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Can Omitted Carbon Abatement Explain Productivity Stagnation?

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ABSTRACT

Explaining the secular stagnation of productivity growth is a widely recognized challenge to economists and policymakers. One potentially important explanation without much attention concerns the ongoing low-carbon transition. This paper explores whether considering greenhouse gas emissions can explain productivity stagnation in OECD countries. We propose a quantile shadow-price Fisher index to gauge green total factor productivity (TFP) based on the newly developed penalized convex quantile regression approach. The quantile shadow-price Fisher index requires neither the real price data nor an *ad hoc* choice of quantiles and allows the quantiles to move in the inter-period sample. An empirical application to 38 OECD countries during 1990–2019 demonstrates that the measured productivity growth is considerably higher when the GHG emissions are accounted for. For countries that have reduced GHG emissions most actively, the average green TFP growth rate could double the conventional TFP growth. The impacts of ignoring human capital and different representations of fixed capital on green TFP growth are also discussed explicitly.

JEL Classification: C14, D24, O4

1 | Introduction

The secular stagnation of productivity growth has occurred in virtually all Western countries since the financial crisis that started in the US in 2008 and subsequently led to the European debt crises and the period known as the Great Recession (see, e.g., Syverson 2017; Crafts 2018). Several possible explanations for productivity stagnation have been suggested in economics.

Firstly, since technological progress is traditionally seen as the main driver of productivity growth, it seems natural that the recent stagnation may be due to the slowdown of innovations.

Most notably, Gordon (2012) and Bloom et al. (2020) have suggested that new ideas get harder to find over time. As previous innovations have already been utilized, it is increasingly more difficult to generate genuine innovations that would further boost productivity growth. Bloom et al. (2020) provide evidence that links declining innovation to productivity stagnation.

Secondly, since most countries have unemployment and underutilized productive capacity, aggregate productivity slowdown could also relate to inefficient allocation of resources in the economy. Empirical work in the US and Europe suggests that business dynamism (e.g., firm entry, job creation, or job

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turnover) has been declining (see, e.g., Decker et al. 2016; Grossman et al. 2017), which can slow down productivity growth. Further, De Loecker et al. (2020) suggest that there have been rising markups, which further suggests that the market power of firms has been increasing. Such increasing market power is connected to productivity slowdown. Both declining business dynamism and rising markups can contribute to the misallocation of resources. Previous misallocation studies (e.g., Hsieh and Klenow 2009; Restuccia and Rogerson 2017) focused on comparing developing countries with the US, but during the current productivity stagnation it has been suggested that misallocation of resources might have something to do with the declining productivity and it might be related to the previous two explanations. For example, increasing market power and markups can lead to inefficient allocation of resources.

The third type of explanation refers to measurement challenges in total factor productivity (TFP). For example, the digital economy provides new goods such as information and entertainment services free of charge (e.g., Brynjolfsson et al. 2021). Since free digital services and improved quality of services are not included in the conventional national accounts, measured productivity growth can be downward biased due to mismeasurement.

One potentially important explanation for productivity stagnation, which relates to the broader theme of mismeasurement but has thus far attracted little attention, hinges on the ongoing transition to mitigate climate change. Specifically, reducing greenhouse gas (GHG) emissions requires massive capital investments and innovation efforts, which are included in the measured capital stock (or capital services) and labor inputs. However, such inputs do not contribute to the measured GDP. Since the conventional TFP measures ignore the social benefits of GHG abatement, the measured TFP can slow down when the inputs of the GHG abatement are included, but the outputs are excluded.

The purpose of this paper is to explore whether considering GHG emissions can explain productivity stagnation in OECD countries. Our first contribution is to empirically investigate the impacts of GHG emissions, fixed capital, and human capital on productivity growth. We measure productivity growth with and without GHG emissions, compare green TFP growth based on either capital stocks or capital services and calculate green TFP growth with and without human capital. The results confirm that the measured productivity growth is considerably higher when the GHG emissions are accounted for. For countries that have reduced GHG emissions most actively, the average green TFP growth rate could double the conventional TFP growth. Further, the choice of fixed capital and human capital would also have non-negligible impacts on green TFP growth.

To achieve our main purpose, the second contribution of this paper is to construct a novel quantile shadow-price Fisher index to gauge green TFP growth. The proposed quantile shadow-price Fisher index does not require the real price data for input-output variables and can avoid an *ad hoc* choice of quantiles which may lead to different productivity estimates and allow quantiles to move in the inter-period sample.¹

To operationalize the proposed index, the third contribution of this paper is to develop a penalized convex quantile regression

(CQR) approach to estimate shadow prices. In doing so, we regularize the CQR approach by adding an extra regularization term on subgradients to increase the convexity of the objective function. Compared to the conventional full frontier approach, penalized CQR can guarantee the uniqueness of estimated shadow prices and take inefficiency into account explicitly. Furthermore, the proposed approach is more robust to outliers and heterogeneity by inheriting the appealing features from quantile regression.

The rest of the paper is organized as follows. The next section presents a motivating example. Section 3 introduces the Fisher ideal TFP index and the shadow-price Fisher index and proposes the quantile shadow-price Fisher index. The newly developed penalized CQR approach is presented in Section 4. Section 5 describes the data and variables and discusses the impact of GHG emissions on productivity estimates. Section 6 further discusses green productivity estimates with alternative capital and labor specifications. Section 7 concludes this paper with future research avenues. A formal proof, a more detailed literature review, additional figures and tables, and shadow price estimates are provided in the [Online Supporting Information](#).

2 | A Motivating Example

To gain insight, we begin with a specific industry-level example to illustrate the main ideas. In recent decades, the energy industry in Finland has experienced rapid technological and structural change, together with a massive investment in renewable wind and solar energy. The GHG emissions of this industry peaked in 2003, but decreased by 65 percent by the year 2020. The purpose of this section is to illustrate how the conventional measures of TFP fail to capture the technological progress targeted at reducing emissions.

The thick black line in Figure 1 plots the development of conventional TFP in Finland's electricity industry in the years 1995–2019 according to the standard growth accounting method (Bontadini et al. 2022).² Despite the rapid diffusion of technological innovations in renewable wind and solar energy and the substitution of fossil fuels by renewable biofuels in the district heat and industrial heat production, the conventional TFP measure indicates a declining trend in productivity since 2003. The average yearly productivity change in the years 2003–2019 was –2.3 percent. Since the output of energy has remained rather constant over time, the negative TFP trend is due to the capital investment in renewable energy generation.

The simplest thinkable fix would be to adjust the growth accounting TFP measures for the GHG emissions. Using industry-level data from Statistics Finland,³ we can simply subtract from the total value added of the industry a hypothetical social cost of the GHG emissions to estimate green TFP. To this end, we also need an estimate of the unit cost of GHG. In this example, we rely on the OECD's midpoint estimate for carbon costs, which was €60 per tonne in 2020 (considered as a low-end estimate for the year 2030).⁴ For the sake of illustration, we also consider unit costs of €40 per tonne and €80 per tonne.

The green TFP lines (in green color) in Figure 1 illustrate how increasing the unit cost of GHG from zero toward the OECD's

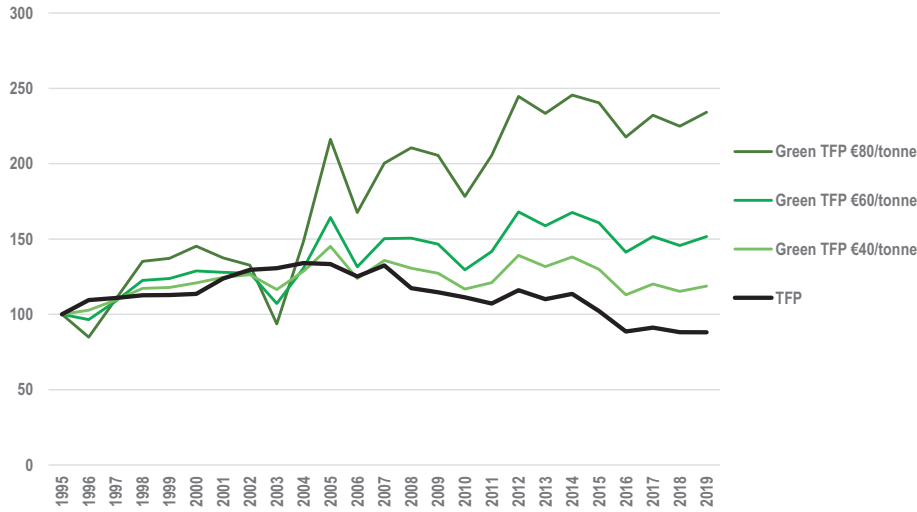


FIGURE 1 | Conventional TFP and green TFP in Finland's energy industry in 1995–2019.

midpoint estimate and beyond results in a notable increase in green TFP. Setting the unit cost of GHG to €40 per tonne already suffices to turn the declining TFP into a modest green TFP growth. Using the OECD midpoint estimate of €60 per tonne results with the average yearly green TFP growth of 2.8 percent in 2003–2019. If the unit cost is set at €80 per tonne, the corresponding average yearly growth rate is 8.8 percent.

