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Green Investment and Productivity Dynamics

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ABSTRACT

This paper reviews existing definitions and measurement efforts to capture the extent of green technological investment, and it provides a measurable definition of green capital asset for a sample of 18 OECD countries from 2004 to 2020. A main goal of this paper is to assess the contribution of green technological capital to productivity growth also taking into account the effects of tightening environmental regulations. The econometric results suggest that: (1) an increase in green technological capital stock generates medium-term productivity gains; (2) stricter environmental regulations boost, rather than hinder, productivity growth. Furthermore, the empirical findings corroborate previous evidence that more stringent nonmarket policies, such as emission limits, can stimulate innovation, thereby contributing to positive productivity returns. The paper provides also some policy insights highlighting the critical role of green technological investment in promoting sustainable growth while mitigating climate change.

JEL Classification: O44, Q43, Q50

1 | Introduction

Climate change has emerged as the most pressing global threat, with global temperatures rising a stark 1.1°C above preindustrial levels (1850–1900) in the past decade (2011–2020) (IPCC 2023a, 2023b). Addressing this effectively demands consideration of its interactions with other global challenges that could impede economic growth and lead to environmental disasters. The urgency is clear in the Paris Agreement's aim to limit warming to 1.5°C above preindustrial levels (United Nations Framework Convention on Climate Change 2015). Achieving this ambitious goal necessitates a significant boost in technological investment to accelerate the energy transition, requiring a quadrupling of annual clean technology investments according to IRENA (2022) and CPI and IRENA (2023).[1]

However, while the policy question of how to scale up investments to accelerate the green transition has gained significant attention over the last decade (e.g., OECD 2013, 2017), a common and widely shared definition of what can be classified as "green asset" and a recommended measurement approach are still lacking. The lack of a universally agreed-upon definition of green investment, with varying classifications across asset classes, complicates the assessment of its macroeconomic impacts. This challenge is compounded by the limited and often inconclusive empirical research exploring the intricate relationships between production, capital formation, emissions, and inequality. Recently, Pisani-Ferry (2021) argued that the macroeconomic perspective on environmental economics has been largely disregarded due to decarbonization strategies being considered relevant only beyond traditional macroeconomic horizons. This underscores an urgent need for focused discussion on how climate action impacts economic systems at large.

This paper advances the discussion on green investment by pursuing three key objectives. First, it reviews existing definitions and measurement approaches, highlighting their shared aspects and shortcomings. Building upon this, we then provide a measurable definition of green technological asset and compute the green technological capital stocks for 18 OECD countries over the years 2004–2020. Finally, we assess the direct effect of scaling up green technological capital on productivity growth and we investigate the relationship between stricter environmental regulation, green technological capital, and productivity, testing the Porter hypothesis that more stringent environmental policies will incentivize innovation, thereby offsetting compliance costs and positively influencing productivity growth.

Our findings suggest that increasing green technological capital (approximated by renewable energy capital assets) generates significant medium-term productivity gains. Furthermore, corroborating the Porter hypothesis, we find that more stringent environmental regulation fosters green technological investment, contributing to positive productivity returns.

The paper is organized as follows: Section 2 presents the background literature, Section 3 provides an overview of the main challenges in defining and measuring green investment, while Section 4 discusses our conceptual framework. Then, Section 5 illustrates the dataset; Section 6 describes our empirical strategy; and Section 7 discusses econometric results, and finally, Section 8 concludes with a summary of our main findings.

2 | Background Literature

The growing concerns about climate change and its economic impact have led to a flourishing literature on the relationship between green investment, environmental regulation, and economic growth. But as there is not yet a unique definition of what can be included within the boundaries of green investment, most studies have examined different categories of expenditures/items potentially considered as green investments. For example, OECD (2017) showed that investing in smart, modern, clean, and resilient infrastructure can stimulate short-term growth and support robust long-term growth in both advanced and emerging economies.

Alternatively, Batini et al. (2022) considering private and public green investment as a whole, estimated the multipliers associated with green capital spending on power generation using renewable sources, showing that they are about two to seven times larger than those associated with "non-eco-friendly" expenditure—defined as spending on alternative energy technologies or land/sea uses. As pointed out by the authors, green spending thus exerts long-term positive effects on macroeconomic performance. A possible rationale for this finding is related to "green spending being both more labor intensive and richer in domestic content" (Batini et al. 2022, 2), thus creating positive spillover effects resulting in higher labor demand and wage growth.

Despite employing varied definitions and measures of green investment, prior research has largely concentrated on its link to green economic growth (Mo et al. 2022; Shen et al. 2021; Wang, Umar, et al. 2021) and, more extensively on the nexus between renewable energy and economic development (Buyihan et al. 2022; Makiela et al. 2022; Tutak and Brodny 2022; Doytch and Narayan 2021; Sohag et al. 2020; Dogan et al. 2020; Yao and Zhang 2019; Ozcan and Ozturk 2019; Bhattacharya et al. 2016; Menegaki 2011). For instance, Mo et al. (2022) found a positive long-term impact of green investment on green growth, defined by the authors as an increase in pollution-reducing activities enabled by technology, in several heavily polluted Asian economies. Additionally, Shen et al. (2021), and similarly Wang, Umar, et al. (2021), argued that green investment enhances the effectiveness of climate markets and energy systems contributing significantly to green growth. Particularly, an increase in green investment improves technological innovation, energy savings, and efficiency of industrial structure, which, in turn, promotes growth.

There are also many studies on the nature of the relationship between renewable energy and economic growth. To summarize the different strands of the literature in this area, we can group them into the following categories: the first argues that there is no a causal link between renewable energy use and economic growth (Buyihan et al. 2022; Menegaki 2011); the second instead finds that investing in renewable energy can boost economic growth and productivity (Tutak and Brodny 2022; Doytch and Narayan 2021; Yao and Zhang 2019), but that the effect depends on a country's level of development (Makiela et al. 2022; Wang, Li, et al. 2021); and a third stream indicates that increasing renewable energy has a negative impact on economic growth (Dogan et al. 2020; Ozcan and Ozturk 2019; Bhattacharya et al. 2016).

Other authors have investigated the channels through which green investment (and renewable energy) can boost economic growth. For example, Sohag et al. (2020) analyzed the dynamic impact of renewable energy on economic growth, exploring the channels through which the use of renewable energy sources in the production process spurs total factor productivity, incorporating the role of human capital, innovation, and trade openness. Their findings show that a higher share of renewable energy in the total energy mix enhances economic efficiency and productivity directly as well as indirectly through different channels: lessening pressure on the balance of payments, decreasing abatement costs for carbon emissions, enhancing energy security, creating new job opportunities, and decreasing dependency on imported oil. Along these lines but looking at firms' level data, Ambec and Lanoie (2008) analyzed the different factors through which environmental investments may raise firms' benefits or reduce their costs. They identified seven possible channels producing these positive effects: (a) better access to markets; (b) more possibilities for differentiation of products; (c) commercialization of pollution-control technology; (d) risk management and relations with external stakeholders; (e) cost of material, energy, and services; (f) cost of capital; (g) labor costs.

