t by households or the government, plus investment, so that

$$Y_t = C_t + \mathrm{p}_t \mathbb{I}_t, \tag{3}$$

where $\mathbb{I}_t$ is a vector of investments in inputs and p_t the corresponding vector of relative prices.[5]

We assume that investment goods are competitively priced, so that the price of each investment good reflects the marginal rate of transformation into consumption goods. As we explain later, this implies that standard measures of productivity growth are welfare-relevant in the absence of climate damages. We impose no functional form on the damage function $D_t(\cdot)$ and on the function $L(\cdot)$ that governs how carbon accumulates and depreciates in the atmosphere, or on the drivers of the mapping between the use of production factors and emissions ϕ_t. Hence we nest macro-climate models with explicit assumptions on any of these equations (e.g., Nordhaus 1992).

Finally, preferences are such that welfare equals the present value of consumption, as follows

$$\boldsymbol{V}_t = \mathbb{E}_t \left[\sum_{s=0}^{\infty} \prod_{k=t}^{t+s} \beta_k C_{t+s} \right], \tag{4}$$

where $\mathbb{E}_t$ is the expectation operator and β_t is the (possibly stochastic) discount factor. Consumption enters linearly in this present value without loss of generality, given the possibly time-varying discount factor. Section 2.5 elaborates.

2.2. Emissions-Adjusted Productivity

We define the welfare-relevant measure of productivity in our economy with emissions, TFPE, as the marginal effect of a bundle of inputs $F_t(\mathbb{K}_t)$ on welfare V_t:

$$TFPE_t \equiv \frac{\mathrm{d}\, \boldsymbol{V}_t}{\mathrm{d}\, F_t(\mathbb{K}_t)}. \tag{5}$$

[5]Emissions are not recorded as part of the national accounts, even in countries with emissions trading schemes such as the EU ETS. This is because such permits are intermediate inputs or taxes, and thus not part of total value added.

Proposition 1 derives how to calculate TFPE and documents how it differs from the standard productivity measure, TFP, that quantifies the rate at which inputs convert to outputs:

$$TFP_t \equiv \frac{\partial Y_t}{\partial F_t(\mathbb{K}_t)} = \frac{Y_t}{F_t(\mathbb{K}_t)} = A_t D_t(S_t). \tag{6}$$

Proposition 1. *The marginal effect of inputs on the present value of consumption is given by*

$$TFPE_t = TFP_t \left(1 - \frac{E_t}{Y_t} SCC_t\right), \tag{7}$$

where SCC_t is the social cost of carbon, defined as the present value of the marginal reduction in future consumption caused by an additional unit of emissions:

$$SCC_t \equiv -\mathbb{E}_t \left[\sum_{s=1}^{\infty} \prod_{k=t}^{t+s} \beta_k \frac{dC_{t+s}}{dE_t} \right].$$

Derivation. Starting from the definition of TFPE in (5), we use the definition of output (3) to write

$$TFPE_t = \frac{\partial V_t}{\partial C_t}\frac{\partial C_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial V_t}{\partial \mathrm{p}_t \mathbb{I}_t}\frac{\partial \mathrm{p}_t \mathbb{I}_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial V_t}{\partial E_t}\frac{\partial E_t}{\partial F_t(\mathbb{K}_t)}. \tag{8}$$

The first term captures the effect of inputs on today's consumption, the second their effect on investment and thus future consumption, and the third the effect operating through emissions. Under the competitive pricing of investment goods, the envelope theorem implies that the marginal effects of consumption and investment on welfare are equal. Hence we can write

$$\frac{\partial V_t}{\partial C_t} = \frac{\partial V_t}{\partial \mathrm{p}_t \mathbb{I}_t} = 1 \quad \Rightarrow \quad TFPE_t = TFP_t + \frac{\partial V_t}{\partial E_t}\frac{\partial E_t}{\partial F_t(\mathbb{K}_t)}.$$

which uses that $\partial C_t/\partial F_t(\mathbb{K}_t)$ and $\partial \mathrm{p}_t \mathbb{I}_t/\partial F_t(\mathbb{K}_t)$, sum to $\partial Y_t/\partial F_t(\mathbb{K}_t) = Y_t/F_t(\mathbb{K}_t) \equiv TFP_t$.

The final term in (8) is the product of the marginal welfare cost of emissions and the marginal effect of inputs on emissions. The former is the negative of the social cost of carbon (SCC_t). The latter is equal to ϕ_t in equation (2). Inverting the emissions function and inserting the production function yields that $\phi_t = TFP_t(E_t/Y_t)$. Inserting ϕ_t and SCC_t into (8) gives the expression from Proposition 1:

$$TFPE_t = TFP_t - TFP_t \left(\frac{E_t}{Y_t}\right) SCC_t,$$

Corollary 1. *In the absence of emissions or if emissions do not harm welfare, i.e. $SCC_t = 0$, TFP_t measures the marginal effect of a bundle of inputs $F_t(\mathbb{K}_t)$ on the present value of consumption $\boldsymbol{V}_t$.*

Proposition 1 provides two main insights. First, it shows that adjusting productivity for emissions only requires data on emissions, aggregate output, and the social cost of carbon. The latter serves as a sufficient statistic, that embodies any assumption on the damage that emissions do to the present value of consumption. Second, it shows that in the absence of emissions, standard TFP is welfare-relevant: it equals the marginal effect of inputs on the present value of consumption (Corollary 1). That is because a part of output is used for investment goods, which means that today's output affects future consumption. When investment goods are appropriately priced, the envelope theorem yields that their marginal effect on welfare is equal to the marginal effect of consumption on welfare. Intuitively, that is because the price of investment goods encodes the present value of consumption that will be derived from those goods.

2.3. Productivity at the Country Level

We have thus far derived TFPE for a global economy. To adjust productivity for emissions at the country level, one has to decide whether domestic consumers internalize the global externality of their emissions. If a country internalizes the effect of its emissions on consumption across countries, the expression for TFPE is largely unchanged. The production function of country i reads

$$Y_{it} = A_{it} F_{it}(\mathbb{K}_{it}) D_{it}(S_t). \tag{9}$$

TFPE still measures the marginal effect of $F_{it}(\mathbb{K}_{it})$ on the present value of *global* consumption C_t, taking into account that production directly affects domestic consumption and investment, and global consumption through a rise in the stock of carbon in the atmosphere:

$$\begin{aligned} TFPE_{it} &= A_{it} D_{it}(S_t) + \mathbb{E}_t \sum_{s=1}^{\infty} \left(\prod_{k=t}^{t+s} \beta_k \frac{\mathrm{d}\, C_{t+s}}{\mathrm{d}\, E_{it}} \frac{\partial E_{it}}{\partial F_{it}(\mathbb{K}_{it})} \right), \\ &= TFP_{it} \left(1 - \frac{E_{it}}{Y_{it}} SCC_t \right). \end{aligned}$$

It is equally possible, however, to calculate emissions-adjusted productivity under the assumption that households only internalize domestic climate damages, so that welfare is defined by:

$$\boldsymbol{V}_{it} = \mathbb{E}_t \left[\sum_{s=0}^{\infty} \prod_{k=t}^{t+s} \beta_{ik} C_{it+s} \right]. \tag{10}$$