This example also helps to illustrate the sensitivity of the green TFP estimates to the unit cost of GHG. In practice, a more objective estimation of the social cost of GHG proves a very challenging task. Moreover, climate policy involves various types of policy measures, including investment and innovation subsidies, emissions taxes, tradeable emissions permits, as well as more conventional command and control instruments, which may distort the market prices of green capital goods. These observations motivate us to consider an alternative approach that relies on the marginal products of GHG and factors of production, referred to as *shadow prices*.

3 | Quantile Shadow-Price Fisher Index

This section starts by reviewing the Fisher ideal TFP index, the Malmquist TFP index, and the shadow-price TFP index. Subsequently, a new quantile shadow-price Fisher index is proposed. Suppose there are I observations, indexed by $i = 1, \dots, I$. For each observation i , $\mathbf{y} = (y_{i1}, \dots, y_{in})' \in \mathbb{R}_{++}^n$, $\mathbf{b} = (b_{i1}, \dots, b_{ij})' \in \mathbb{R}_{++}^j$, and $\mathbf{x} = (x_{i1}, \dots, x_{im})' \in \mathbb{R}_{++}^m$ denote the desirable output, undesirable output, and input quantity vectors, respectively; $\mathbf{p} = (p_1, \dots, p_n)'$ and $\mathbf{w} = (w_1, \dots, w_m)'$ are the associated desirable output and input price vectors, respectively. For the sake of inter-period comparison, notations 0 and 1 indicate the base period and target period, respectively.

A TFP index is typically defined as the ratio of the output quantity index and input quantity index. Accordingly, the Fisher ideal TFP index can be stated as

$$F(\mathbf{p}^{0,1}, \mathbf{w}^{0,1}, \mathbf{y}^{0,1}, \mathbf{x}^{0,1}) \equiv \frac{F_o(\mathbf{p}^{0,1}, \mathbf{y}^{0,1})}{F_i(\mathbf{w}^{0,1}, \mathbf{x}^{0,1})} \quad (1)$$

$$F_o(\mathbf{p}^{0,1}, \mathbf{y}^{0,1}) \equiv \left[\frac{\mathbf{p}^0 \mathbf{y}^1}{\mathbf{p}^0 \mathbf{y}^0} \times \frac{\mathbf{p}^1 \mathbf{y}^1}{\mathbf{p}^1 \mathbf{y}^0} \right]^{1/2} \quad (2)$$

$$F_i(\mathbf{w}^{0,1}, \mathbf{x}^{0,1}) \equiv \left[\frac{\mathbf{w}^0 \mathbf{x}^1}{\mathbf{w}^0 \mathbf{x}^0} \times \frac{\mathbf{w}^1 \mathbf{x}^1}{\mathbf{w}^1 \mathbf{x}^0} \right]^{1/2} \quad (3)$$

where $F_o(\mathbf{p}^{0,1}, \mathbf{y}^{0,1})$ and $F_i(\mathbf{w}^{0,1}, \mathbf{x}^{0,1})$ are the Fisher ideal output and input quantity indices, respectively.

The Fisher ideal TFP index requires neither estimation nor assumption on optimizing behavior, which is particularly convenient at the macro-level (e.g., countries, regions). In practice, however, the Fisher ideal TFP index requires market prices of all inputs and outputs (i.e., \mathbf{p} and \mathbf{w}) that are not always reliable or available. For example, if a market faces imperfect competition (e.g., natural monopolies) or government interventions (e.g., taxes, subsidies, tariffs), the prices of inputs or outputs would greatly deviate from their actual market prices. Notably, in the case of measuring green productivity (or environmental productivity), the non-market goods and services are modeled as inputs or outputs, but their market prices are notoriously hard to measure.

Alternatively, the Malmquist TFP index is also widely used to measure TFP growth (see, e.g., Jeon and Sickles 2004; Zhou 2018; Odeck and Schøyen 2020). For instance, the standard input-oriented Malmquist TFP index is defined as

$$M(\mathbf{y}^{0,1}, \mathbf{x}^{0,1}) \equiv \left[\frac{D_i^0(\mathbf{y}^0, \mathbf{x}^0)}{D_i^0(\mathbf{y}^1, \mathbf{x}^1)} \times \frac{D_i^1(\mathbf{y}^0, \mathbf{x}^0)}{D_i^1(\mathbf{y}^1, \mathbf{x}^1)} \right]^{1/2} \quad (4)$$

where $D_i^t(\mathbf{y}, \mathbf{x}) = \sup\{\theta > 0 : (\mathbf{x}/\theta, \mathbf{y}) \in \mathcal{T}\}$ denotes the input distance function characterizing the production possibility set \mathcal{T} of period t ($t \in \{0, 1\}$).

Färe and Grosskopf (1992) demonstrate that if one assumes constant returns to scale (CRS), profit maximization, and allocative efficiency of inputs \mathbf{x} and outputs \mathbf{y} in both periods, the Malmquist TFP index (4) equals the Fisher ideal TFP index (1). However, Balk (1993) convincingly argues that these conditions

are so strong that they are unlikely to be fulfilled in practice. Under slightly milder conditions, the Malmquist TFP index can reasonably approximate the Fisher ideal TFP index, and vice versa, even if the prices and technology change (Balk 1993).

Kuosmanen et al. (2004) propose an intermediate route between the Fisher and Malmquist TFP indices by introducing the following shadow-price Fisher TFP index.

$$F_s(\rho^{0,1}, \omega^{0,1}, y^{0,1}, x^{0,1}) \equiv \left[\frac{\rho^0 y^1}{\rho^0 y^0} \times \frac{\rho^1 y^1}{\rho^1 y^0} \right]^{1/2} / \left[\frac{\omega^0 x^1}{\omega^0 x^0} \times \frac{\omega^1 x^1}{\omega^1 x^0} \right]^{1/2} \quad (5)$$

where $\rho = (p_{i1}, \dots, p_{in})'$ and $\omega = (w_{i1}, \dots, w_{im})'$ are the desirable output and input shadow-price vectors. Note that there are alternative interpretations of the shadow price in the literature (Kuosmanen and Zhou 2021). In this paper, we interpret the shadow prices ρ and ω as the subgradients of \mathcal{T} to y and x , respectively.

Formally, we have the following equivalence relation between the Fisher ideal TFP index and the shadow-price Fisher TFP index.

Theorem 1. *The shadow-price Fisher TFP index (5) and the Fisher ideal TFP index (1) are equivalent, if the shadow prices are unique and the allocative efficiency condition is held.*

Proof. See proof in Kuosmanen et al. (2004). □

There are well-known measurement issues with labor and capital. Quality of labor input depends on education and experience. The capital stock is an aggregate of various types of buildings, machinery, and increasingly intangible assets. Further, capital investment is inherently risky.⁵ Regarding the prices, in many countries, the labor markets have frictions, and hence, the average wage rate and its change over time do not necessarily capture the marginal product (see, e.g., Frank 1984; Lee and Saez 2012; Webber 2015). For capital inputs, De Loecker et al. (2020) present evidence about growing markups and monopoly power, which can also affect the accounting measures of capital stock and capital services. Therefore, using shadow prices instead of market prices for inputs can help mitigate the negative effects of the low quality of price data for some countries.

When inputs x are not allocated efficiently, the price-based Fisher index (i.e., the Fisher ideal TFP index) may not accurately reflect the true cost of producing the desired output level, as it does not consider the opportunity cost of allocating resources away from their best alternative use. If prices are distorted by market failures, the shadow prices that capture the tradeoffs and substitution possibilities between inputs and outputs seem more relevant index weights.