Finally, looking at the nexus between economic growth and environmental regulation, a significant strand of the literature has focused on the relation between environmental regulation and productivity growth by testing the validity of the Porter hypothesis—that is, assessing whether stricter environmental regulation could lead to positive productivity returns through innovation (Porter and van der Linde 1995). De Santis et al. (2021) investigated this nexus for 18 OECD countries over 1990–2015, finding that environmental policy has a productivity-growth-promoting effect. In addition, Wang et al. (2019) found that environmental policy has a positive impact on green productivity growth but only within a certain level of stringency.[2] Albrizio et al. (2014) showed that tightening environmental policy in OECD countries is associated with a short-term increase in industry-level productivity growth only in technologically advanced countries. Other studies focused on the impact of environmental regulation on innovation; this literature is rather vast and diversified. Some studies found a positive correlation between regulation and innovation. For example, by using sector-level data from Spanish industry, Del Río et al. (2011) pointed out the relevance of stringent environmental regulation in explaining investment patterns in environmental technologies. The authors add that these investments are positively and strongly related to human and physical capital intensity, as well as R&D intensity, and that they can enhance firms' technological capabilities and human capital. Similarly, Kesidou and Demirel (2012) found that the stringency of environmental regulation, along with factors such as cost savings and firms' organizational capabilities, influences investment in environmental technologies within a sample of UK manufacturing firms. Hence, the authors conclude that firms respond to stricter regulations with higher levels of eco-innovations. Additionally, Ambec and Barla (2002), André et al. (2009), and Carrión-Flores and Innes (2010) suggested that well-designed environmental regulation can improve competitiveness by promoting product and process innovation.

3 | Defining and Measuring Green Investment

The lack of a consistent definition of green investment in official statistics presents a significant challenge in identifying qualifying asset classes. This definitional ambiguity extends to the academic literature, where opinions diverge on the categorization of green assets and the fundamental metrics for evaluating their environmental impact. Moreover, current approaches to data collection on green investment tend to emphasize financial expenditures, falling short of providing a robust macroeconomic measure.

In a pioneering and comprehensive effort, Inderst et al. (2012) provided an overarching review of the concepts and definitions associated with green investments. Their analysis covered diverse areas, including the macroeconomic level, green goods and services, foreign direct investments, and patents, as well as various asset classes like stocks, bonds, and alternative investments. Their conclusion suggests that a universally accepted and exact operational definition of what constitutes "green" investment is unlikely to emerge. As recognized by the authors, there are some areas of major controversy related to sectors that might or might not be included (e.g., nuclear; "green" agriculture, IT, financial services). Furthermore, despite the diverse definitions, a significant overlap exists across sectors (e.g., renewable energy), commodities (e.g., carbon or renewable energy credits), services (e.g., waste management), and technologies (e.g., energy efficiency enhancements). However, given the absence of consensus, the authors refrain from proposing a unified definition, advocating instead for an adaptable and evolving approach. Therefore we can say that the term "green investment" is defined and used variably in the literature.

As an example, (Sukhdev et al. 2010, 5), referring to the UN Environmental Programme, define green investment broadly, starting with the idea of "green economy." They describe this as an economy that fosters improved human well-being and social equity, coupled with a significant reduction in environmental risks and ecological scarcities. They argue that realizing this requires significantly more investment in economic sectors that build upon and enhance the planet's natural capital or diminish ecological scarcities and environmental risks. These include: renewable energy, low-carbon transport, energy-efficiency buildings, clean technologies, improved waste management, improved freshwater provision, sustainable agriculture, forestry and fisheries.

To narrow down measurable definitions of green investment, existing approaches can be classified according to both the unit of analysis and the methodology employed, allowing for a distinction between:

- Firm-based definitions, which classify investments as green based on the characteristics of the investing entity and its environmental, social, and governance (ESG) objectives and/or its corporate social responsibility (CSR) pledges. This approach considers investments made by firms that meet specific sustainability criteria, regardless of the nature of the assets acquired. It aligns with the definition of "sustainable investment" proposed by Escrig-Olmedo et al. (2017). Similarly, Martin and Moser (2015) refer to green investment as a form of CSR activity aimed at reducing carbon emissions.[3]
- Industry-based definitions, where an investment is considered green based on the industry in which it occurs (e.g., renewable energy production, waste management, infrastructure), irrespective of the firm undertaking it. For example, this approach underpins the framework proposed by the OECD (2017).
- Product-based definitions, in which investments are characterized as green based on the type of asset being acquired, focus on the environmental characteristics of the investment itself rather than the investing entity or industry.[4]

Macroeconomic measurements of green investment are typically based on attempts to aggregate product-based definitions or green investment. Along these lines, the work of Eyraud et al. (2013) constitutes the first attempt to provide a measurable definition and an empirical estimate of green investment, based on the idea that are "green" those investment needed for reducing greenhouse gas and air pollutant emissions without significantly reducing the production and consumption of nonenergy goods. The authors identified three main investment components that can be classified as green: (i) low-emission energy supply, which refers to investment that involves shifting energy supply from fossil fuels to less polluting alternatives, (ii) energy efficiency, that includes technologies reducing the amount of energy required to provide goods and services, and (iii) carbon sequestration, that involves halting ongoing deforestation, reforesting, and sequestering more carbon in soils through new agricultural practices. Along these lines, their measure considers financial investment in renewable technologies (including large hydroelectric projects), selected energy-efficient technologies (e.g., smart grids or power storage), and research and development (R&D) in clean energy.[5] They also develop an econometric analysis of the factors affecting financial investment in renewables for a panel of 35 countries over the period 2000–2010, by retrieving data from the Bloomberg New Energy Finance (BloombergNEF) database.

More recently, the European Investment Bank (2023) developed a measure of climate change mitigation investment, by aggregating total renewable investment, estimates on energy efficiency investment, rail and inland waterways transport investment, gross fixed capital formation in forestry, and R&D in low-carbon emitting technologies.[6] European Investment Bank (2023) data are fully consistent with the definition of green investment illustrated above, but they available only at very aggregate level for the EU (as a whole), United States, and China thus not being very helpful for a policy-oriented investigation of the contribution of green investment to sustainable growth. Furthermore, Batini et al. (2022) estimate green multipliers for 11 countries building a proxy of green expenditure defined as the sum of renewable energy capital spending and construction costs of clean nonrenewable energy. As recognized by the authors, "data on investments in green or non- eco-friendly energy are not easy to come by, as much of it relates to private finance. [. . .] As a result, the datasets used [. . .] have been built specifically for this project thanks to the support by various international energy agencies, universities, NGOs and multilateral development organizations" (Batini et al. 2022, 2) but without the possibility of publishing it. Finally, in a recent publication, CPI and IRENA (2023) provide an estimate of renewable energy investment for the period 2013–2021, resorting to the CPI's data effort (2022). The data are mainly based on CPI's elaboration from BloombergNEF and IEA, and they refer to aggregate geographical areas (e.g., North America, comprising the United States and Canada).

Amid the many datasets cited above the sole data publicly available are those provided by the IEA on clean energy investment, as published in the latest *World Energy Outlook* (IEA 2023). However, available information is highly aggregated for large groups of countries (i.e., North America, Central and South America, Europe, Africa, Middle East, Eurasia, Asia Pacific) and the time coverage is quite limited—2015–2021 with estimates for 2022.

Table 1 summarizes the main measures of green investment and spending developed in the literature so far. For the purposes of our analysis, considering the geographical coverage and data availability, we resort to the BloombergNEF and the Climate Policy Initiative (CPI) data, providing a reliable proxy for green investment—defined respectively as energy transition investment for the former and climate investment for the latter. Notice that we only look at existing measures of green investment at the aggregate level. These metrics do not necessarily overlap with those of capital spending that contribute to emissions abatement, but rather with those promoting the energy transition. This is particularly evident for all measures in Table 1, with the only exception of the data collected by the European Investment Bank (2023), including a broader set of mitigation investments (including transport infrastructures and natural capital)—albeit with the caveats mentioned above. Being mostly focused on the energy dimension of the low-carbon transition, these measures do not capture the capital formation that contributes to emissions reduction, for example, by abating pollution and resource consumption or enhancing biodiversity. Moreover, investments that contribute to emissions reduction by "greening" value chains—for instance, by promoting upstream diversification of inputs or downstream diversification of products—are also largely disregarded. Last, most data sources do not distinguish between public and private investment sources. With the only exception of CPI (2022) and CPI and IRENA (2023), the other measures reported in Table 1 do not track separately public and private green investment, providing a further obstacle

TABLE 1 | Aggregate measures of green investment and spending.