This was the approach used to evaluate climate policy in the United States between 2017 and 2021 (Voosen 2021). To calculate TFPE in this setting, we use estimates of the social cost of carbon that focus solely on domestic economic costs, sometimes referred to as the domestic cost of carbon (DCC_{it}, see Kotchen 2018):

$$\begin{aligned} TFPE_{it} \equiv \frac{\mathrm{d}\, \boldsymbol{V}_{it}}{\mathrm{d}\, F_{it}(\mathbb{K}_{it})} &= A_{it} D_{it}(S_t) + \mathbb{E}_t \sum_{s=1}^{\infty} \left(\prod_{k=t}^{t+s} \beta_{ik} \frac{\mathrm{d}\, C_{it+s}}{\mathrm{d}\, E_{it}} \frac{\partial E_{it}}{\partial F_{it}(\mathbb{K}_{it})} \right), \\ &= TFP_{it} \left(1 - \frac{E_{it}}{Y_{it}} DCC_{it} \right). \end{aligned}$$

A practical concern with country-level TFPE measurement is that advanced economies have moved some of their emissions to other countries. This may artificially raise TFPE growth. We address this by using trade-adjusted emissions which, in contrast to territorial emissions, attribute carbon emissions to the country where goods are consumed rather than to where they are produced. Appendix B.1 provides a formal motivation. In practice, both emissions series are highly correlated (e.g., the U.S. correlation between growth of trade-adjusted and territorial emissions is 0.93).

2.4. TFPE and Green GDP

To complete our introduction of the TFPE measure from Proposition 1, we discuss its relation with Green GDP: national income net of climate damages. Building on Weitzman (1976), the literature on green accounting argues that climate damages are a negative investment, in the sense that they reduce the remaining stock of natural capital at the global economy's disposal (Weitzman and Löfgren 1997, Fenichel and Abbott 2014, Muller et al. 2011, Nordhaus 2021). In integrated assessment models, there is an additional indirect cost of climate change: lower natural capital reduces the incentives for other factor accumulation, further depressing output. Green GDP subtracts these costs from national income.

There are three complementarities between Green GDP and TFPE. First, TFPE is a welfare-relevant measure of efficiency under more general conditions than those under which Green GDP is welfare relevant. Green GDP calculations build on the proof in Weitzman (1976) that aggregate output is the annuity value of households' consumption path under the assumption of a constant interest rate, time-invariant technology, and a linear utility aggregator. We summarize his argument formally in Appendix A. TFPE, on the other hand, measures the marginal effect of a bundle of inputs on the present value of consumption, and is therefore welfare-relevant as long as the envelope condition applies (Proposition 1).[6]

Second, there is a conceptual ambiguity in country-level Green GDP from which TFPE does not suffer. In Weitzman (1976), national accounts are welfare-relevant because they measure the annuity value of current and future consumption (whether or not the externality imposed on foreign households is internalized). For a country's Green GDP to capture the welfare of its households, one should subtract the product of *global* emissions and the domestic cost of carbon from aggregate output. If the aim is instead to measure the effect of domestic production on the present value of global consumption, one should subtract the product of *domestic* emissions and the global cost of carbon (as in, e.g., Muller et al. 2011). TFPE faces no such choice: because it measures the marginal effect of an increase in the domestic use of inputs—and of the emissions they generate—on consumption, it should unambiguously be calculated with domestic emissions.

The final complementarity is that, in settings where the assumptions for Green GDP do hold and where the Muller et al. (2011) approach is followed, TFPE equals the Solow residual of Green GDP. This follows from equations (1) and (2):

[6] Productivity is furthermore a better welfare proxy than output if labor comes with disutility (Basu and Fernald 2002).

$$\frac{Y_t - E_t \times SCC_t}{F_t(\mathbb{K}_t)} = A_t D(S_t)\left(1 - \frac{E_t}{Y_t} SCC_t\right) = TFPE_t.$$

This result, in turn, means that TFPE is the correct variable to use in any growth accounting exercise for green national accounts. Proposition 1 further implies that such an exercise can distill the contribution of productivity to overall green growth without additional assumptions beyond those made to calculate TFP and the social cost of carbon.

2.5. Generalizations

Appendices C.1 and C.2 show that Proposition 1 extends both to settings with concave utility and to settings in which emissions have welfare costs. Appendix C.3 explains that it is straightforward to extend our framework to other variables that affect future output, such as non-carbon greenhouse-gas emissions, or investments with spillovers such as R&D.

3. Quantification

To calculate TFPE, we need data on carbon emissions, output, TFP, and the social cost of carbon. We obtain TFP and output from the Penn World Table (PWT, Feenstra et al. 2015), as it has near-global coverage through 2023. Carbon dioxide emissions come from the trade-adjusted series compiled from 1990 by the Global Carbon Project (Ritchie et al. 2023, Andrew and Peters 2024).[7]

We trace out TFPE at social costs of carbon of \$50, \$250, and \$900 per metric ton in 2017, expressed in 2017 dollars. Estimates in the literature differ widely because of differences in methodology, discounting, and whether they value domestic or global damages. Our aim is not to resolve these disagreements, but to ask how large the damages must be for TFPE to diverge meaningfully from TFP.

The first two values cover the range commonly used in cost-benefit analysis. U.S. policy used values up to \$48 during the second Obama administration and at the beginning of the Biden administration, rising to \$180 by 2023. Moore et al. (2024), synthesizing 1,823 estimates from 147 studies, report a central estimate of \$252 when broader damages are included (consistent with our framework, see Appendix C.2). We use \$900 to represent an upper-tail estimate from the literature, close to the estimate in Bilal and Känzig (2026), whose time-series approach implies substantially larger global damages. While their estimate is an outlier, the corresponding quantification of TFPE illustrates the effect of emissions on the path of productivity if damages are indeed large.

We do not include calculations for a social cost of carbon below \$50. While we could calculate TFPE based on significantly lower costs — e.g., the whole distribution of *domestic* carbon costs across countries, which can be substantially lower — this turns out to be redundant: the next section shows that, at \$50, the adjustment to productivity growth is already economically negligible.

[7] Appendix B.1 motivates the use of consumption-based emissions.

Finally, we allow the social cost of carbon to grow at 2.1% per year, the median rate across the models reported by Nordhaus (2017) and Prest et al. (2022). The cost grows because proportional damages apply to a growing economy, and because the marginal damages themselves might be time-varying. Below, we always refer to the social costs of carbon at their 2017 levels.

4. TFPE Estimates

This section answers our main question: does accounting for climate damages alter a country's productivity performance? We first examine growth rates and then turn to the level of TFP and TFPE.

4.1. Trends in TFPE Growth

We first show that adjusting for emissions only changes measured productivity growth meaningfully when climate damages are sufficiently large. In this case, TFPE in many advanced economies grows faster than TFP because improvements in emissions efficiency offset part of the slowdown in measured productivity. We illustrate this first for the U.S. before turning to international evidence.

Figure 2a compares conventional TFP growth, which shows the well-known productivity slowdown after 2005, with TFPE for the three values of the social cost of carbon. The effect of adjusting for emissions is negligible at a social cost of carbon of \$50 and modest at \$250. Rises in future consumption as a result of lower emissions are simply too small relative to the benefits of conventional productivity growth to alter the overall dynamics.