Nevertheless, the shadow-price Fisher TFP index has some practical limitations. First, it is not immediately obvious how the shadow-price Fisher TFP index can be applied to measure green TFP growth when considering environmental bads. Second, the shadow prices ρ and ω are generally non-unique in the conventional frontier estimation, leading to an inaccurate approximation from the shadow-price TFP index to the Fisher ideal TFP index (Balk 1993; Kuosmanen et al. 2004). Third, while the

shadow-price Fisher index is easy to compute whilst remaining consistent with the economic theory, it may be sensitive to random noise, heteroscedasticity, and outliers. This is because the estimated shadow prices merely rely on the conventional full frontier (e.g., the DEA frontier). Moreover, the information on inefficiency is usually neglected in shadow pricing environmental bads.

To mitigate the effects of these potential biases on green TFP measure, we extend the shadow-price Fisher index (5) to a more generalized setting, develop an approach to ensure the uniqueness of shadow price estimates and take the inefficiency explicitly into account. Specifically, we propose the following quantile shadow-price Fisher index.

$$F_s^b(\tilde{\rho}^{0,1}, \tilde{\delta}^{0,1}, \tilde{\omega}^{0,1}, y^{0,1}, x^{0,1}, b^{0,1}) \equiv \left[\frac{\tilde{\rho}^0 y^1 - \tilde{\delta}^0 b^1}{\tilde{\rho}^0 y^0 - \tilde{\delta}^0 b^0} \times \frac{\tilde{\rho}^1 y^1 - \tilde{\delta}^1 b^1}{\tilde{\rho}^1 y^0 - \tilde{\delta}^1 b^0} \right]^{1/2} / \left[\frac{\tilde{\omega}^0 x^1}{\tilde{\omega}^0 x^0} \times \frac{\tilde{\omega}^1 x^1}{\tilde{\omega}^1 x^0} \right]^{1/2} \quad (6)$$

where $\tilde{\rho}$, $\tilde{\delta}$, and $\tilde{\omega}$ are the quantile-based, locally estimated shadow prices for desirable outputs, undesirable outputs, and inputs, respectively. The local estimation of these shadow prices using quantile functions is introduced and discussed in the next section.⁶ The value of F_s^b above (below) unity reveals green TFP growth (decline). Note that when introducing the undesirable outputs in productivity measure, their effects are subtracted from the desirable outputs in the quantile shadow-price Fisher index (6), leading to a higher productivity estimate in comparison with a situation where undesirable outputs b are omitted. It is because even though the adjusted $\tilde{\rho}' y' - \tilde{\delta}' b'$ ($t \in \{0, 1\}$) is obviously smaller than $\tilde{\rho}' y'$, the change $(\tilde{\rho}' y' - \tilde{\delta}' b') / (\tilde{\rho}' y' - \tilde{\delta}' b')$ tends to higher than $\tilde{\rho}' y' / \tilde{\rho}' y'$ when the undesirable outputs b decrease over time, i.e., $b^0 > b^1$.

When x and b are not allocated efficiently (from the societal point of view), the shadow prices still capture the tradeoffs between inputs and outputs whereas the market prices are distorted. For undesirable outputs such as GHG emissions, there do exist markets for tradeable permits, but the scarcity of permits is artificially created by government regulation. The market price of emission permits would reflect the true social cost of GHG only under the strong assumption that the government regulation is socially optimal. However, the markets for tradeable permits do not cover all regions and all industries, even in those countries where markets for tradeable permits exist.

If we recognize the need to shadow price the GHG emissions, for the sake of consistency, it seems better to apply the shadow prices for other inputs as well. For green TFP and TFP, we mainly care about the relative proportions of shadow prices and their change over time, not the absolute magnitudes.

To pave the way to empirical estimation, the following result concerning price normalizations is worth noting.

Lemma 1. *Choosing desirable output y_1 as a numeraire and normalizing all shadow prices of period t by the corresponding $\tilde{\rho}_1^t$ does not affect the quantile shadow-price Fisher index F_s^b , that is $F_s^b(\tilde{\rho}^0/\tilde{\rho}_1^0, \tilde{\rho}^1/\tilde{\rho}_1^1, \tilde{\delta}^0/\tilde{\rho}_1^0, \tilde{\delta}^1/\tilde{\rho}_1^1, \tilde{\omega}^0/\tilde{\rho}_1^0, \tilde{\omega}^1/\tilde{\rho}_1^1, y^{0,1}, x^{0,1}, b^{0,1}) = F_s^b(\tilde{\rho}^0, \tilde{\rho}^1, \tilde{\delta}^0, \tilde{\delta}^1, \tilde{\omega}^0, \tilde{\omega}^1, y^{0,1}, x^{0,1}, b^{0,1})$.*

Proof. See the Online Appendix A.1. □

This result demonstrates that, without a loss of generality, we can choose one of the desirable outputs as a numeraire good and express shadow prices of all other outputs and inputs in terms of the numeraire. This result is particularly convenient in applications that only include a single desirable output such as the GDP.

4 | Quantile Function Estimation

To estimate the quantile shadow-price Fisher index (6), in this section we develop penalized CQR to obtain the robust and unique shadow prices at each quantile and then apply this local estimation strategy to derive $\tilde{\rho}$, $\tilde{\delta}$, and $\tilde{\omega}$.⁷ The quantile shadow-price Fisher index (6) thus can enable shadow pricing environmental bads with the efficiency level of each observation accounted.

Kuosmanen and Zhou (2021) introduced the CQR approach for estimating shadow prices and marginal abatement costs in the general multi-input multi-output setting using the directional distance function (Chung et al. 1997). In the special case that includes only a single desirable output y_1 , as in our empirical application, we can utilize Lemma 1 and simplify the directional distance function to the following reduced form econometric model

$$y_i = f(\mathbf{x}_i, \mathbf{b}_i) + \varepsilon_i \quad (7)$$

where f can be interpreted as a production function and ε_i is a random error term.⁸

To estimate quantile production functions, we do not assume an *a priori* functional form or smoothness for f but rather assume certain shape constraints such as monotonicity and concavity. That is, the function f is supposed to be a family of continuous, monotonic increasing, and/or globally concave, and/or homogeneous functions. While undesirable outputs \mathbf{b} might appear to be modeled similar to inputs \mathbf{x} in the econometric estimation of (7), we do recognize that \mathbf{b} are undesirable outputs by placing them in the nominator when computing the F_s^b index.

We can transform the non-parametric production function (7) to the following conditional non-parametric quantile function

$$Q_y[\tau | (\mathbf{x}, \mathbf{b})] = f(\mathbf{x}, \mathbf{b}) + F_\varepsilon^{-1}(\tau) \quad (8)$$

where the quantile τ ($0 < \tau < 1$) denotes that Q_y splits the observed data into proportions τ below and $(1 - \tau)$ above, and F_ε is the cumulative distribution function of the error term ε_i .

Following Kuosmanen and Zhou (2021), for a given quantile τ , we can differentiate Q_y with respect to \mathbf{b} or \mathbf{x} to obtain

$$\begin{aligned} \frac{\partial Q_{y_i}}{\partial \mathbf{b}_i} &= \frac{\partial Q_y[\tau | (\mathbf{x}, \mathbf{b})]}{\partial \mathbf{b}_i} = \boldsymbol{\theta}_i \\ \frac{\partial Q_{y_i}}{\partial \mathbf{x}_i} &= \frac{\partial Q_y[\tau | (\mathbf{x}, \mathbf{b})]}{\partial \mathbf{x}_i} = \boldsymbol{\beta}_i \end{aligned} \quad (9)$$

where $\boldsymbol{\theta}_i$ and $\boldsymbol{\beta}_i$ are referred to as the shadow prices of undesirable outputs and desirable inputs. Such shadow prices locally

estimated at the level of τ can be denoted as the quantile-based shadow prices of inputs and undesirable outputs, respectively (cf. Färe et al. 1993; Dai et al. 2020).