Definition	Indicator	Source
Green investment (Eyraud et al. 2013)	Financial investment in renewables	BloombergNEF
	Energy efficiency investments	BloombergNEF
	Corporate and government R&D	BloombergNEF
Climate change mitigation investment (European Investment Bank 2023)	Investment in energy efficiency—estimates	IEA
	Total investment in renewable energy	IEA
	Transport investments (rail and inland waterways)	OECD ITF
	Gross fixed capital formation (GFCF) in forestry	Eurostat and BEA
	R&D investment in low-carbon technologies	JRC-SETIS, IEA, IMF, OECD
Green spending (Batini et al. 2022)	IEA estimates of capital spending on power generation using renewable energy	IEA
	Overnight construction cost—clean nonrenewable energy (nuclear energy)	OECD's Nuclear Energy Agency, IAEA
Climate investment (CPI 2022; CPI and IRENA 2023)	Annual investments in renewable energy	CPI, IEA, BloombergNEF

for data-driven policy design. Overall, these caveats call for better data collection and dissemination both at the micro- and macrolevels.

4 | Conceptual Framework

In this section, we provide an overview of our conceptual framework, serving as a schematic representation for assessing the impact of green capital deepening on productivity dynamics, within the context of environmental policy effectiveness.

We identify two key reasons for considering green capital as a direct input in the production process. First, green technologies are not consumed in a single production process, but rather are amortized over a longer timespan. For instance, while expenditures on fossil fuels are consumed entirely in a single production cycle (making them intermediate inputs), green technology adoption such as spending on renewable energy allows for energy generation and cost savings over multiple future production cycles. Second, when a business spends on green technologies, it is devoting "resources to projects designed to increase future rather than current output",[7] meeting the intertemporal criterion for inputs capitalization of tangible and intangible assets discussed by Corrado et al. (2005) and Corrado and Hulten (2010). In particular, while firms need to sustain higher upfront costs to adopt green technologies, they also benefit from higher costs savings in the longer term. In this respect, expenditures in green technologies should not only be considered as capital formation, but more precisely as creation of innovative capital—similar for instance to investment in hardware and communication technologies in the computer revolution (Jorgenson and Stiroh 1999, Corrado et al. 2017).

Accordingly, and referring to the sources of growth literature, we consider green technological capital as a production input contributing directly to productivity growth via increasing capital deepening. At the same time, green technological capital may indirectly affect productivity dynamics by interacting with other technological and traditional assets. This interaction encompasses several key mechanisms. First, green capital may exhibit synergies with existing technologies, resulting in improved efficiency in resource utilization of installed capacity. This technological synergy underscores the potential for a more sustainable and efficient production system through the integration of eco-friendly technologies with traditional machinery. Then, the use of green technological capital can foster innovation and generate knowledge spillovers, enhancing the efficiency of other forms of technological capital—such as conventional manufacturing systems. For instance, smart grids can significantly reduce energy waste in automotive assembly lines.

Furthermore, it is plausible to assume that environmental regulation influences both the formation and adoption of green technological capital, thus favoring short to medium-run productivity gains. Environmental policies influence the economic landscape through three primary channels: price system, direct support, and regulatory environment. First, environmental policies can affect the price system by internalizing the external costs of environmental degradation. For instance, carbon pricing policies increase the costs of greenhouse gas emissions, thereby incentivizing firms to invest in green technologies.[8] Second, environmental policies can directly support firms investing in green technological capital by means of subsidies, grants, R&D support, as well as tax incentives. Finally, environmental policies shape the regulatory environment within which firms operate, for example, mandating environmental standards that may encourage firms to invest in green capital to comply with the regulation.

Overall, environmental policies, by influencing the accumulation and utilization of green technological capital, can play a pivotal role in affecting productivity dynamics. They can push economies toward sustainable growth paths by promoting the integration of environmental and macroeconomic policy goals, laying down the conditions for environmentally sustainable economic growth.

Figure 1 provides a representation of a sources of growth model augmented to encompass the role of green capital and environmental policies. Output per worker is assumed to be a function of green, technological, and standard capital, and environmental

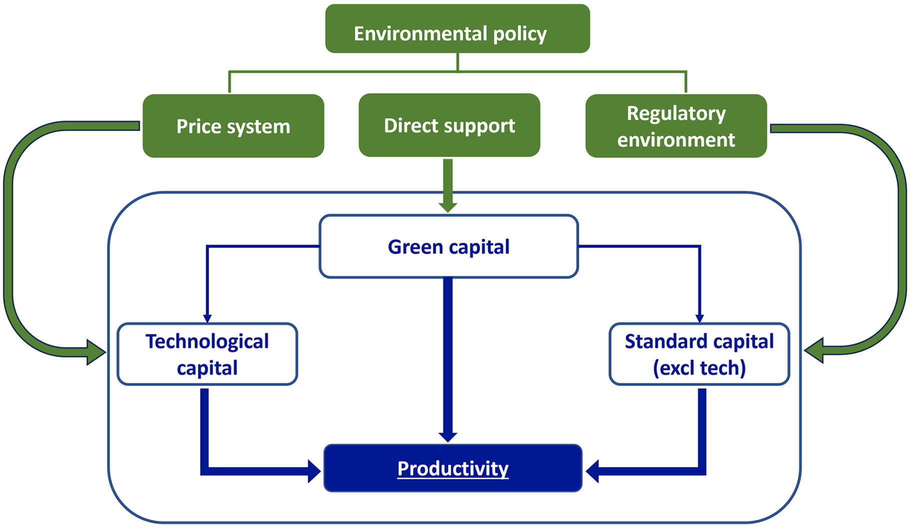

FIGURE 1 | Conceptual framework. *Source:* Authors' representation.

policies affect the formation and adoption of green technological capital and, in turn, productivity growth. This framework constitutes the foundation for the empirical analysis conducted in Section 6.

5 | Construction of the Dataset

The dataset used in this paper includes information on renewable green investment, gross fixed capital formation, hours worked, labor productivity, and the stringency of environmental policies for 18 OECD countries, over the period 2004–2020.[9]

5.1 | Capturing Green Investment and Green Capital

The primary source of data on green investment is BloombergNEF, which provides information on investments in energy transition assets across the following areas:

- Renewable energy: wind (on- and offshore), solar (large- and small-scale), biofuels, biomass and waste, marine, geothermal, and small hydro;
- Energy storage: stationary storage projects (large- and small-scale), excluding pumped hydro, compressed air, and hydrogen. The majority are battery projects;
- Nuclear power: reactors under construction and major refurbishments;
- Hydrogen: hydrogen electrolyzer projects, thermochemical hydrogen production, pipelines and underground storage;
- Carbon capture and storage (CCS): large- and small-scale commercial CCS projects, dedicated transport and storage;
- Electrified transport: sales of electric cars, commercial vehicles, and buses, as well as home and public charging investments. Hydrogen fuel cell vehicles and refueling stations are also included in this category;
- Electrified heat: residential heat pump investments;
- Sustainable materials: circular economy (recycling) and bioplastics.

The methodology used by BloombergNEF is based on the aggregation of project-level data from public and proprietary sources. Data are derived from financial disclosures by firms, government reports, regulatory filings, and direct engagement with industry stakeholders. BloombergNEF cross-validates these inputs against secondary sources, such as auction results, power purchase agreements, and equipment supplier records, to ensure accuracy. Investment values reflect actual financial commitments (e.g., project commissioning costs, equipment purchases, and construction contracts) rather than announced or planned expenditures, minimizing overestimation biases. The dataset is updated quarterly, with historical revisions applied retroactively to maintain consistency.