The picture changes dramatically at a \$900 social cost of carbon. Rather than exhibiting a slowdown after the mid-2000s, TFPE growth *rises* over time. The crossover occurs around 2005, precisely when conventional measures identify the beginning of the U.S. productivity slowdown. At this value of the SCC, improvements in emissions intensity more than offset weaker measured TFP growth. Average TFPE growth is identical before and after 2005 at a social cost of carbon of \$812.

Figure 2b assesses the drivers of TFPE growth by decomposing it into contributions from TFP, output, emissions, and the social cost of carbon. The contributions are obtained from discrete-time approximations to the partial derivatives of TFPE with respect to the variables:

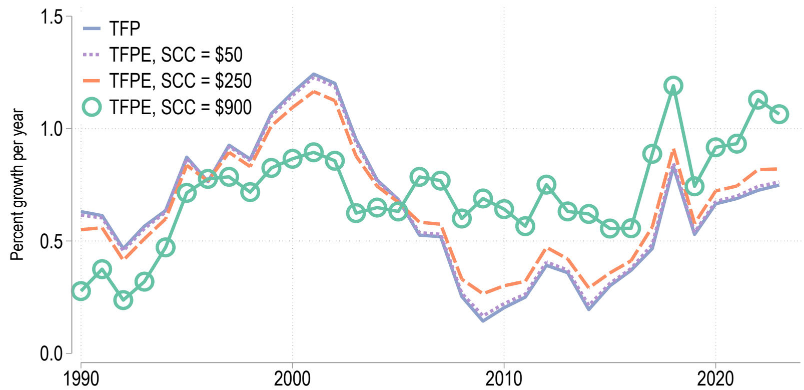
$$\frac{\Delta TFPE_t}{TFPE_{t-1}} \approx \frac{1}{TFPE_{t-1}}\Bigg[\left(1-\frac{E_{t-1}SCC_{t-1}}{Y_{t-1}}\right)\Delta TFP_t+\left(\frac{E_{t-1}SCC_{t-1}TFP_{t-1}}{Y_{t-1}^2}\right)\Delta Y_t \\ -\left(\frac{TFP_{t-1}SCC_{t-1}}{Y_{t-1}}\right)\Delta E_t-\left(\frac{E_{t-1}TFP_{t-1}}{Y_{t-1}}\right)\Delta SCC_t\Bigg].$$

We plot the decomposition using a social cost of carbon of \$900, but this choice only affects the scale of the vertical axis; the relative size of each component remains unchanged under different values.

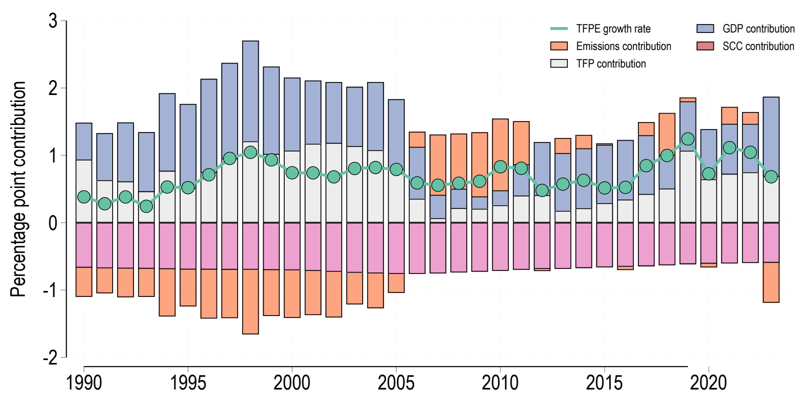
The figure shows that the contribution of emissions flips in sign at around the same time when TFP growth slows down: emissions rose until 2005, reducing TFPE growth, and fell in the years that followed. The social cost of carbon has a fairly stable negative effect, since it grows at a rate of 2.1%

Figure 2. Emissions-Adjusted Productivity Growth for the United States

A. Path of TFP and TFPE growth



B. Drivers of TFPE growth (SCC = $900)



Notes: Panel A plots the paths of TFP and TFPE growth for the United States between 1990 and 2023. To mitigate cyclical variation, each series is smoothed using a 7-year moving average. Panel B presents a stacked bar chart that decomposes TFPE growth (at a social cost of carbon of $900). Each bar gives the partial derivative of TFPE with respect to the respective variable, multiplied by the change in that variable, so that the sum of the bars equals the green-circled line.

per year. GDP contributes positively to TFPE in all years of the plot, although the contribution is minimal during the Global Financial Crisis, and lower in the 2010s than in earlier years.

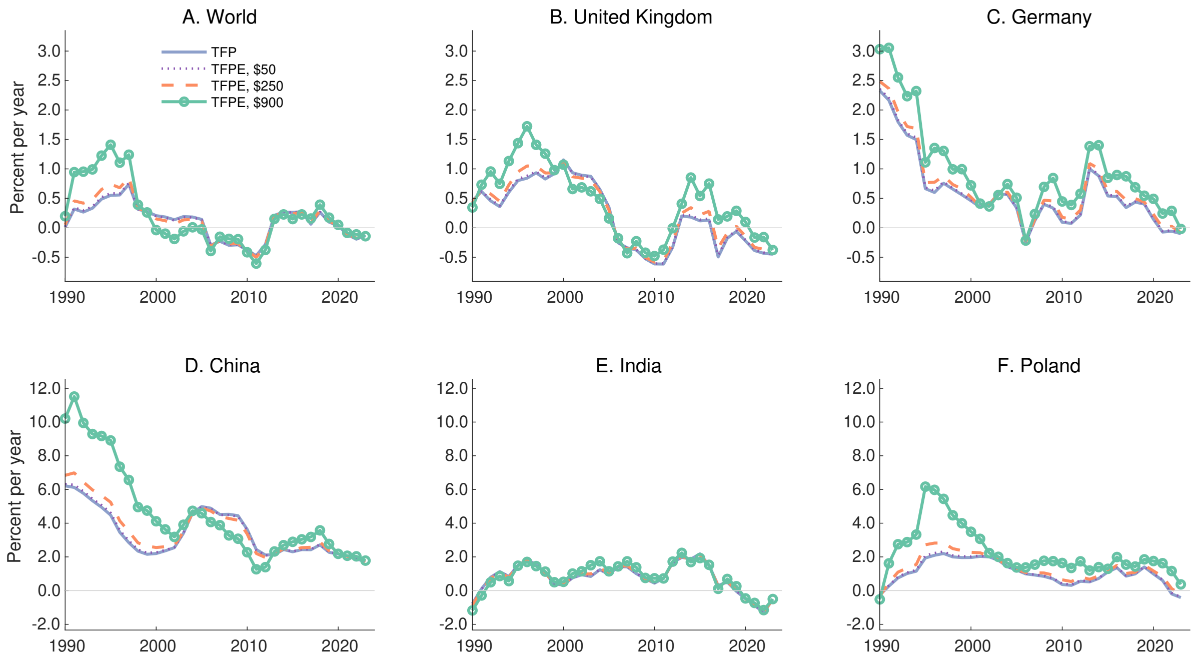
Figure 3 presents the equivalent analysis for the world as a whole and five selected economies. Across panels, TFPE is virtually indistinguishable from TFP when the social cost of carbon is $50, and the adjustment remains modest at $250, mirroring the results for the US. At a carbon cost of $900, the productivity patterns in TFPE space can differ qualitatively from measured TFP growth.[8]

World TFPE growth exceeds TFP growth in the early 1990s, falls below it in parts of the 2000s, and follows a similar pattern after the Global Financial Crisis.[9] The finding that world TFP and TFPE growth rates are similar in recent years might be surprising, given that emission intensity has

[8]We provide a table with TFPE estimates for all countries on http://www.maartenderidder.com/research.