To estimate the shadow prices of inputs and undesirable outputs at a given quantile τ , we can solve the following CQR problem (Kuosmanen and Zhou 2021)

$$\begin{aligned} \min_{\alpha, \beta, \theta, \varepsilon^-, \varepsilon^+} \quad & (1 - \tau) \sum_{i=1}^N \varepsilon_i^- + \tau \sum_{i=1}^N \varepsilon_i^+ \\ \text{s.t.} \quad & y_i = \alpha_i + \beta_i' \mathbf{x}_i + \theta_i' \mathbf{b}_i + \varepsilon_i^+ - \varepsilon_i^- \quad \forall i \\ & \alpha_i + \beta_i' \mathbf{x}_i + \theta_i' \mathbf{b}_i \leq \alpha_h + \beta_h' \mathbf{x}_i + \theta_h' \mathbf{b}_i \quad \forall i, h \\ & \boldsymbol{\beta}_i \geq \mathbf{0}, \boldsymbol{\theta}_i \geq \mathbf{0} \quad \forall i \\ & \varepsilon_i^+ \geq 0, \varepsilon_i^- \geq 0 \quad \forall i \end{aligned} \quad (10)$$

where the estimated $\hat{\boldsymbol{\theta}}$ and $\hat{\boldsymbol{\beta}}$ are the shadow prices of undesirable outputs and inputs at the level of τ , respectively. In the CQR problem (10), the first set of constraints can be interpreted as multivariate regression equations. The second set of constraints denotes a system of Afriat inequalities that impose concavity. The third set of constraints imposes monotonicity, and the last refers to the sign constraints of the error terms. Note that the error term ε_i in (7) is decomposed into two non-negative components ε_i^+ and ε_i^- in (10), which capture the asymmetric deviations from the quantile production function (Wang et al. 2014).

Note that the sign constraint imposed on undesirable outputs (i.e., $\boldsymbol{\theta}_i \geq \mathbf{0}$) guarantees non-negative shadow prices for undesirable outputs, which follows a normative interpretation of the quantile production function as benchmark technology (cf. Hailu and Veeman 2001; Kuosmanen and Zhou 2021). Of course, this constraint can be relaxed to allow for the weak disposability of undesirable outputs. Furthermore, problem (10) presents a VRS specification of the quantile production function through the intercept term α_i , which is a free variable. An additional constraint that forces α_i to be zero leads to a CRS specification.

However, the estimated shadow prices $\hat{\boldsymbol{\theta}}$ and $\hat{\boldsymbol{\beta}}$ by CQR (10) are not necessarily unique (Dai et al. 2023a). To obtain the unique estimates, a natural way is to regularize the CQR problem by imposing an L_2 -norm regularization on the subgradients $\boldsymbol{\theta}_i$ and $\boldsymbol{\beta}_i$. Given a prespecified regularization parameter $\gamma \geq 0$, the penalized CQR problem is formulated as

$$\begin{aligned} \min_{\alpha, \beta, \theta, \varepsilon^-, \varepsilon^+} \quad & (1 - \tau) \sum_{i=1}^N \varepsilon_i^- + \tau \sum_{i=1}^N \varepsilon_i^+ + \frac{\gamma}{2} \sum_{i=1}^N (\|\boldsymbol{\beta}_i\|^2 + \|\boldsymbol{\theta}_i\|^2) \\ \text{s.t.} \quad & y_i = \alpha_i + \beta_i' \mathbf{x}_i + \theta_i' \mathbf{b}_i + \varepsilon_i^+ - \varepsilon_i^- \quad \forall i \\ & \alpha_i + \beta_i' \mathbf{x}_i + \theta_i' \mathbf{b}_i \leq \alpha_h + \beta_h' \mathbf{x}_i + \theta_h' \mathbf{b}_i \quad \forall i, h \\ & \boldsymbol{\beta}_i \geq \mathbf{0}, \boldsymbol{\theta}_i \geq \mathbf{0} \quad \forall i \\ & \varepsilon_i^+ \geq 0, \varepsilon_i^- \geq 0 \quad \forall i \end{aligned} \quad (11)$$

Problem (11) has a strongly convex objective function such that the subgradients $\boldsymbol{\beta}_i$ and $\boldsymbol{\theta}_i$ cannot take any value for a given objective function and feasibility. For any given $\gamma > 0$, the penalized CQR can ensure the uniqueness of subgradients (Theorem 2) and even avoid the quantile crossing problem (cf. Dai et al. 2023b).

Theorem 2. *The quantile shadow prices $\hat{\beta}$ and $\hat{\theta}$ estimated by penalized CQR (11) are unique for all $\gamma > 0$.*

Proof. See the online Appendix A.2. \square

Note that the subgradients estimated by CQR may be unbounded at the domain boundary of a convex hull, resulting in the overfitting problem in CQR (see, e.g., Mazumder et al. 2019; Dai 2023). Penalized CQR, on the other hand, avoids this issue effectively through the regularization in problem (11), which presents another appealing feature of penalized CQR over CQR. Alternatively, the overfitting problem can be addressed by incorporating Lipschitz regularization into convex regression (Mazumder et al. 2019), where an additional boundedness constraint is imposed on subgradients (e.g., $\|\cdot\|_2 \leq L$ and $\|\cdot\|_\infty \leq L$, where L is the tuning parameter). Nevertheless, the comparative effectiveness in addressing overfitting between penalized CQR and Lipschitz CQR warrants further scrutiny.

To operationalize the proposed penalized CQR approach, the value of tuning parameter γ needs to be prespecified. The standard approaches in machine learning, such as cross-validation and Stein's unbiased risk estimate, can be used to determine the optimal value of γ (see, e.g., Mazumder et al. 2019; Dai 2023). However, any $\gamma^* > 0$ is sufficient for ensuring the uniqueness of shadow prices. For sufficiently small γ , the optimal solutions to (10) are also the optimal solutions to (11) due to the exact regularization property in convex quadratic programming problems (see Friedlander and Tseng 2008). That is, a small γ could reduce the influence of regularization on $\hat{\beta}_i$ and $\hat{\theta}_i$ as much as possible but can guarantee their uniqueness.

In practice, we employ a local estimation strategy to determine the quantile-based shadow prices $\bar{\rho}$, $\bar{\delta}$, and $\bar{\omega}$ when computing the quantile shadow-price Fisher index F_s^b . Note that in the special case of a single desirable output, the normalized shadow price $\bar{\rho} = \rho_1/\rho_1$ equals unity by construction. For each observation, we solve the problem (11) for a given number of quantiles and then use the geometric mean of the shadow prices ($\bar{\delta}$ or $\bar{\omega}$) estimated on the two quantiles nearest to the observation as its shadow price. However, for those observations that fall below the lowest quantile or above the highest quantile, the shadow prices of the nearest quantile (i.e., the lowest or highest quantile) are directly used. Following Kuosmanen and Zhou (2021), we consider here 10 equidistant quantiles, i.e., $\tau = (0.05, 0.15, \dots, 0.85, 0.95)$. Formally, the normalized quantile-based shadow prices $\bar{\delta}/\rho_1$ and $\bar{\omega}/\rho_1$ for each observation are calculated as

$$\bar{\delta}/\rho_1 = \begin{cases} (\hat{\theta}_i^{\tau^*-0.1} \times \hat{\theta}_i^{\tau^*})^{1/2} & \text{if } 0.05 < \tau^* < 0.95, \\ \hat{\theta}_i^{\tau^*} & \text{otherwise} \end{cases} \quad (12)$$

$$\bar{\omega}/\rho_1 = \begin{cases} (\hat{\beta}_i^{\tau^*-0.1} \times \hat{\beta}_i^{\tau^*})^{1/2} & \text{if } 0.05 < \tau^* < 0.95, \\ \hat{\beta}_i^{\tau^*} & \text{otherwise} \end{cases} \quad (13)$$

where τ^* denotes the nearest quantile above the observation and $\tau^* - 0.1$ denotes the nearest quantile below the observation, as determined by the difference between $\hat{\varepsilon}_i^+$ and $\hat{\varepsilon}_i^-$. Such a local estimation strategy can make full use of the information of each

observation and take the inefficiency explicitly into account. The estimation of the shadow prices $\hat{\theta}_i^r$ and $\hat{\beta}_i^r$ can be implemented in Python using the pyStoNED package (Dai et al. 2024) with the standard solver Mosek (10.0.40).¹¹

5 | Quantile Productivity Measure

5.1 | Data and Variables

We proceed to apply the quantile shadow-price Fisher index to empirically estimate productivity growth in 38 OECD countries from 1990 to 2019. This application focuses on quantifying productivity growth estimated by the quantile shadow-price Fisher index and identifying the impacts of GHG emissions on productivity measures.

We consider a baseline model specification with the following inputs and outputs:

- Capital input: Capital stocks at constant 2017 national prices (in millions, 2017 US\$).
- Labor input: Total working hours (in millions of hours).
- Desirable output: Real GDP at constant 2017 national prices (in millions, 2017 US\$).
- Undesirable output: Total GHG emissions excluding Land Use Change and Forestry (in million tonnes of CO₂ equivalents).

The source data on capital, labor, and GDP were collected from the Penn World Table 10.01 (PWT) (Feenstra et al. 2015)¹² and the data on GHG emissions were from the World Bank database.¹³ The descriptive statistics of the variables are reported in Table C1 in the Online Appendix.