Data—expressed in billions of US dollars at current prices—are available at both quarterly and annual frequency from 2004 onward, with breakdowns by area, country, and asset class (e.g., asset finance vs. small-scale solar). However, the dataset excludes investments in R&D and uncommissioned pilot projects. Furthermore, quarterly figures exclude energy storage, electrified heat, electrified transport,[10] and hydrogen investment, as data for these categories are only available on an annual basis. Additionally, there are further data limitations: (i) energy efficiency investment is not covered; (ii) public investment is largely unrecorded; and (iii) time coverage varies across different areas.[11] Overall, quarterly data availability is limited. For our set of 18 OECD countries, high-quality annual data on different categories of energy transition expenditures are only consistently available from 2015 onward.

For these reasons, we first focus on total green investment in G7 economies over the 2015–2020 period, for which a complete set of data on the different green technological assets is available.[12] This focus allows for a clearer assessment of the relevance of individual green assets in the most recent years. As shown in Figure 2, green investment in G7 countries has substantially increased, from $160 billion in 2015 to $227 billion in 2020. Up to the COVID-19 pandemic, investment in renewable energy represented the largest component of green investment, with investment in electrified transport expanding more substantially only in recent years.

Renewable energy constitutes the only area for which investment figures are available with good coverage at country level from 2004 onward. Bearing in mind this and the data limitations discussed above—in line with Eyraud et al. (2013)—the remainder of the paper will focus on renewable energy investment. BloombergNEF compiles data on capital expenditures across a range of renewable technologies; the database covers all major renewable energy projects above specific thresholds—including solar, wind, biomass, and waste-to-energy projects over 1 MW; hydropower projects between 1 and 50 MW; wave and tidal projects; and large biofuel projects. When deal values are not disclosed, BloombergNEF estimates investment amounts based on comparable transactions, and all figures are back-checked and updated as new information becomes available. The statistics used in this analysis are based on historical, confirmed, and disclosed investment figures.[13]

Figure 3 shows the dynamics of renewable green investment, distinguishing between G7 and non-G7 countries. Data suggest that G7 economies recorded a steady increase in renewable green investment over the years, especially at the beginning of the period, while in the non-G7 countries included in our sample, investment in renewable energy increased at a lower pace.

Furthermore, the dynamics of green technological investment by country (Figure 4)[14] reveal considerable cross-country heterogeneity. On average, the share of renewable investment remained below 1% of GVA across all countries throughout the period. Nevertheless, most economies experienced a broad-based increase in the share, albeit at varying rates. While not shown in the plot, renewable green investment increased notably in the sample as a whole over the last decade 2010–2020 (+15.86%) but with one European country (Portugal) experiencing a negative change in the same time period.

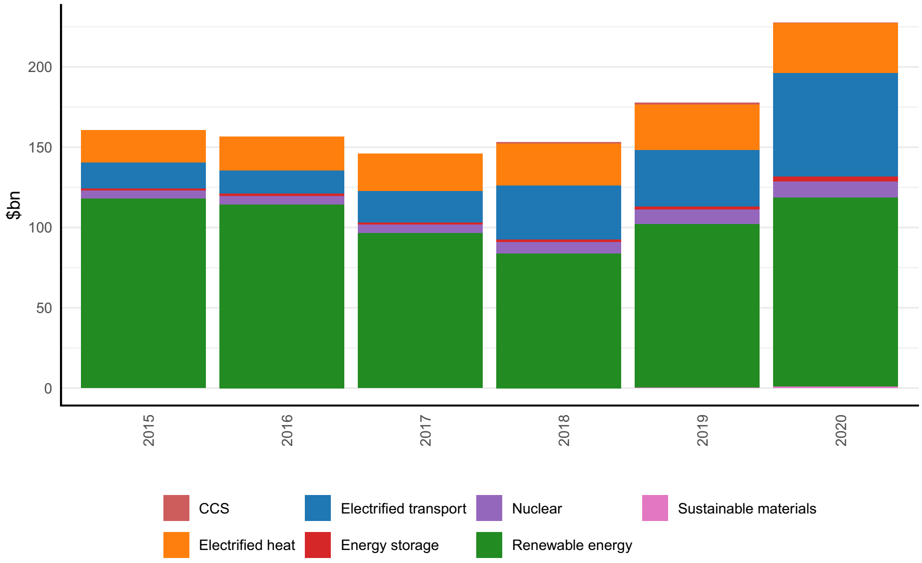

FIGURE 2 | Green investment, 2015–2020, total, G7 countries. *Source:* Authors' elaboration on BloombergNEF.

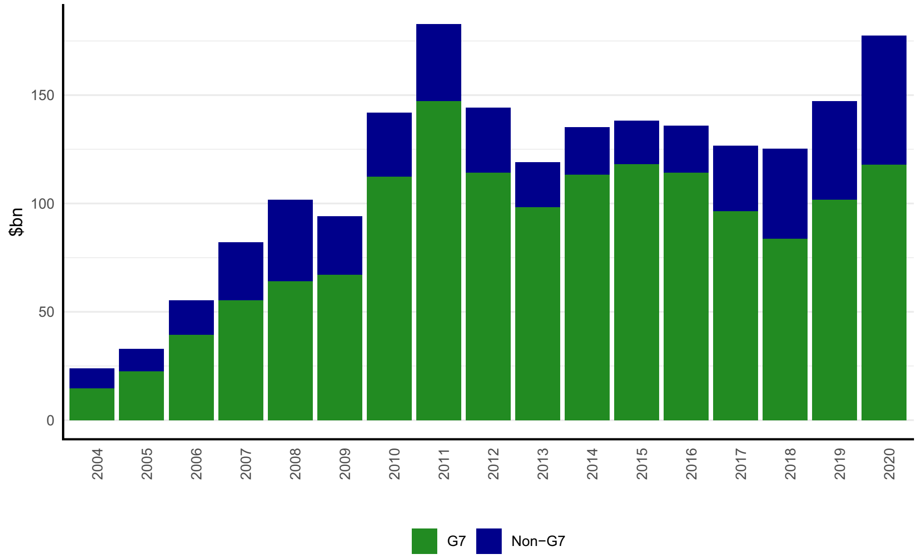

FIGURE 3 | Renewable green investment, 2004–2020. *Source:* Authors' elaboration on BloombergNEF.

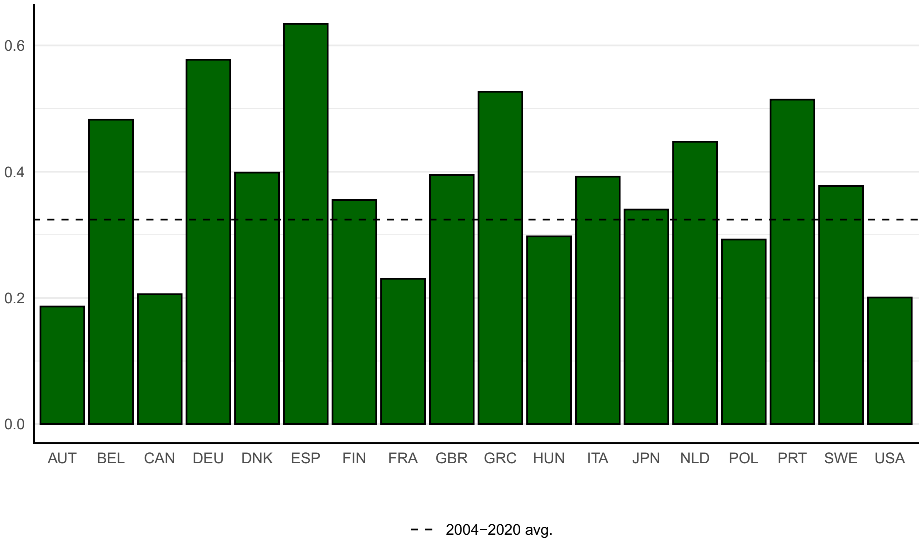

FIGURE 4 | Renewable green investment (per GVA) by country, 2004–2020 time averages. *Source:* Authors' elaboration on BloombergNEF.