[9]As there is no standard world-level productivity series, we compute it as the weighted average of country-level growth. See Appendix B.2. World TFP growth was particularly strong in the 1990s but slowed significantly in the 2000s as the share of low-productivity countries in global GDP rose.

Figure 3. TFP and TFPE growth in the world and in selected economies



Notes: The figure plots 7-year centered moving averages of TFP and TFPE growth for the world as a whole and five selected economies.

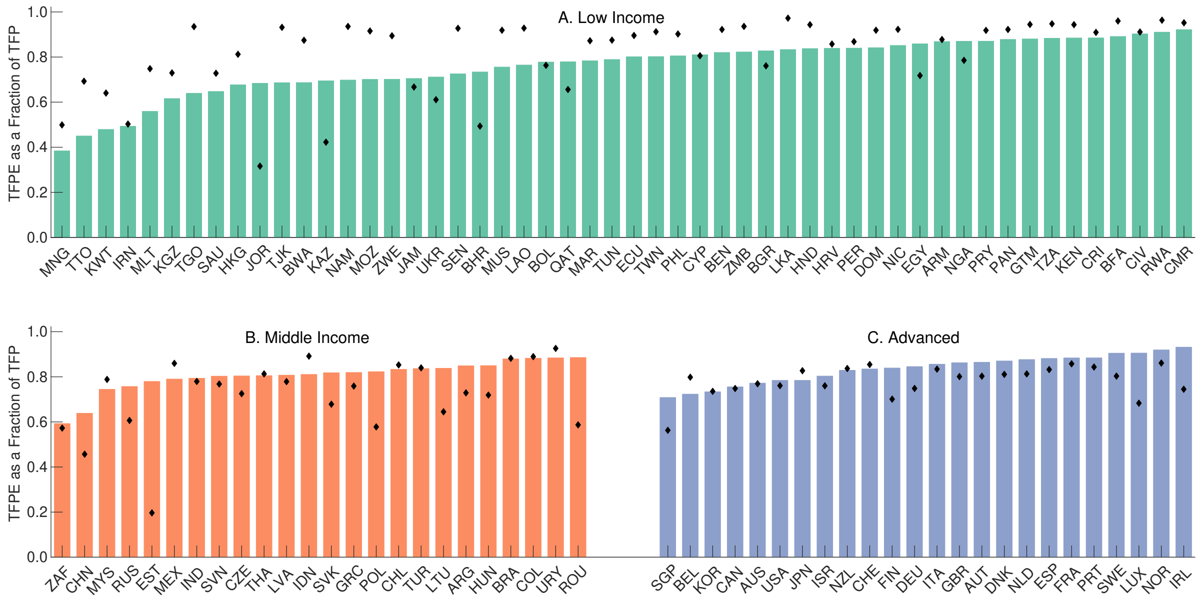
been declining at a global level. But TFPE growth depends on the change in the damage wedge, $(E/Y)SCC$, and, at the global level, the declining emissions intensity merely offsets the 2.1% annual increase in the marginal damage from emissions.

In many European economies, illustrated here by the United Kingdom and Germany, TFPE growth has generally exceeded TFP growth, and the wedge is substantial when evaluated at the high social cost of carbon. Their decarbonization started earlier than in the US, so a positive adjustment is already visible in the 1990s. It is also significant during the recovery from the Global Financial Crisis, which means that the "productivity puzzle" is smaller when TFPE is used.[10]

Transition economies such as China and Poland display large positive TFPE adjustments in the 1990s, reflecting rapid declines in emissions intensity during periods of structural transformation. For China, the high-cost TFPE series later moves closer to, and at times below, TFP as the pace of emissions-intensity improvement slows relative to the rise in the social cost of carbon. India is a notable example of a country where growth adjustment is close to zero (Panel E). That is due to the fact that the emissions intensity of Indian production fell at roughly the same pace as the social cost of carbon rose.

[10]The only advanced economies where TFP growth exceeded TFPE growth are Japan and South Korea.

Figure 4. The level gap between TFP and TFPE



Notes: The figure plots the $TFPE/TFP$ ratio, assuming the social cost of carbon is \$900. The bars show the latest available data (2023). The diamonds show data for 1990 (except Namibia, for which it is 1991, and Norway, where the emissions data begin in 2003).

4.2. Level Gap Between TFP and TFPE

We have thus far considered the wedge between the growth rates of TFPE and TFP. But TFPE can only grow faster than TFP if there is a gap between their *levels*: in an economy with net-zero carbon emissions, TFP and TFPE grow at identical rates. Focusing solely on growth can thus obscure that some countries already have low emissions intensity from the outset. We therefore calculate $TFPE/TFP = 1 - \frac{E}{Y}SCC$. This ratio equals one for an economy without emissions, and can be negative for an economy in which emissions generate climate damages exceeding GDP.

The global TFPE-to-TFP ratios are 0.986, 0.930, and 0.747 for a carbon cost of \$50, \$250 and \$900, respectively. This has a stark corollary: the value of the economic benefits of reducing global emissions to zero is equivalent to a one-off increase of 1.4%, 7% and 25.3%, respectively, in conventional productivity. Thus, only if one values climate damages at a moderate to high social cost of carbon are the economic benefits of climate policy meaningful in comparison to the benefits of TFP growth.

Turning to the rest of the world, Figure 4 plots the ratio of TFPE to TFP in 2023 (bars) and in 1990 (diamonds) across all countries in our sample. For readability, we only present the results for the social cost of carbon of \$900 – for lower costs, the ratio is commensurately closer to 1.

Two patterns stand out. First, TFPE lies below TFP everywhere, and the magnitude of the gap does not vary systematically across countries. Except for several low-income countries, including Mongolia, Trinidad and Tobago, and Iran, countries within each income group span the range from 0.6 to 0.9 in terms of the TFPE/TFP ratio. The U.S. TFPE over TFP ratio varies between 0.7 and 0.75, which means that the U.S. economy was 25% to 30% less productive once global climate damages (valued at a high cost of $900) are taken into account.

Second, there is a stark difference between advanced economies and low-income economies in terms of the longer-term direction of travel. The comparison between 1990 and 2023 reveals a broad upward shift in the TFPE/TFP ratio in advanced economies: most of the diamonds lie below the bars, indicating that the level gap has narrowed over time. In contrast, for most low-income economies, the gap has widened, consistent with the bell-shaped relationship between emissions and development, as documented in Arnaut et al. (2023).