5.2 | Quantile Productivity Analysis

Since the United Nations Framework Convention on Climate Change was established in earlier 1990s, the international community has been committed to tackling climate change and proposed a series of climate actions (Kuosmanen et al. 2020; Dai et al. 2020). Consequently, a large share of capital investments over the recent decades has been devoted to reducing GHG emissions instead of increasing GDP, while productivity slowdown has been reported in certain developed countries (see, e.g., Syverson 2017; Crafts 2018). A natural question arises as to whether the productivity slowdown is a mismeasurement due to the omission of undesirable outputs in traditional TFP measures. Therefore, we proceed to investigate the impact of GHG emissions on productivity growth by applying the proposed quantile shadow-price Fisher index to the traditional TFP and green TFP measures.

Using panel data of 38 OECD countries during 1990–2019, we solve problem (11) in its CRS form and subsequently obtain the quantile shadow-price Fisher index (6). Figure 2 presents the cumulative TFP and green TFP measures for the OECD countries on average. Note that we simply set $\gamma^* = 0.01$ to slightly restrict the subgradients but still obtain the unique shadow

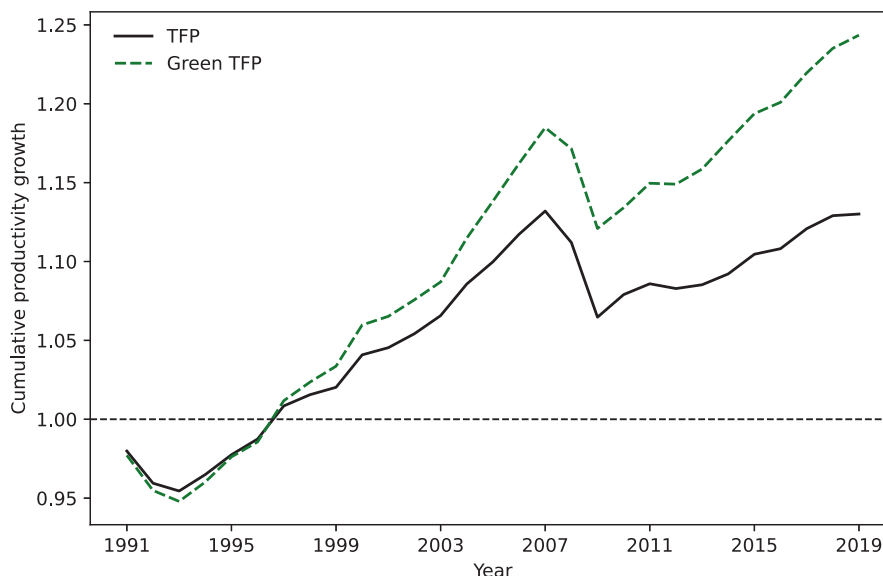


FIGURE 2 | The cumulative TFP and green TFP measures.

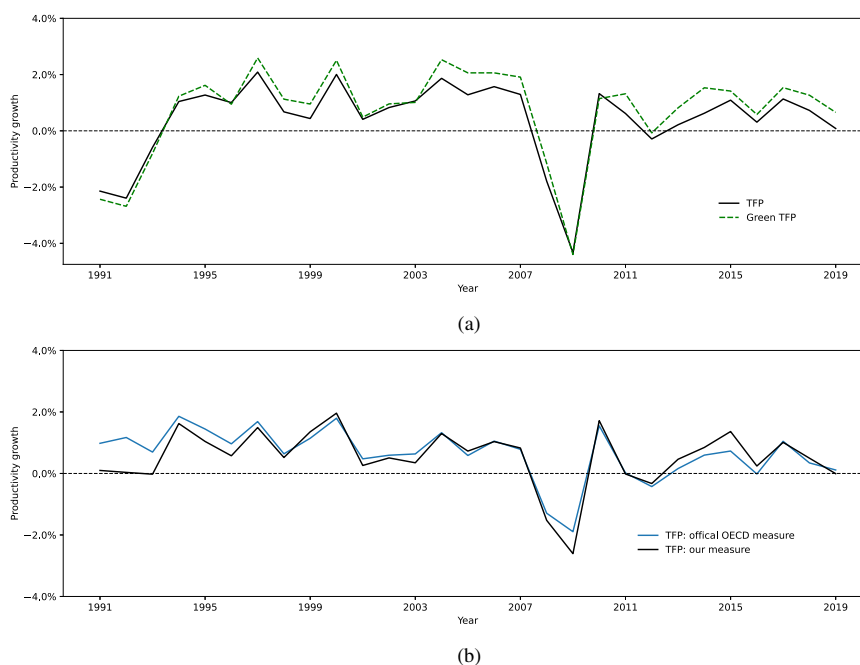


FIGURE 3 | (a) Our estimated productivity growth per year (38 OECD countries), (b) Our estimated and official OECD productivity growth per year (24 OECD countries). Yearly comparison of alternative productivity estimates.

prices. See the shadow price estimates in the [Online Supporting Information](#).

As shown in Figure 2, the cumulative green TFP growth closely follows the cumulative TFP growth in the early years of the sample period. However, following the Kyoto Protocol in 1997, green TFP began to diverge and showed stronger growth relative to TFP, suggesting the increased emphasis on carbon abatement among OECD countries. Both measures experience a sharp decline during the global financial crisis of 2008–2009. After the crisis, TFP growth recovers slowly but at a much lower rate than before the crisis, while green TFP resumes its relatively rapid growth trajectory, gradually and consistently widening the gap with TFP.

This result strongly suggests that ignoring the massive investments in carbon abatement can indeed help to explain why the measured TFP growth has slowed down, as in contrast, the green TFP exhibits strong cumulative growth. There is strong technological progress, but a large proportion of it aims at reducing GHG emissions.

Figure 3a demonstrates the geometric average of annual productivity growth based on the quantile shadow-price Fisher index across all 38 OECD countries during 1990–2019 with and without GHG emissions.¹⁴ It is evident that the average TFP growth and green TFP growth are not identical, yet they show a similar evolution path. The green TFP growth is generally higher than

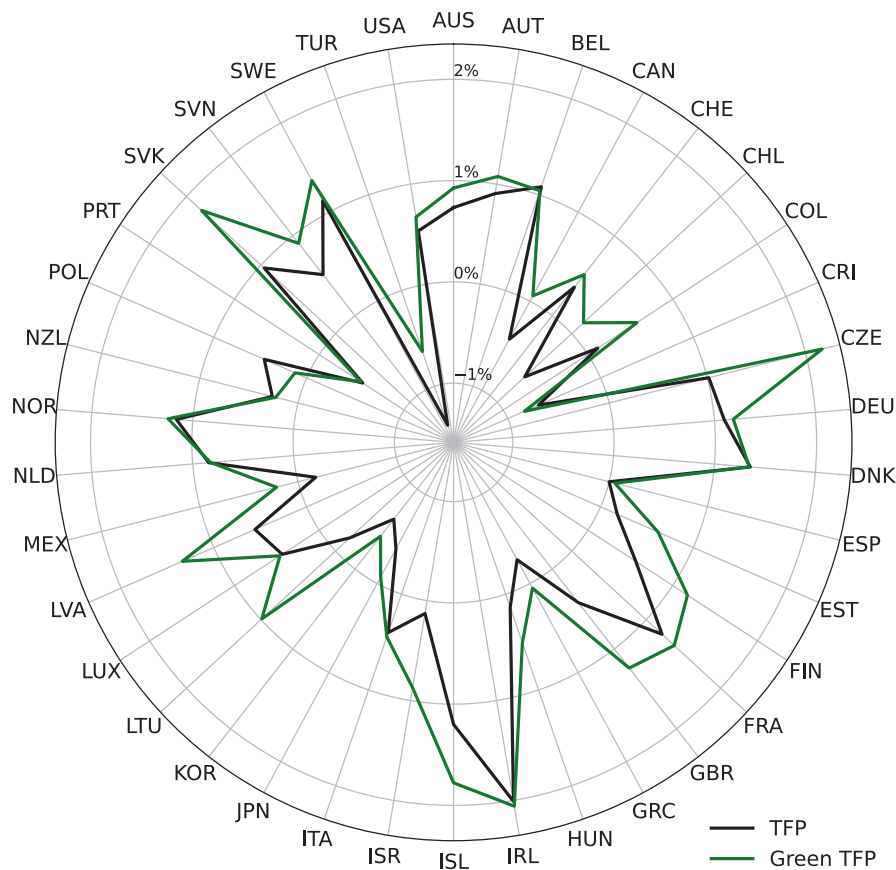


FIGURE 4 | Productivity growth per country: With and without GHG emissions.

the TFP growth over the period 1990–2019. The largest difference between these two productivity measures occurred in 2014, with an absolute difference of 0.91 percentage points. The average absolute difference over the period amounts to 0.40 percentage points, which cannot be omitted from the productivity measure.