In order to test the impact of green capital deepening on productivity in section 6, we estimate a measure of the renewable green capital stock by using the permanent inventory method (PIM). Details on the methodology and assumptions made are provided in Appendix A.

The evolution for the estimated stock of renewable green capital for G7 countries is shown in Figure 5.

5.2 | Other Data Sources

The empirical analysis uses sectoral national accounts and productivity data from the EUKLEMS & INTANProd database, which covers 27 EU Member States, the United Kingdom, the United States, and Japan across 38 NACE industries from 1995 to 2020.[15] Data are expressed in real terms—at 2020 prices—and then standardized by hours worked.

Furthermore, the stringency of environmental policies is measured using the OECD environmental policy stringency (EPS) index. The EPS is a country-specific and internationally comparable measure of the stringency of environmental policy, developed for the OECD countries by Botta and Kožluk (2014) on the basis of the taxonomy of de Serres et al. (2010). The index was recently updated by Kruse et al. (2022). The level of stringency in environmental regulation refers to how much polluting or environmentally detrimental behavior is penalized, either explicitly or implicitly. The aggregate EPS index consists of three equally weighted subindices, ranging between 0 (not stringent) and 0.6 (highest stringency) and measuring the stringency of:

- Market-based policies, such as taxes, permits, trading schemes, and certificates.
- Nonmarket based policies, such as those that mandate emission limits and performance standards.
- Technology support policies, encompassing those policies that support innovation in clean technologies and their adoption, for example, R&D support, feed-in tariffs, auctions.

The index is based on the degree of stringency of 13 environmental policy instruments, primarily related to climate and air pollution. The index ranges from 0 (not stringent) to 6 (highest degree of stringency).[16]

Figures 6–9 show the dynamics of the EPS index and its subcomponents in our sample, comparing the stringency in 2004 vis-à-vis 2020 and its average for the whole sample. Overall, a consistent increase in the stringency of environmental regulation (total index, Figure 6) can be observed across all countries in the period considered. While some countries started from relatively low stringency level at the beginning of the period, almost all countries had a stringency level in 2020 above the 2004–2020 average.

The disaggregation of the total index in its subcomponents shows that there is substantial heterogeneity across subindices. Market-based EPS scores (Figure 7) increased over the period considered in all sample economies compared to 2004. On average, this is the score that increased the most, with a rise of 85.12%. However, most economies still show relatively low stringency levels compared to the sample average. In comparison to other subindices, nonmarket-based EPS scores (Figure 8) have been consistently higher through the entire period, increasing steadily between 2004 and 2020 (35.60%).[17] Finally, the stringency index associated with technology support measures (Figure 9) differs significantly across countries over the whole time span with Denmark, Spain, Greece, Portugal, Sweden, and the United States remaining below the sample average. As discussed by Kruse et al. (2022, p. 27), the decline in the technology support EPS score in some countries over the last decade "largely account*[s]* for the recent flattening of the overall EPS."

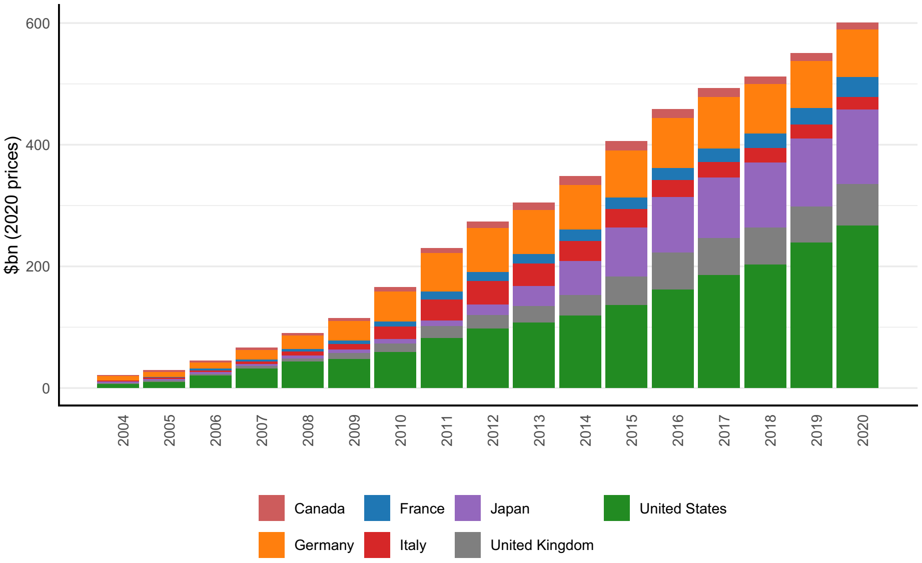

FIGURE 5 | Renewable green capital in G7 countries, 2004–2020. *Source*: Authors' elaboration on BloombergNEF and EUKLEMS & INTANProd data.

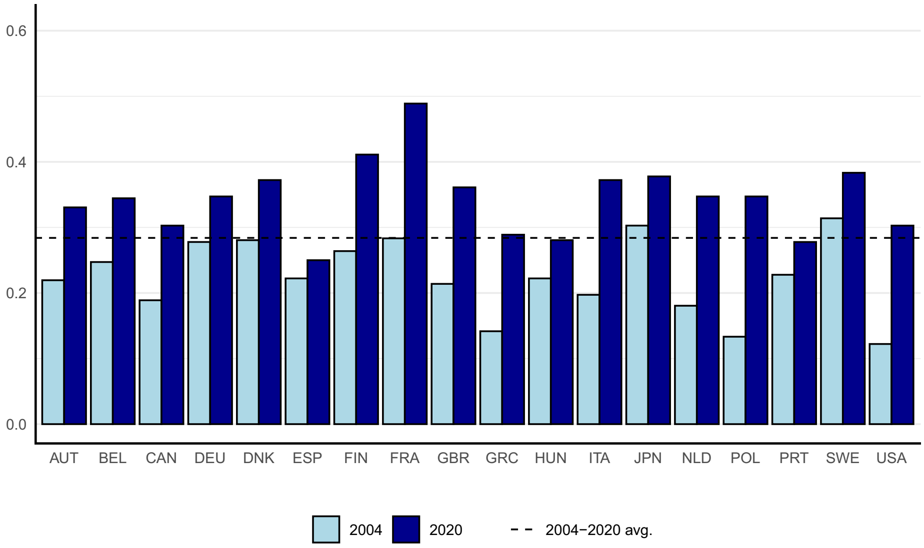

FIGURE 6 | Economic policy stringency by country, total index, 2004–2020. *Source:* Authors' elaboration on OECD data.

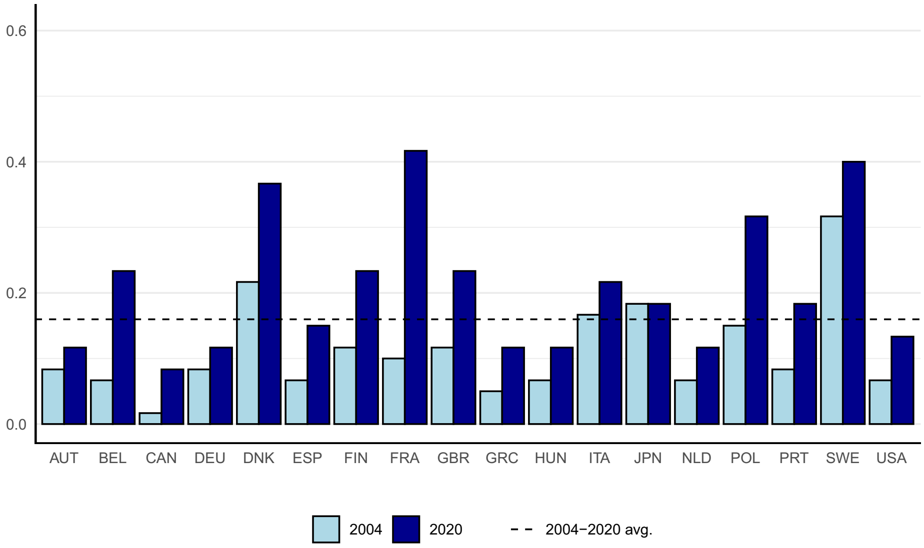

FIGURE 7 | Economic policy stringency by country, market policies, 2004–2020. *Source:* Authors' elaboration on OECD data.