5. Application: TFPE under Climate Policy Scenarios

In the final exercise, we illustrate TFPE's potential as an indicator for evaluating future climate policy. Such policy is challenged by the lack of easily understood measures of the benefits of climate action, in units that are comparable to the benefits of other policies. TFPE is a natural candidate to fill this gap. It can be used to compute the productivity-equivalent gains for any policy scenario, under any assumption about how climate policy and the greening of the economy affect traditional TFP, and for any value of the social cost of carbon consistent with those assumptions.[11]

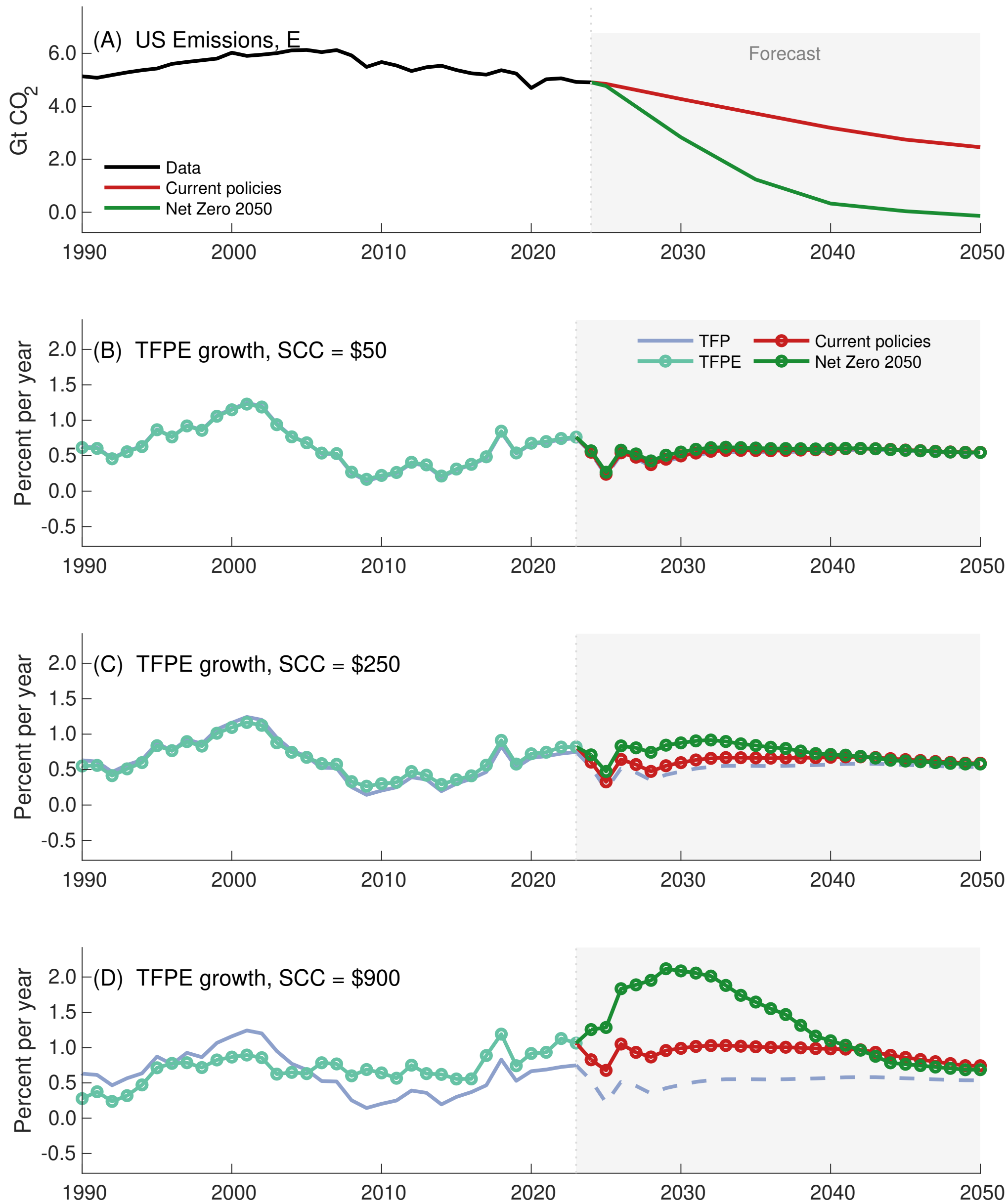
We illustrate this by adjusting the future path of U.S. TFP growth for emissions under the climate policies currently in place and in a scenario where carbon emissions fall to net zero by 2050. We take these two scenarios from the Network for Greening the Financial System's (NGFS) REMIND-MAgPIE model. "Current Policies" extrapolates 2024 policies and serves as the baseline. In this scenario, U.S. emissions roughly halve by 2050 (Panel A in Figure 5). The second, "Net Zero 2050", is an orderly transition in which U.S. net carbon emissions decline to zero by 2050 and halve around 2030. For TFP growth, we use baseline projections from the Congressional Budget Office's Long-Term Outlook for 2025–2050 and leave this projection unchanged when comparing policy scenarios.[12]

In contrast to our findings on historical productivity growth, future productivity adjustments can be very large even under the consensus social cost of carbon of $250 (Panel C in Figure 5). Under the Net Zero scenario and the $250 social cost of carbon, growth of TFPE is nearly *double* the baseline CBO TFP projection over 2025–2035. If the true social cost of carbon is closer to $900, the growth rate of TFPE is significantly different from that of TFP under either policy scenario (Panel D). Even under Current Policies, the growth of TFPE is about double that of TFP. In the Net Zero scenario, TFPE growth in the middle of the transition is about four times TFP growth.

[11] Note that, as in the earlier sections, the social cost of carbon refers to the marginal reduction in the present value of consumption that arises as a result of greater emissions. It does not refer to a carbon tax or carbon market price.

[12] Mehrotra (2024) notes that the raw TFP effects transitioning to net-zero (not counting climate benefits) are likely to be quantitatively small at less than 0.2 percent of the steady state *level* of output. The adjustment of annual growth rates would therefore be negligible. We adjust the CBO TFP growth projection to reflect the average wedge between the PWT and CBO TFP series, which arises because the PWT captures the entire economy while CBO's is confined to the non-farm business sector, and the CBO residualizes labor quality. Over 2025–2050, the CBO projects TFP growth averaging about 1.1% per year. The adjusted projection averages around 0.6% per year.

Figure 5. TFPE Growth in the United States in the Current Policies and Net Zero 2050 Scenarios



Notes: Panel A plots U.S. CO_2 emissions E (in Gt). The black line is realized data through 2024; from 2024 it splits into the NGFS Current Policies (red) and Net Zero 2050 (green) scenarios. Emissions are territorial (energy and industrial processes), from the NGFS Phase V REMIND-MAgPIE scenarios. Panels B, C and D plot 7-year moving averages of TFP and TFPE, under the assumption of SCC (in 2017) equal to \$50, \$250 and \$900, respectively.

These plots hold the TFP growth path fixed across scenarios. If transition costs do affect the path of TFP, the relative growth rate of TFPE would be *even greater*, making it even more relevant for productivity to be adjusted for emissions. More broadly, this exercise highlights that translating emissions into productivity units is likely to become more salient over time, as economies struggle with the climate challenge, consider policy options, and potentially transition to net zero.