It is worth noting that the financial crisis has greatly affected productivity growth for OECD countries. This is because the economic crisis results in a serious problem for economic growth, which further affects both the factor inputs, especially capital investment, and GHG emissions. The 2008 global financial crisis was accompanied by an average of 4.40% decline in green TFP for the entire OECD countries during 2008–2009. Although this crisis was a major shock, the TFP effect was temporary. In contrast, GHG abatement efforts have relatively modest short-term effects, but the persistence of abatement has a large effect on long-term growth.

Figure 3b compares the geometric average productivity growth between our quantile shadow-price Fisher TFP estimates and the official OECD measures across 24 Western OECD countries during 1990–2019.¹⁵ Our TFP estimates generally align with the official OECD measures, but are consistently slightly lower than the official measures across most of the observed period. In the CRS setting with two inputs, TFP growth essentially depends on the relative weights assigned for labor and capital. The comparison result implies that our estimated shadow prices tend to assign a higher weight for capital and a lower weight for labor

than the cost shares in the traditional residual-based method used by the OECD. This is because the capital input exhibited much higher growth than the labor input in all OECD countries during this period.

Figure 4 describes the yearly average productivity growth with and without GHG emissions at the country level. Several interesting findings are worth noting. First, the traditional TFP measure tends to underestimate productivity growth, even during a period of carbon reduction or the financial crisis. There is a noticeable difference in productivity growth between the TFP measures for all countries (0.36 percentage points; the absolute difference between green TFP and TFP), especially for transition economies such as the Czech Republic (1.15) and Lithuania (1.18). After the Kyoto Protocol came into effect in 2005, most countries reduced GHG emissions according to their commitments. Notably, the GHG emissions of Denmark, Finland, and the United Kingdom decreased by 42%, 36%, and 34%, respectively, during 2006–2019. However, this period still witnessed varying degrees of upward difference between the green TFP and traditional TFP measures, indicating that neglecting the impact of GHG emissions will overestimate the contribution from conventional factor inputs and, in turn, underestimate productivity growth. This finding is consistent with Jeon and Sickles (2004), Yörük and Zaim (2005), and Shen et al. (2017), which also note that the traditional TFP index undervalues the Luenberger green TFP index for OECD countries. Overall, the productivity growth slowdown may partly be explained by the carbon reduction efforts by OECD countries.



FIGURE 5 | Green productivity growth per year: CRS and VRS specifications.

Second, productivity growth depends on the GHG emissions reduction relative to the other two factor inputs. Under the Kyoto Protocol, OECD countries invest much more capital in facilitating low-carbon transition by utilizing cleaner production technologies, switching to cleaner fuels, or establishing market-based instruments (e.g., emissions trading systems). That is, if a country is willing to reduce GHG emissions even by a small proportion, then more conventional inputs are needed and they will increase far faster than the GHG emissions abatement. In this case, the green TFP growth will be higher than the TFP growth; in other words, the GHG emissions reduction leads to a greater enhancement in productivity growth than the other two conventional inputs.

Third, the countries from the transition economies can serve as the benchmark in terms of green development. The transition economies have relatively higher productivity growth than other OECD countries, particularly when introducing the GHG emissions in the entire sample period, indicating that these countries utilize the resources more efficiently but emit relatively lower GHGs. A similar finding has been detected in Kuosmanen et al. (2020). However, these advantages would fade away under the double constraints of the global financial crisis and the GHG emissions reduction targets, as reflected by the low green TFP growth from 2006 to 2019 in transition economies.

Fourth, for countries that have reduced GHG emissions most actively, the average green TFP growth rate could double the conventional TFP growth. For example, Estonia reduced more than twice GHG emissions (the largest decrease in percentage values) during the sample period, and the productivity growth increased from 0.18% (TFP growth) to 0.62% (green TFP growth). However, for the countries that are continuously increasing GHG emissions, the difference between TFP growth and green TFP growth is relatively small. For example, Australia's GHG emissions increased by 16.9%, and the country saw only a 0.19 percentage point difference between green TFP and TFP growth.

Finally, there exists a large variance in both green TFP and TFP growth among OECD countries (cf. Dai 2023), suggesting that the GHG emissions reduction has not been cost-efficient and that there is a lack of coordination between economic growth, environmental protection, and resources utilization. Therefore, the current policy to improve productivity growth is inefficient, and resource misallocation across the OECD countries exists (as will be further demonstrated below).

Figure 5 compares the average green TFP growth measured by the quantile shadow-price Fisher index under the CRS and VRS

TABLE 1 | Descriptive statistics and difference tests.

| | TFP | | Green TFP |
|----------------------|-----------|-------------------------------------|-------------------------------------|
| | w_L/w_K | $\tilde{\omega}_L/\tilde{\omega}_K$ | $\tilde{\omega}_L/\tilde{\omega}_K$ |
| Mean | 491.69 | 288.86 | 224.15 |
| Std. Dev. | 256.13 | 451.23 | 381.15 |
| Min | 54.10 | 0.00 | 0.00 |
| Max | 1228.68 | 1613.60 | 1778.31 |
| <i>t</i> test | | -13.199*** | -19.671*** |
| Pearson test | | 0.549 | 0.504 |
| Li test ^a | | 351.91*** | 361.53*** |

^aThe non-parametric Li test is applied to analyze the difference between two distributions, where the null hypothesis is that the comparative distributions are equal in their entire support (Li et al. 2009).

*** $p < 0.01$.

specifications. It reveals that the productivity growth estimates are robust to the CRS or VRS specification. Specifically, the median absolute difference between the CRS- and VRS-based green TFP growth is 0.33 percentage points. The largest difference appears in Finland (9.5; 2004–2005), and the smallest difference is close to zero for 2.2% of all the observations with 4-digit decimal accuracy. Further, there are only 65 cases (5.9%) where the absolute value is greater than 2 percentage points, and there are 81.9% of the sample where the difference is less than 1 percentage point (see Figure C1 in the Online Appendix).

Since the relative prices of labor and capital can be inferred from the PWT data, we next examine the magnitude of allocative inefficiency by calculating the ratio

$$\mu = \frac{\tilde{\omega}_L}{\tilde{\omega}_K} \bigg/ \frac{w_L}{w_K}$$

where μ denotes the allocative efficiency score (Musau et al. 2021). If $\mu = 1$, there is no resource misallocation; if $\mu \neq 1$, it suggests potential inefficiencies in the allocation of capital and labor.

Table 1 reports the descriptive statistics of the market price ratio (w_L/w_K) and the shadow price ratio ($\tilde{\omega}_L/\tilde{\omega}_K$). On average, the market price ratio is higher than the shadow price ratio under both TFP and green TFP specifications, which suggests that the allocation of capital and labor is inefficient at the OECD level. The difference tests also show that there is a statistically significant difference between the market price ratio and the shadow price

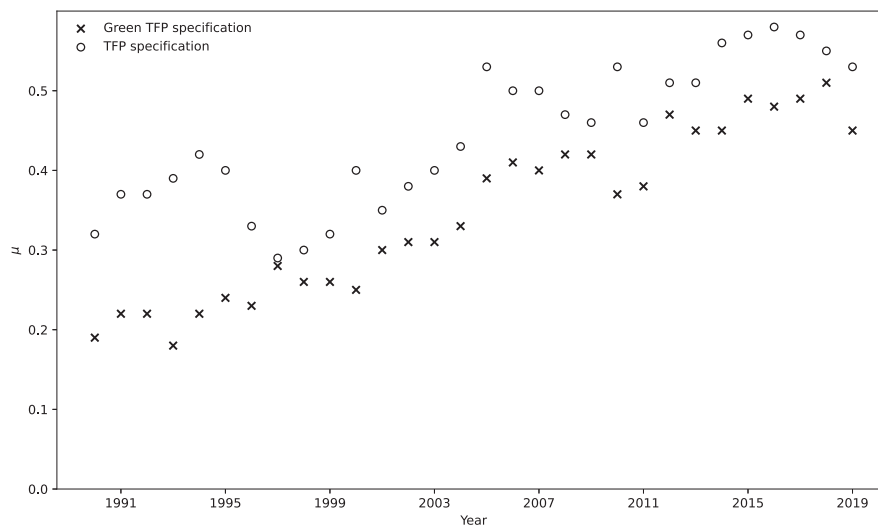


FIGURE 6 | Average allocation inefficiency at the OECD level.

ratio, confirming the observed allocative inefficiencies for OECD countries.