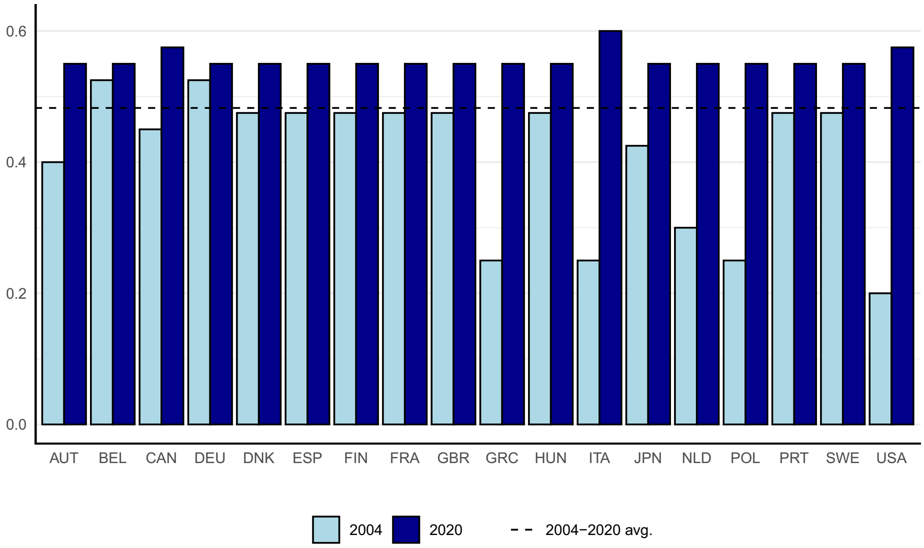

FIGURE 8 | Economic policy stringency by country, nonmarket policies, 2004–2020. *Source:* Authors' elaboration on OECD data.

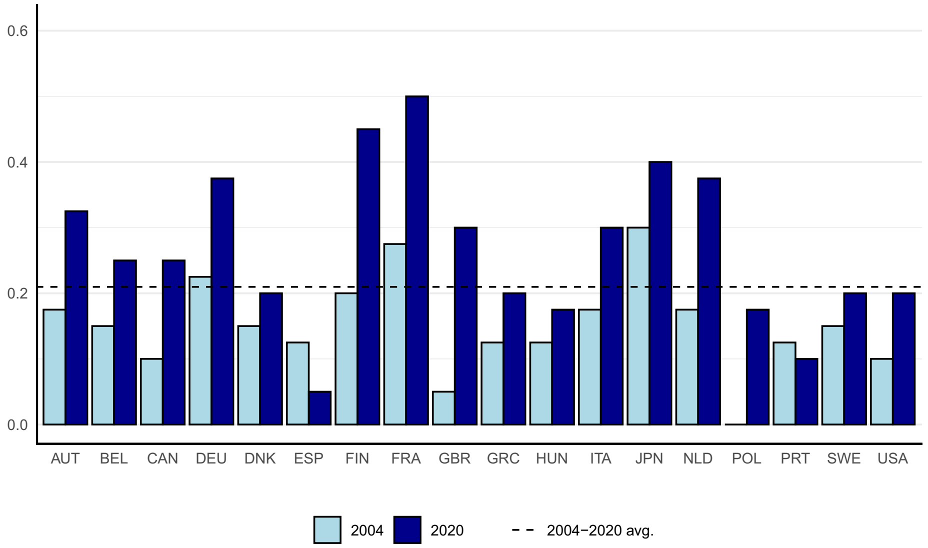

FIGURE 9 | Economic policy stringency by country, technology support policies, 2004–2020. *Source:* Authors' elaboration on OECD data.

TABLE 2 | Data description.

Variable	Description	Source
y	Labor productivity—GDP per hour worked	EUKLEMS & INTANProd
k	Capital intensity—Capital per hour worked	EUKLEMS & INTANProd
k_{green}	Green technological capital per hour worked	BloombergNEF, EUKLEMS & INTANProd
EPS	Environmental policy stringency index—total	OECD
EPS_{MKT}	Environmental policy stringency index—market policies	OECD
EPS_{NMKT}	Environmental policy stringency index—nonmarket policies	OECD
$TECHSUP$	Environmental policy stringency index—technology support	OECD

6 | Empirical Strategy and Econometric Results

In this section, we illustrate our empirical strategy for evaluating the contribution of green technological capital to labor productivity growth, also considering the potential influence of environmental policies. Notice that in the empirical analysis, green technological capital refers only to renewable capital. We start by providing some additional information about the sources of the main variables used in the empirical analysis in Table 2, where productivity and capital intensities are expressed in natural logarithms and measured in per hour terms. Similar to the other variables, green technological capital is then standardized by hours worked.[18]

TABLE 3 | Summary statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
$\Delta \ln(y)$	272	0.008	0.018	−0.074	0.070
$\Delta \ln(k_t)$	272	0.009	0.028	−0.102	0.124
$\Delta \ln(k_{green,t})$	272	0.225	0.387	−0.153	4.394
EPS	306	0.304	0.061	0.122	0.489
EPS_{MKT}	306	0.161	0.094	0.017	0.417
EPS_{NMKT}	306	0.506	0.068	0.200	0.600
$TECHSUP$	306	0.246	0.122	0.000	0.600

Source: Authors' elaboration on OECD.Stat, EUKLEMS & INTANProd.

Table 3 shows the summary statistics for the variables of interest.[19] The dataset is organized as an unbalanced panel as there is some missing information for the initial year of the time series.

Before moving to the empirical strategy and results, we look at the correlation of our estimate of green technological capital and the environmental policy indicators to get the sense of the econometric findings.

Figure 10 plots the cross-country relationships between green technological capital per hour (k_{green}) and the total EPS score and its subindexes. While the overall correlation between policy stringency and green capital intensity is positive, the analysis reveals substantial heterogeneity across countries and across the EPS subindexes. Some economies achieve relatively high levels of green capital intensity with moderate policy stringency, while others exhibit lower green capital intensity despite more stringent environmental frameworks. This heterogeneity, observed across both larger (e.g., France and the United States) and smaller economies (e.g., Denmark, Poland, and Hungary), suggests that further investigation is needed to disentangle policy effectiveness from structural and institutional factors. This is the purpose of the econometric analysis presented below.

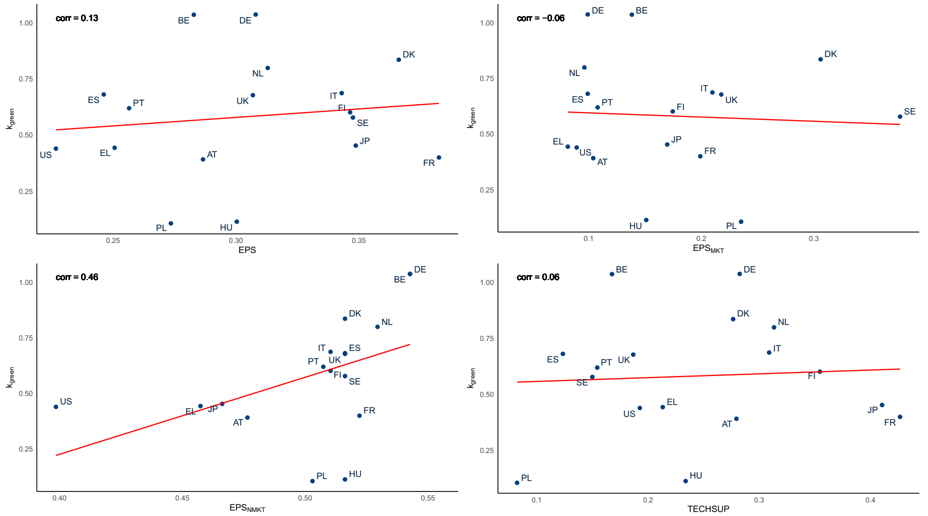

FIGURE 10 | Green technological capital and environmental policy stringency, averages by time, 2004–2020. *Source:* Authors' elaboration on BloombergNEF and EUKLEMS & INTANProd.