6. Conclusion

We propose TFPE, a welfare-relevant productivity measure that subtracts from TFP the future consumption losses generated by current emissions. Building on Weitzman (1976) and the extensive macro-climate literature, we show that TFPE can be computed from TFP, emissions, output, and the social cost of carbon and that it coincides with the Solow residual of Green GDP. Historically, TFPE differs materially from TFP only when estimates of climate damages are high: at the upper end, the recent U.S. productivity slowdown disappears and cross-country comparisons change. TFPE growth vastly exceeds TFP growth in the 1990s at the world level at such social costs. By contrast, during a transition to net zero, TFPE can grow substantially faster than TFP even at conventional social costs of carbon. TFPE therefore provides a simple way to express the benefits of decarbonization in units that are comparable to those used to evaluate traditional growth-enhancing policies.

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‘Emissions-Adjusted Total Factor Productivity’ Online Appendix

Appendix A. TFPE and green accounting

In this appendix, we first review the insight of Weitzman (1976), which states that under specific conditions —- linear utility in consumption, no technological progress, a constant real interest rate, and a competitive equilibrium with no externalities – net national product represents the annuity value of welfare in competitive equilibrium. We then show how the damage function analysis on which we build connects to this insight, particularly how the intertemporal nature of TFPE recovers the welfare-relevant measure of productivity, at least within this stylized model. The philosophy of this exercise is to focus on an environment where Weitzman's insight holds exactly and then examine how the TFPE approach links to green, or comprehensive, accounting.

A.1. Review of the Weitzman (1976) insight

Notation is as follows. L is (constant) labor, N is a stock of natural (environmental) capital, E is emissions which is equal to the negative net investment in the stock of natural capital N: $\frac{\partial N(t)}{\partial t} = -E$. We denote with μ the price of a unit of natural capital. Let $\mathscr{S}(L,N)$ be the production possibilities set at time t. Following Weitzman (1976), time is continuous. Net national product (NNP), defined as national product net of the depreciation of production inputs, is given by the function

$$Y(L,N,\mu) := \max_{C,E\in\mathscr{S}(L,N)} C - \mu E,$$

where μ is the price of the (negative) investment in natural capital. Consider a dynamic, continuous-time competitive equilibrium with no externalities. We denote variables in the competitive equilibrium with asterisks. In such an equilibrium, we have

$$Y^*(t) := Y(L,N^*,p) = C^* - \mu E^* \tag{A.1}$$

$$\frac{\partial Y}{\partial N}\,|_* = r\mu - \dot{\mu}. \tag{A.2}$$

The first equation says that what is actually produced by the economy at any time maximizes its income: in other words, relative prices are equal to marginal rates of transformation. The second equation is the optimality condition for natural capital, which can be rewritten as $r = \frac{\partial Y/\partial N}{\mu} + \frac{\dot{\mu}}{\mu}$. In words, the required return is equal to the dividend rate plus capital gain.

The primary argument in Weitzman (1976) is that welfare in the competitive equilibrium at time t is the same as welfare that would be generated by a constant consumption path, with consumption equal to the (constant) $NNP(t)$ forever:

$$W^*(t) := \int_t^\infty e^{-r(s-t)} C^*(s) ds = \int_t^\infty e^{-r(s-t)} NNP(t) ds = \frac{Y^*(t)}{r}.$$

Thus, the current value of NNP is the annuity value of competitive equilibrium welfare:

$$Y^*(t) = r \int_t^\infty e^{-r(s-t)} C^*(s) ds = rW^*(t).$$

Proof. To see this, totally differentiate $Y(L, N^*, \mu)$; recalling that L is constant,

$$\frac{dY^*}{dt} = \frac{\partial Y^*}{\partial N^*} \frac{dN^*}{dt} + \frac{\partial Y^*}{\partial \mu} \frac{d\mu}{dt},$$

and note that $\frac{dN^*}{dt} = -E^*$ and $\frac{\partial Y^*}{\partial \mu} = -E^*$by the first competitive equilibrium equation above and the envelope theorem. Thus:

$$\frac{dY^*}{dt} = -(r\mu - \dot{\mu}) E^* + -E\dot{\mu} = -r\mu E^* = r(Y^*(t) - C^*(t)).$$

Solving this differential equation yields

$$Y^*(t) = r \int_t^\infty e^{-r(s-t)} C^*(s) ds.$$

A.2. Relationship between the social cost of carbon and μ

Recall that the competitive equilibrium above is efficient. Thus, we might anticipate that the competitive prices reflect the true social marginal rates of substitution. In the case of emissions of CO2, we might anticipate that μ is equal to the social cost of carbon. We now show more formally that this is indeed the case. Solving (A.2) we obtain

$$\mu(t) = \int_t^\infty e^{-r(s-t)} \frac{\partial Y}{\partial N}(s) ds.$$

Furthermore, we now combine this with the damage function specification for (net) output. Assume

$$Y = ALD(N) = ALD(S) \quad \dot{S} = -\dot{N} = E,$$

where L is (constant) labor, A is a constant productivity term, N is a stock of natural capital, S is the deviation of CO2, from the pre-industrial stock, $D(\cdot)$ is a damage function, with $D' \oint 0$. Then

$$\mu(t) = \int_t^\infty e^{-r(s-t)} ALD'(N(s)) ds = -AL \int_t^\infty e^{-r(s-t)} \frac{\partial D(S(s))}{\partial S(s)} ds =$$

$$= -AL \int_t^{\infty} e^{-r(s-t)} \frac{\partial D(S(s))}{\partial E(t)} \frac{\partial E(t)}{\partial S(s)} ds.$$

In this simple model we have $\frac{\partial E(t)}{\partial S(s)}$ is $1/\frac{\partial S(s)}{\partial E(t)} = 1/1 = 1$. Thus,

$$\mu(t) = -AL \int_t^{\infty} e^{-r(s-t)} \frac{\partial D(S(s))}{\partial E(t)} ds = SCC(t),$$

which follows from our definition of the SCC in the main text. So by Weitzman (1976), we should use $NNP := C^* - SCC \times E^*$as an income measure that is informative of welfare.

A.3. TFP and TFPE

We next show that TFPE is the welfare-relevant measure of productivity when output is measured through green NNP - that is, it is measured as output adjusted for depletion of natural capital.

TFP: If TFP was calculated in terms of the appropriately estimated net national product, then TFP would be the correct measure of productivity:

$$TFP \equiv \frac{\partial Y(t)}{\partial L(t)} = A(t)D(N(t)).$$

However, the way we traditionally measure productivity is with GDP. Consequently, TFP reported by statistical agencies worldwide is, in terms of the variables defined in the model here, given by:

$$\frac{\partial(Y(t) + \mu(t)E(t))}{\partial L(t)} = \frac{\partial Y(t)}{\partial L(t)} + \mu(t)\frac{\partial E(t)}{\partial L(t)} = \frac{\partial Y(t)}{\partial L(t)} + \mu(t)\phi(t),$$

where $\phi(t)$ satisfies $E(t) = \phi(t)L(t)$. This measure overestimates the welfare-relevant TFP by not subtracting the value of emissions that the economy generates.