Figure 6 displays the evolution of the average allocation inefficiency at the OECD level. All the years exhibit allocative inefficiencies, as all the points in the figure are less than 1 and are distributed within the range of 0.15 to 0.55 in both TFP and green TFP specifications. A possible explanation for the allocative inefficiencies is that a large proportion of capital is allocated to the abatement of GHG emissions. Therefore, in the case of resource misallocation, shadow prices seem more suitable than market prices for measuring productivity growth.

6 | Alternative Model Specifications

To examine the impact of different forms of physical capital inputs, we compare the baseline model with an alternative specification in which capital input is represented by capital services. We also compare the baseline model with an extended specification that includes human capital to examine the impact of human capital accumulation.

6.1 | Capital Services

Reliable figures for fixed capital are crucial for a better understanding of productivity growth, but they are often denoted by two interrelated but distinct concepts: Capital stocks and capital services. The former refers to the stock of physical assets at a point in time, whereas the latter represents the flow of services created by these assets in a period. Compared to capital services, capital stocks are less relevant for measuring productivity growth and are more likely to overestimate TFP growth (see, e.g., Schreyer 2001; Schreyer 2004). In this subsection, we are primarily interested in the impact of alternative representations of fixed capital (capital stocks vs. capital services) on the green TFP growth estimates obtained from the quantile shadow-price Fisher index approach.

In practice, we calculate the capital services per country per year ($rkna2_{i,t}$) by using

$$rkna2_{i,t} = \begin{cases} (1 - labsh_{i,t}) \times rgdpna_{i,t} & t = 2017; \\ [(1 - labsh_{i,2017}) \times rgdpna_{i,2017}] \times rkna_{i,t} & t \neq 2017 \end{cases}$$

where $labsh$ denotes the share of labor compensation in GDP at current national prices, $rgdpna$ represents the real GDP at constant 2017 national prices (in millions, 2017US\$), and $rkna$ is the capital services at constant 2017 national prices (2017 = 1). The data of the above variables were also collected from PWT. Figure C2 in the Online Appendix illustrates the difference between the capital services and the capital stocks for all OECD countries, where capital services grew significantly faster than capital stocks during the sample period.

Figure 7 depicts the scatter plot of green TFP growth estimated with capital services vs. capital stocks. If an observation (i.e., an OECD country) is located below the 45-degree line (i.e., the red dot line), then the green TFP growth with capital services is smaller in terms of the average value than that with capital stocks. Obviously, the green TFP growth with capital stocks is generally higher than that with capital services from 1990 to 2019. This suggests that if the fixed capital input is denoted by capital stocks, the growth of green TFP could be overestimated, while the contribution of capital assets to economic growth could be underestimated. This finding is in line with the traditional TFP growth analysis (see, e.g., Schreyer 2001; Schreyer 2004).

At the country level, we also observe that the proxy of fixed capital has non-negligible impacts on the green TFP measure. Table 2 reports the average green TFP growth and economic growth for three example countries. For instance, Italy's annual green TFP declined by 0.11% from 2010 to 2019 when estimated with capital services, but grew by 0.52% when estimated with capital stocks. Over the same period, the capital services of Italy grew by 0.66% per year, which was higher than the increase in capital stocks (0.59%). The resulting 0.07 percentage points difference translated to the 0.63 percentage points adjustment to the green TFP

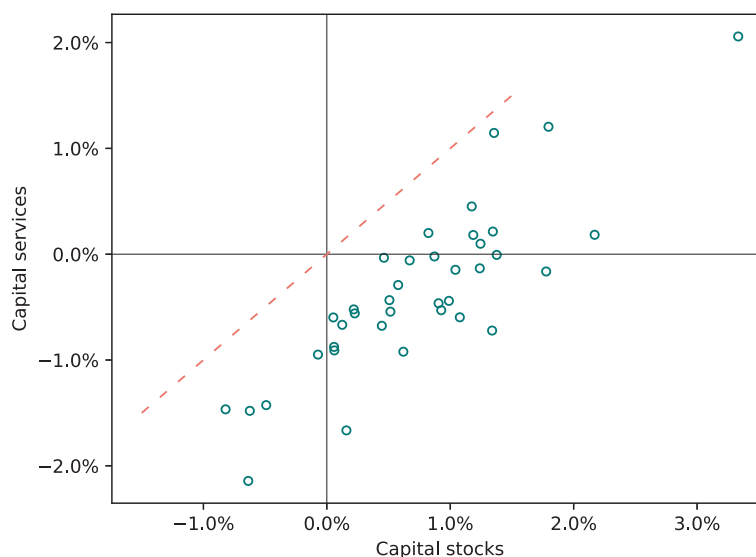


FIGURE 7 | Green TFP growth estimated with capital services or capital stocks.

TABLE 2 | Green TFP growth and economic growth.

| | | Italy | Poland | Turkey |
|---------------------------------|-----------|-------|--------|--------|
| Output | 1990–2099 | 1.41 | 3.42 | 3.12 |
| | 2000–2009 | 0.48 | 3.83 | 3.61 |
| | 2010–2019 | 0.24 | 3.50 | 5.47 |
| Capital services | 1990–1999 | 2.57 | 4.69 | 6.47 |
| | 2000–2009 | 2.39 | 4.89 | 6.07 |
| | 2010–2019 | 0.66 | 4.15 | 6.60 |
| Capital stocks | 1990–1999 | 2.22 | 3.95 | 6.15 |
| | 2000–2009 | 2.12 | 4.30 | 5.79 |
| | 2010–2019 | 0.59 | 3.96 | 6.49 |
| Green TFP with capital services | 1990–1999 | −0.15 | −1.14 | −3.27 |
| | 2000–2009 | −1.69 | −0.94 | −2.25 |
| | 2010–2019 | −0.11 | 0.12 | −0.84 |
| Green TFP with capital stocks | 1990–1999 | 0.84 | 0.60 | −1.65 |
| | 2000–2009 | 0.04 | −0.04 | −0.42 |
| | 2010–2019 | 0.52 | 1.00 | 0.33 |

measure. Therefore, the green TFP growth of Italy was overestimated with capital stocks. The overestimation can also be observed in all other countries or periods.

6.2 | Human Capital

Inspired by endogenous growth models, extensive empirical studies have demonstrated the positive externalities of human capital on TFP growth (see, e.g., Barro 2001; Henderson and Russell 2005; Bowlus and Robinson 2012). Recently, several studies have highlighted various potential environmental benefits of human capital accumulation (see, e.g., Yao et al. 2020; Angrist et al. 2023), which may help to reduce GHG emissions and

affect green productivity. We thus, in this subsection, incorporate human capital into quantile production functions to investigate the impact of human capital on green TFP measures. Note that human capital is proxied by the average years of schooling in the population aged 25 years and older.¹⁶

Figure 8 shows the estimated densities of green TFP growth with human capital for 1991, 2001, 2011, and 2019. A relatively larger discrepancy in the overall distribution appeared in 2019, indicating that the cross-country differences in green TFP growth have become larger. Furthermore, the center of the four distributions does not shift rightward. That is, the green TFP does not always grow with time in OECD countries, even though human capital is considered in the production model.

Figure 9 depicts the average green TFP growth with and without human capital for each OECD country. If an observation is located below the 45-degree line (i.e., the red dot line), then the green TFP growth with human capital is larger than that without human capital. Furthermore, if human capital is reasonably well measured, an increase in green TFP growth after considering human capital in the quantile production function indicates a relative shortage of human capital (or measurement error in labor input, equivalently). Similarly, a decrease in green TFP growth can be interpreted that there exists sufficient or even redundant human capital (Henderson and Russell 2005).