The central objective of the empirical investigation is to evaluate the productivity effects of scaling up green technological capital, with a particular focus on the conditional impact of environmental regulation. Our primary expectations are twofold: (i) increasing green technological capital might lead to medium-term productivity gains; (ii) in line with the Porter hypothesis (Porter and van der Linde 1995), we assume that stricter environmental policies will incentivize innovation, thereby leading to positive productivity outcomes.[20] To verify these assumptions, and building on the database discussed above, first we econometrically test a benchmark equation for a standard production function augmented with green technological capital and then we use this framework to evaluate the impact of different measures of environmental stringency.

The benchmark specification is as follows:

$$\Delta y_{i,t} = \beta_0 + \sum_{c=1}^{C} \beta_C \Delta x_{i,t}^{C} + \sum_{d=1}^{D} \beta_D x_{i,t}^{D} + \sum_{e=1}^{E} \beta_E X_{i,t}^{E} + \gamma_t + \eta_i + \epsilon_{i,t} \tag{1}$$

where i is the country and t is the time. $x_{i,t}^{C}$ is the vector of covariates (in log differences), $x_{i,t}^{D}$ is the vector of covariates in levels, $X_{i,t}^{E}$ are the control variables (when applicable, intangible assets), η_i represents the country-specific fixed effects and γ_t captures the time-specific fixed effects.

The model specifications are estimated on data pooled across countries and over time, using the generalized least squares (GLS) method to account for heteroscedasticity and serial correlation of the error terms. However, the coefficients estimated using GLS regression might suffer from simultaneity bias, meaning the dependent variable and one or more covariates could be determined jointly. This issue is a common concern in the literature on production function estimation, where instrumental variables are typically employed to address such endogeneity problems. Therefore, we test our model using the Arellano–Bond estimator, that is a generalized method of moments (GMM) estimator specifically designed for dynamic panel data models. The Arellano–Bond estimator addresses endogeneity biases by using lagged levels of the dependent variable (and potentially other exogenous or predetermined variables) as instruments for the differenced equation. We thus instrument total capital stock and green technological capital stock with their lagged level at $t-2$ and their lagged first differences.[21]

Regression results are shown in Table 4.[22] Columns 1 and 2 report GLS and GMM estimates of the benchmark equation, while in columns 3 (GLS) and 4 (GMM), the model is augmented with green technological capital to test its contribution to labor productivity growth. Columns 5–8 present the effects of EPS by testing the EPS index and its subcomponents individually. Columns 9 (GLS) and 10 (GMM) then examine potential synergies between public R&D and renewable green capital. As highlighted by the IEA (2025), public R&D has played a significant role in advancing solar, wind, and other renewable energy technologies, resulting in cost reductions and improved efficiency. These advancements have, in turn, attracted substantial private investment in the deployment of such technologies and may have contributed to productivity gains.

Our findings show that, albeit small, scaling up green technological capital input has a positive and significant effect on productivity growth: a 1% increase in the growth rate of green capital per hours worked leads to an increase in labor productivity growth ranging between 0.006 and 0.01 pp, depending on the model specification. This is a small, but plausible contribution if compared to the total (standard) capital input as a 1% increase in standard capital deepening generates 0.41% pp to 0.55% pp increase in labor productivity growth coherently with the production function literature. Further, the positive contribution of green technological capital deepening is statistically robust across different model specifications and when tested with GMM the coefficient is slightly larger suggesting that, as other tangible capital assets, it might be affected by a downward endogeneity bias. The models in columns from 5 to 8 evaluate the effect of environmental regulation on productivity growth. Overall, environmental stringency has a positive impact on productivity growth even if not statistically significant (Column 5). A different picture emerges

TABLE 4 | Regression results.

Variables	(1) GLS	(2) GMM	(3) GLS	(4) GMM	(5) GLS	(6) GLS	(7) GLS	(8) GLS	(9) GLS	(10) GMM
$\Delta\ln(k)$	0.449^{***}	0.436^{***}	0.443^{***}	0.497^{***}	0.442^{***}	0.444^{***}	0.446^{***}	0.445^{***}	0.414^{***}	0.554^{***}
	(11.294)	(3.867)	(11.323)	(4.621)	(11.225)	(11.385)	(11.507)	(10.808)	(9.820)	(6.907)
$\Delta\ln(k_{Green})$			0.006^{***}	0.010^{*}	0.006^{***}	0.006^{***}	0.006^{***}	0.006^{***}	0.008^{**}	0.010^{**}
			(2.951)	(1.882)	(2.952)	(2.712)	(2.929)	(2.851)	(2.032)	(2.223)
$\ln(EPS)$					0.002					
					(0.235)					
$\ln(EPS_{MKT})$						−0.005				
						(−1.404)				
$\ln(EPS_{NMKT})$							0.020^{**}			
							(2.317)			
$\ln(TECHSUP)$								−0.001		
								(−0.607)		
$\ln(RD_{GOV}) \times \ln(k_{Green})$									0.016^{**}	0.012^{**}
									(2.438)	(1.978)
Observations	272	240	272	240	272	272	272	269	238	238

Note: Labor productivity growth as dependent variable; Annual data; *z* statistics in parentheses; all specifications are estimated with year and country fixed effects.
$^{*}p < 0.1$. $^{**}p < 0.05$. $^{***}p < 0.01$.

when we look at the three subcomponents of EPS individually. Results in Column 6 suggest that strengthening environmental regulation through market policies, for example, carbon taxes and trading schemes, does not affect productivity growth. On the other hand, nonmarket policies—such as emission limits—seem very effective in fostering innovation (Column 7). The stringency associated with technology support measures has statistically insignificant impact on productivity growth (Column 8).[23]

As stated above, we also test the framework conditions through which green technological capital might contribute to productivity growth via the indirect channels in Figure 1, we interact the level of the green capital stock with public investment in R&D. Estimates support the assumption of a self-reinforcing mechanism between green technological capital and the dynamics of government R&D spending; when interacted with the level of green capital, a 1% increase in government R&D leads to a 1.4%–1.6% increase in productivity after 2 years, depending on the model's specification (Columns 9 and 10). The lagged effect suggests that the impact of innovation support takes time to materialize (Deleidi et al. 2019; Ciaffi et al. 2024). Notice that in Columns 9 and 10, the number of observations is reduced because the time coverage of lagged public R&D data is slightly smaller. Summing up, our findings suggest that increasing the growth rate of green technological capital deepening positively affects productivity growth and that this effect further enhanced by non-market based environmental regulatory measures.

7 | Policy Discussion

As discussed in the introductory sections of this paper, scaling up green investment by a factor of 3 to 4 at the global level is a key policy challenge to remain on track with the goals of the Paris Agreement (IRENA 2022; CPI and IRENA 2023; IPCC 2023b). Besides ensuring a timely and just transition, scaling up green investment might potentially contribute to reducing structural economic vulnerabilities while enhancing energy security in the overall economy and its key sectors. But the shift toward green investment also implies significant costs (e.g., initial capital costs for the private sector, fiscal costs, risk of job destruction, etc.). While the climate change mitigating effect of policy interventions aimed at increasing, directly or indirectly, green investment is well documented, its macroeconomic effects are less clearly identified. The review of the existing literature on macroeconomic definitions of green investment presented in the third section highlighted there is still no consensus around this concept, thus suggesting the need to further improve green investment definition and measurement. The lack of a clear indication about what type of assets can be classified as green investment makes measurement rather challenging. This also reflects on the ability to make comprehensive policy evaluations of the green transition and better define environmental mitigation strategies. In this regard, international organizations and statistical offices may have a role to play in further developing definitions and reporting requirements on green investments.