TFPE: In the context of the model presented in this Appendix, we define TFPE as follows:

$$\begin{aligned}
TFPE(t) \equiv \frac{\partial V(t)}{\partial L(t)} &= \frac{\partial\left(\int_t^\infty e^{-r(s-t)}C(s)ds\right)}{\partial L(t)} = \frac{\partial\left(\int_t^\infty e^{-r(s-t)}\left(Y(s)+\mu E(s)\right)ds\right)}{\partial L(t)} \\
&= \frac{\partial\left(\int_t^\infty e^{-r(s-t)}\left(A(t)L(t)D(N(s))+\mu(s)E(s)\right)ds\right)}{\partial L(t)} \\
&= A(t)D(N(t)) + A(t)L(t)\int_t^\infty e^{-r(s-t)}\left(\frac{\partial D(N(s))}{\partial E(t)}\frac{\partial E(t)}{\partial L(t)}\right)ds + \mu(t)\frac{\partial E(t)}{\partial L(t)} \\
&= A(t)D(N(t)) + A(t)L(t)\int_t^\infty e^{-r(s-t)}\left(\frac{\partial D(N(s))}{\partial E(t)}\phi(t)\right)ds + \mu(t)\phi(t) \\
&= A(t)D(N(t)) + \phi(t)A(t)L(t)\int_t^\infty e^{-r(s-t)}\left(\frac{\partial D(N(s))}{\partial E(t)}\right)ds + \mu(t)\phi(t) \\
&= A(t)D(N(t)) - \mu(t)\phi(t) + \mu(t)\phi(t) = A(t)D(N(t))
\end{aligned}$$

This shows that TFPE is indeed the welfare-relevant measure of productivity. Our framework is thus consistent with and bridges the two canonical traditions in the climate literature: the green accounting literature and the literature on integrated assessment models and damage functions.

Appendix B. Data Appendix

B.1. Territorial versus trade-adjusted emissions

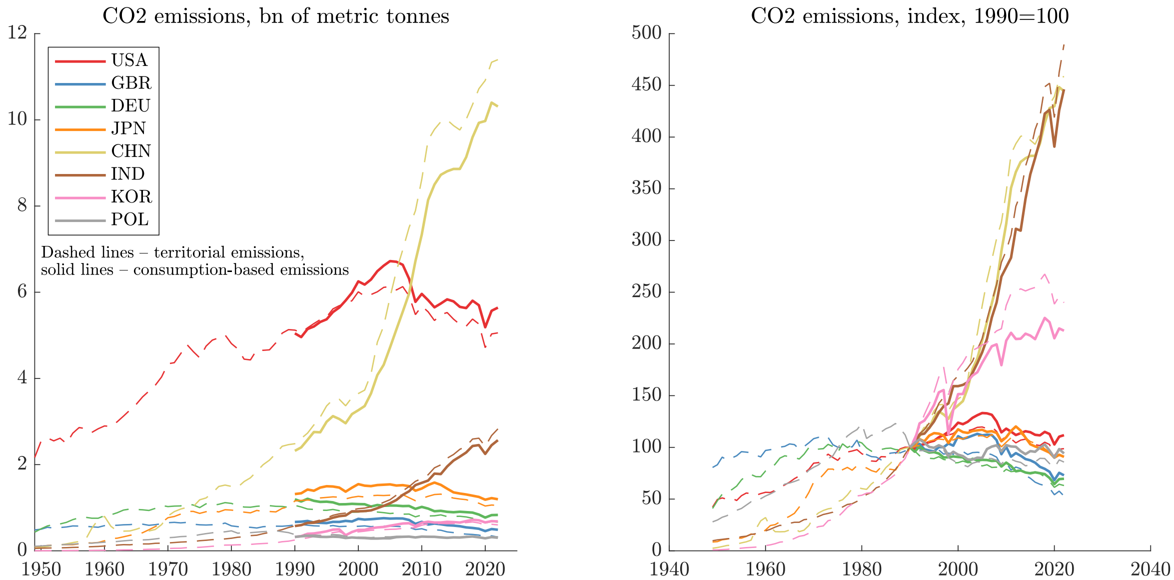
We rely on trade-adjusted emissions, also known as consumption-based emissions, to calculate TFPE. These measure the total amount of emissions involved with consumption in a country. This is in contrast to territorial emissions, also known as production-based emissions, which instead measure total emissions involved in domestic production. Both are equal at the global level. At the country level, consumption-based emissions exceed territorial emissions in many advanced economies, including the United States and most of Europe. High-export countries such as China instead feature higher territorial emissions than consumption-based emissions.

The use of consumption-based emissions is motivated by a simple extension of the framework. Rather than using the closed economy's emissions function, assume that emissions E_{it} in any country i are driven by a combination of domestic production and production in every other country in the world. Total emissions are given by

$$E_{it} = \sum_{j\in J}\phi_{ijt}F_{jt}(\mathbb{K}_{jt}),$$

where J denotes the set of countries in the world economy, including i. In this framework, emissions-adjusted productivity is given by

Figure A1. Carbon Dioxide Emissions in Selected Economies



Notes: This figure plots the path of annual territorial and consumption-based CO_2 emissions from the Global Carbon Project (Andrew and Peters 2024). The left-hand figure plots emissions in billions of metric tons across selected countries, the right-hand figure plots an index of emissions using 1990 as the base year.

$$TFPE_{it} = \frac{\partial C_{it}}{\partial F_{it}(\mathbb{K}_{it})} + \frac{\partial \mathrm{p}_{it}\mathbb{I}_{it}}{\partial F_{it}(\mathbb{K}_{it})} + \left(\frac{\partial \mathbf{V}_{it}}{\partial E_t}\left[\sum_{j\in J}\frac{\partial E_{jt}}{\partial F_t(\mathbb{K}_t)}\right]\right),$$

where E_t denotes global emissions, $E_t = \sum_{j\in J} E_{jt}$. Rewriting yields the familiar TFPE expression,

$$\begin{aligned} TFPE_{it} &= TFP_{it} - SCC_{it}\left[\sum_{j\in J}\phi_{jt}\right], \\ &= TFP_{it} - TFP_{it}\frac{\sum_{j\in J}\left(E_{jt} - \sum_{h\neq i}\phi_{jht}F_{ht}(\mathbb{K}_{ht})\right)}{Y_{it}}SCC_{it}, \\ &= TFP_{it}\left(1 - \frac{\tilde{E}_{it}}{Y_{it}}SCC_{it}\right), \end{aligned}$$

where $\tilde{E}_{it} \equiv \sum_{j\in J}\left(E_{jt} - \sum_{h\neq i}\phi_{jht}F_{ht}(\mathbb{K}_{ht})\right)$ equals trade-adjusted or consumption-based emissions.

An implication of using trade-adjusted emissions is that a country's TFPE will increase if the emissions-intensities of its imports decline, even when domestic technology is unchanged. In practice, this mechanism is responsible for little of the overall variation of TFPE growth, given the high correlation of trends in territorial and trade-adjusted emissions (see Figure A1).