Overall, more points are located below the 45-degree line, indicating that the green TFP growth can increase after incorporating human capital. This suggests that the neglect of human capital or the mismeasurement of labor input in production models underestimated green productivity. Notably, the largest green TFP growth improvements driven by considering human capital occurred in relatively developed countries such as Iceland, Italy, and Japan, as well as the transition economies (e.g., the Czech Republic and Slovenia). This finding is consistent with Henderson and Russell (2005), which investigates the impact of human capital on country-level efficiency estimation. We also

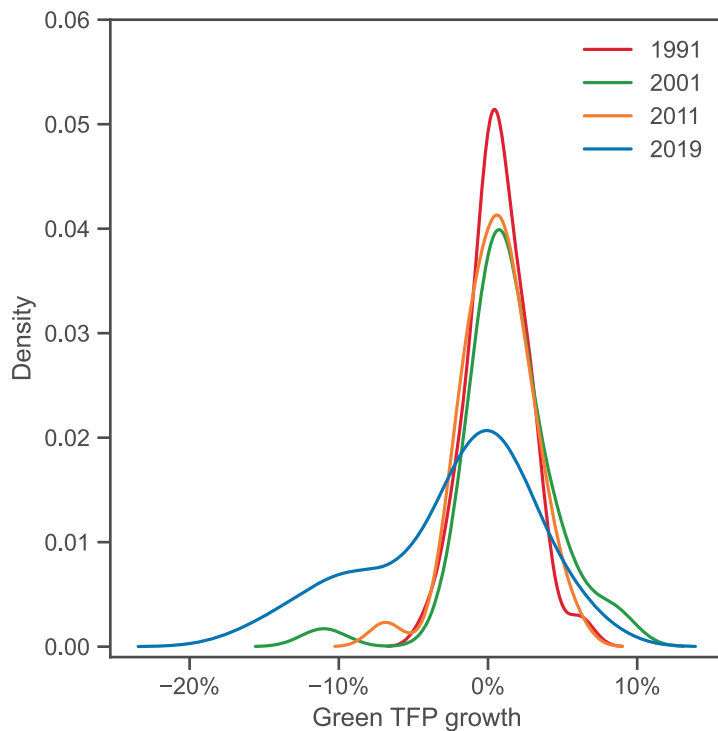


FIGURE 8 | Estimated densities of green TFP growth with human capital.

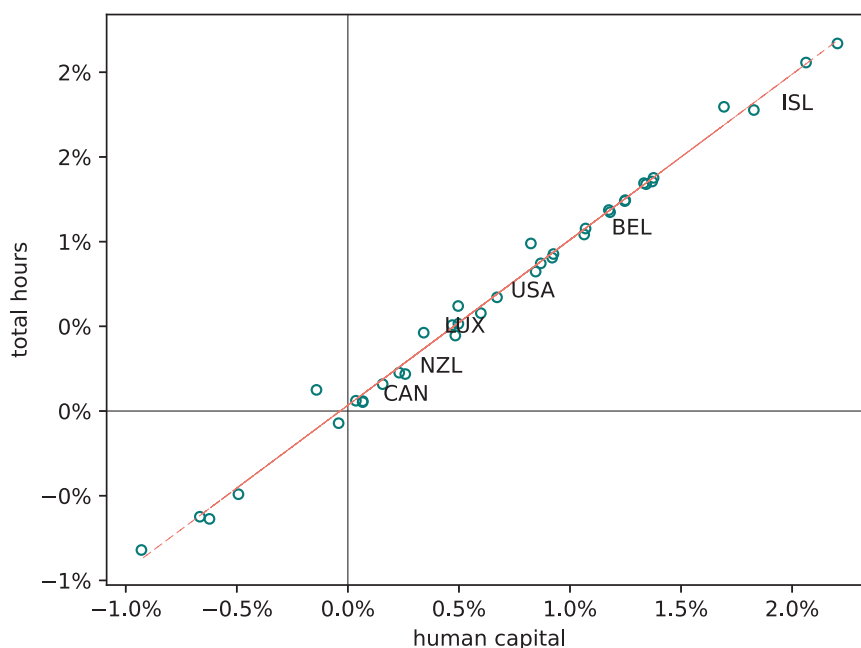


FIGURE 9 | Green TFP growth with and without human capital.

observe that several developed countries such as Canada, Luxembourg, and South Korea have decreased green TFP growth after the inclusion of human capital, indicating that the human capital growth in these countries is poised to be saturated and sufficient.

7 | Conclusions

In this paper, we have shown that the measured productivity growth is considerably higher when the GHG emissions are

accounted for. For countries that have reduced GHG emissions most actively, the average green TFP growth rate could double the conventional TFP growth. Green productivity growth depends on GHG emissions reduction relative to the traditional factor inputs. If the fixed capital input is denoted by capital stocks, then the growth of green TFP can be overestimated, and the contribution from capital assets to economic growth may be underestimated. Furthermore, the positive impact of human capital accumulation on green TFP growth has been confirmed.

Our methodological contribution is to develop a new quantile shadow-price Fisher index to measure green productivity growth based on quantile production functions estimated by the developed penalized CQR approach. We then apply the quantile shadow-price Fisher index to calculate productivity growth for 38 OECD countries over the period 1990–2019 and empirically explore the impacts of GHG emissions, fixed capital, and human capital on productivity measures.

The proposed estimation and index approaches offer four major advantages over conventional methods for measuring green TFP growth. First, the penalized approach has unique quantile shadow price estimates for the inputs and the undesirable output. Second, this approach takes inefficiency explicitly into account and is more robust to outliers and heterogeneity. The estimated shadow prices can reflect the full information of all observations. Third, the quantile shadow-price Fisher index does not require the real price data for input-output vectors, which is necessary for calculating the Fisher ideal index. Therefore, such environmental factors as GHG emissions can be integrated into productivity growth accounting using the Fisher index. Finally, the quantile shadow-price Fisher index can avoid an *ad hoc* choice of quantiles which might lead to different estimations of productivity growth and allow the quantiles to move in the inter-period sample.

While the findings drawn from this study provide insights into the quantile shadow-price Fisher index, the possible future research avenues are also highlighted. Decomposing the quantile shadow-price Fisher index to its components (e.g., efficiency change, quantile change, and technological change) is a fascinating avenue. Such decomposition can help better understand the driving forces of green TFP growth. In addition, the resource misallocation effect at the country level deserves further scrutiny.

Conflicts of Interest

The authors declare no conflicts of interest.

Endnotes

¹ The partial frontier approach (e.g., order- α) has also been applied to estimate the Malmquist index (see, e.g., Wheelock and Wilson 2009; Wheelock and Wilson 2013), where a fixed quantile is typically assumed in the entire estimation. That is, the quantile is a prespecified arbitrary positive constant for the entire study period. See more discussion in the Online Appendix B.

² Source: EUKLEMS & INTANProd—Release 2021, <https://euklems-intanprod-lee.luiss.it/>.

³ Source: <https://pxdata.stat.fi/PxWeb/pxweb/fi/StatFin/>.

⁴ Source: <https://stats.oecd.org/?datasetcode=ecr#>.

⁵ Therefore, we consider human capital and the flow of capital services as robustness checks in Section 6.

⁶ We use tilde to distinguish the quantile-based shadow prices from their full-frontier counterparts.

⁷ In the previous section, the superscript denotes the period. For the sake of generality and to avoid unnecessary clutter, in this section we do not indicate the period to allow one to use a panel data model, cross-sectional models, or a series of rolling windows for the estimation. In this section, the superscript indicates the quantile τ , which should not be confused with the periods.

⁸ Technically, the production function is a special case of the directional distance function, obtained by setting $g^y = 1$, $g^x = 0$, $g^b = 0$. To avoid unnecessary technicalities, this section is phrased in terms of the production function that most readers are familiar with (the directional distance function is thoroughly covered in Kuosmanen and Zhou 2021).

¹⁰ In rare cases where an observation lies exactly on the quantile τ^* , we use the quantiles $\tau^* + 0.1$ and $\tau^* - 0.1$ to calculate $\tilde{\delta}/\rho_1$ and $\tilde{\omega}/\rho_1$.

¹¹ The estimated quantile shadow prices can also be used to calculate the marginal abatement costs of undesirable outputs based on the least-cost abatement alternative (see, e.g., Kuosmanen et al. 2020; Kuosmanen and Zhou 2021; Dai et al. 2020; Kuosmanen et al. 2024).

¹² The corresponding selected variables in PWT are *rmna*, $\text{emp} \times \text{avh}$, and *rgdpna*, respectively.

¹³ DataBank: <https://databank.worldbank.org/source/world-development-indicators/Series/EN.ATM.GHGT.KT.CE>, accessed 1 February 2023.

¹⁴ All empirical results exclusively present TFP and green TFP estimated by the CRS specifications unless otherwise stated.

¹⁵ The official OECD TFP measures are only available for 24 Western OECD countries at <https://data-explorer.oecd.org>.

¹⁶ The data on average years of schooling were collected from PWT, and the corresponding selected variable in PWT is *yr_sch*.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.