B.2. Constructing world TFP series

World TFP is built from country-level total factor productivity in the Penn World Table 11.0. For each country i we form a TFP level $A_{it} = \mathrm{CTFP}i, 2021 \times \mathrm{RTFPNA}_{it}$, which scales the real TFP index at constant national prices (RTFPNA, capturing TFP growth within a country over time) by the cross-country-comparable TFP level in 2021 (CTFP, capturing differences in levels across countries). World TFP growth is then the GDP-weighted aggregate of these country series, $\Delta \ln A_t^W = \sum_i \omega_{it}, \Delta \ln A_{it} + \sum_i \Delta\omega_{it} \ln A_{i,t-1}$ where ω_{it} is country i's share of world GDP (expenditure-side real GDP at chained PPPs). The first term is a within-country contribution, the GDP share-weighted average of national TFP growth; the second is a reallocation term that captures how shifts in GDP shares toward higher- or lower-TFP countries move the world aggregate, independently of any within-country productivity change.

Appendix C. Extensions

We next present three extensions. The first covers non-consumption costs of climate change, such as the utility cost of higher mortality rates. The second derives TFPE for concave utility. The third explains that it is straightforward to extend our framework to other variables that affect future output, such as research and development. Finally, we discuss how TFPE relates to Green national accounts.

C.1. Non-consumption costs of climate change

We have thus far derived TFPE without taking into account any other utility costs of climate change. It is straightforward to show that the expression for TFPE in Proposition 1 can be applied to broader costs, as these simply imply a different definition of the social cost of carbon. Say climate damages impose a non-consumption cost $\Omega(S_t)$, so that welfare net of the damages equals

$$\widetilde{\boldsymbol{V}}_t = \mathbb{E}_t \left[\sum_{s=0}^{\infty} \prod_{k=t}^{t+s} \beta_k \left(C_{t+s} - \Omega(S_{t+s}) \right) \right].$$

An example of what might be included in $\Omega(S_t)$ is a change in old-age mortality, which has large utility costs beyond the direct effect of death on consumption (see, e.g., Carleton et al. 2022). Other forms of environmental progress, such as reduced pollution and improvements in air quality, in the spirit of Muller et al. (2011), can also be modeled along these lines.

Defining emissions-adjusted productivity as the change in the present value of consumption net of climate costs, the new expression for TFPE is largely unchanged from Proposition 1:

$$\begin{aligned} TFPE_t \equiv \frac{\mathrm{d}\, \widetilde{\boldsymbol{V}}_t}{\mathrm{d}\, F_t(\mathbb{K}_t)} &= \frac{\partial \widetilde{\boldsymbol{V}}_t}{\partial C_t} \frac{\partial C_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial \widetilde{\boldsymbol{V}}_t}{\partial \mathrm{p}_t \mathbb{I}_t} \frac{\partial \mathrm{p}_t \mathbb{I}_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial \widetilde{\boldsymbol{V}}_t}{\partial E_t} \frac{\partial E_t}{\partial F_t(\mathbb{K}_t)}, \\ &= TFP_t \left(1 - \frac{E_t}{Y_t} \widetilde{SCC}_t \right). \end{aligned}$$

In words, the broader costs of climate yield an unchanged expression for TFPE but require an alternative definition of the social cost of carbon, which now includes the marginal increase in the present value of non-consumption climate damages due to carbon dioxide emissions.

C.2. Utility

Proposition 1 presents the expression for TFPE as the marginal effect of a bundle of inputs on the present value of consumption. It is also feasible, however, to use the expression for TFPE in Proposition 1 when TFPE is defined as the marginal effect of a bundle of inputs on the present value of utility. Assuming standard time-separable preferences over consumption and exponential discounting at the constant rate β, we define utility and the related measure of TFPE as follows:

$$\boldsymbol{U}_t = \mathbb{E}_t\left[\sum_{s=0}^{\infty}\beta^s u\left(C_{t+s}\right)\right] \quad , \quad TFPE_t \equiv \frac{\mathrm{d}\,\boldsymbol{U}_t}{\mathrm{d}\,F_t(\mathbb{K}_t)}\frac{1}{u'(C_t)}, \tag{A.3}$$

where $u(\cdot)$ satisfies the usual properties. We divide the productivity index at time t by the marginal utility of consumption, in order to measure productivity in consumption units. This is a common approach to enable utility comparisons in interpretable units (see, for instance, Adhami et al. 2024).

The resulting expression for TFPE that we derive in (5) is largely unaltered. The sole substantive change is that the final term in the equation, which captures the present value of climate damages, now discounts climate damages with a specific stochastic discount factor:

$$\frac{\partial \boldsymbol{V}_t}{\partial E_t}\frac{1}{u'(C_t)} = \mathbb{E}_t\left[\sum_{s=1}^{\infty}\beta^s \frac{u'(C_{t+s})}{u'(C_t)}\frac{\mathrm{d}\,C_{t+s}}{\mathrm{d}\,E_t}\right],$$

where the expression on the right is a special case of the SCC as defined in Proposition 1: the stochastic discount factor is now pinned down by the levels of consumption and the derivative of the utility function. Beyond this, the other terms in (5) are unchanged. The first partial derivative is unchanged because we divide the productivity index by marginal utility. As long as competitive investment prices reflect the (stochastically discounted) present value of their effect on consumption, the second partial derivative is also unchanged. Thus, imposing a utility function when calculating TFPE merely imposes additional structure on the social cost of carbon.

C.3. Adjusting productivity for other variables

The framework can be readily applied in settings where variables other than carbon dioxide emissions alter future consumption. Non-carbon greenhouse gasses are obvious examples, but so are investments that are not correctly priced in national accounts, such as education or research and development. Denoting the set of these "carbon-like" variables by X_t, we find

$$\begin{aligned}\frac{\mathrm{d}\,\boldsymbol{V}_t}{\mathrm{d}\,F_t(\mathbb{K}_t)} &= \frac{\partial C_t}{\partial F_t(\mathbb{K}_t)} + \frac{\partial \mathrm{p}_t \mathbb{I}_t}{\partial F_t(\mathbb{K}_t)} + \sum_{X^j\in X}\left(\frac{\partial \boldsymbol{V}_t}{\partial X_t^j}\frac{\partial X_t^j}{\partial F_t(\mathbb{K}_t)}\right),\\ &= TFP_t\left(1 - \sum_{X^j\in X} -\frac{\partial X_t^j}{\partial Y_t}\frac{\partial \boldsymbol{V}_t}{\partial X_t^j}\right).\end{aligned} \tag{A.4}$$

Thus, if the relationship between X_t^j and both aggregate output and the present value of consumption is known, we can adjust productivity in a similar fashion to how we adjust for carbon in Proposition 1. Our application to carbon seems particularly relevant, both because of the recent comovement of TFP and carbon emissions (Figure 1), and because there exists an abundance of estimates of the social cost of carbon – which makes the adjustment for carbon emissions feasible to implement.

A similar logic can be applied to investment goods that are included in aggregate output but that are mispriced, in the sense that their market price does not fully encode the present value of future consumption to be derived from it – such as R&D. In that case, the final derivative $\partial \boldsymbol{V}_t / \partial X_t^j$ of the adjustment term in (equation A.4) would equal the wedge between the input's observed and efficient price.