The primary objective of climate policies is to reduce emissions. In the empirical analysis conducted in this paper, we find a positive relationship between green technological investment and productivity growth thus suggesting that there is not necessarily a trade-off between pursuing climate change mitigation objectives and promoting economic growth. On the contrary, synergies might arise from the implementation of these goals and governments may decide to develop strategies which include policies for controlling climate change that concurrently can spur productivity growth through green investment projects. But scaling public investment is not by itself enough to ensure desired mitigation goals, as "the carrots of investment need to go hand in hand with climate regulatory sticks" (Meckling and Strecker 2022, 419). As emphasized by the existing literature (Chițimiea et al. 2021; Del Río et al. 2011; Kesidou and Demirel 2012; Leiter et al. 2011), regulation and legislation set by governments is seen as a significant driving force capable of positively influencing firms' green investment decisions and performance. In line with the Porter hypothesis, our findings confirm that the introduction of more stringent environmental rules and regulations may have an impact on firms' productivity dynamics by fostering innovation. While stricter environmental regulation does not appear to constrain productivity growth, the introduction of specific types of policies might even stimulate innovation, thus contributing to positive productivity returns. Particularly, in our sample, nonmarket policies—intended as those instruments that work through the imposition of certain obligations such as the introduction of emission limits or technology standards—appear to be the most effective in fostering innovation. Conversely, strengthening environmental regulation through market policies—for example, carbon taxes and trading schemes—could lead to negative (albeit small) effects on productivity growth. The policy implications of this result is that more stringent and well-designed environmental regulations can play a role in boosting innovation. Particularly nonmarket-based instruments are a useful tool to encourage greater innovativeness, as the limitation on some production activities may provide an incentive to firms for the introduction of cleaner and more innovative processes. This does not imply that market-based strategies should be totally discarded, but that a proper combination of the two types of policies should be considered when introducing new environmental regulations or tightening existing ones. In addition, when evaluating environmental regulatory instruments, policymakers should also consider the potential represented by technology support measures, such as public R&D spending on low-carbon energy technologies and price support for solar and wind energy, which appear to have a positive—even though not statistically significant—impact on productivity growth.

On aggregate, climate policies have significant environmental benefits and no large negative economic impacts.[24] Emission reduction goals will require a drastic increase in mitigation policy stringency. While more stringent climate change mitigation policies are needed, these alone are not sufficient to promote investments in green technologies. When designing mitigation strategies, there are several other factors that should be considered that can accelerate green investment and the adoption of green technologies. Firms' disclosure requirements for green investments can help reduce investors' information asymmetries and help allocate capital toward greener technologies. Green public procurement requirements can help increase demand for green goods and accelerate green investments. Moreover, complementary policies are needed to enable the green transition. In particular, skills policies that target the reskilling or upskilling of green workers are essential for addressing environmental challenges, enabling the effective use of green technologies and processes, and promoting a more even distribution of green competences across workers, countries, and sectors. In addition, trade openness, by facilitating the flow of goods, technology, and processes, can contribute to spreading green technology along the global value chains. The enhancement of each of these factors can have a role in paving the way to a faster pace of green investments.

Overall, to achieve the goal of keeping global warming well below 2°C, government financing and well-designed mitigation strategies are crucial but not sufficient to meet green investment needs alone. If policymakers want to fulfill their climate ambitions, they need to mobilize private capital. In this regard, governments have a significant role to play as direct public investment in green capital can generate productive capacity while fostering demand, creating favorable business conditions, and stimulating private investment. Deleidi et al. (2020) provide support for this policy approach by presenting empirical evidence according to which, on average, direct public participation is effective at mobilizing private funds; public investments not only have a positive but also consistently the largest effect on private investment flows, while subsidies and taxes have much smaller z positive impacts. Governments can attract greater flows of private financing toward green projects and opportunities by creating an enabling environment that reduce barriers to private investment, set the right incentives and standards, and ensure openness, transparency, and regulatory stability. Above all, coordinated action across the public and private sector will be required. Public–private cooperation and closer partnerships are thus essential to reduce information, policy, or behavioral barriers to the scaling of green investment, and improve the flow of finance to climate-friendly early-stage financing.

8 | Conclusion

In this paper, we provided an overview on the issues related to the definition and measurement of green investment at the macroeconomic level, assessing its scope for promoting long-run growth while mitigating climate change. First, we conducted a comprehensive review of the existing literature on the topic. Second, we surveyed and discussed different macroeconomic definitions and measurements of green investment, highlighting scope for further work and possible limitations. More specifically, our paper shows that, while there are several definitions of green investment, their practical significance for policy analysis and measuring is hindered by the lack of a clear indication from the official statistics about what type of assets can be classified as "green." Following Eyraud et al. (2013) and resorting to BloombergNEF data, we constructed a database for 18 OECD countries over the years 2004–2020, encompassing observations on green technological investment, productivity, capital stock by asset, hours worked, and EPS. Building upon these data, we provide an estimate of green technological capital, showing its dynamics over time across our sample economies and then we test its productivity contribution also considering the mediating effect of enviromental policy stringency. Our findings suggest that green technological capital generates productivity gains in the medium term: the estimated effect of a 1% increase in green technological capital is small (0.008 pp), but statistically significant and robust across different model specifications. Further, we find that stricter environmental regulation lead to productivity growth by fostering innovation, as suggested by the Porter hypothesis. Summing up, our results might be considered as an early evidence of the lack of a hard trade-off between the goals of mitigating climate change and promoting long-term growth.

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Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting this study include proprietary data from BloombergNEF (https://about.bnef.com) and open-access datasets from EUKLEMS & INTANProd (https://euklems-intanprod-llee.luiss.it/) and OECD (https://data-explorer.oecd.org/). Additional details about specific datasets and access procedures can be provided upon request.

Endnotes

[1] Similarly, the latest IPCC (2023b) synthesis report estimates that "investment requirements for 2020 to 2030 in scenarios that limit warming to 2°C or 1.5°C are a factor of three to six greater than current levels, and total mitigation investments [. . .] would need to increase across all sectors and regions" (IPCC 2023b, 29). Further, The UN Environmental Programme (Sukhdev et al. 2010) recognized that achieving a green economy by increasing green investment would bring a reconfiguration that could lead to a higher share of green sectors in GDP, greener jobs, lower energy and resource-intensive production, lower waste, and pollution and significantly lower greenhouse gas emissions.

[2] The authors estimate green productivity growth through the Malmquist–Luenberger index using data on capital, labor, and energy inputs as well as two measures of desirable and undesirable output.

[3] For a classification and discussion, see Busch et al. (2022).

[4] Along these lines—and albeit not necessarily focused on investment outlays—another significant strand of literature approaches the measurement of green products through the lens of national accounting. These efforts have been recently synthesized in Bhanumati et al. (2024), who summarize a growing body of work by international organizations such as Eurostat, the OECD, and UNDP, as well as country-specific initiatives (e.g., the PACINAS project in Austria). Many European countries regularly produce environmental goods and services sector (EGSS) accounts and estimates of environmental protection expenditure (EPE), thus providing a framework for estimating environmental activity.

[5] Although nuclear may also be considered as a low-emission energy supply, they did not include it in their definition, primarily because of the radioactive waste production involved, differences existing in investment decisions in nuclear and renewable energy and specific characteristics related to investment in this field.

[6] Alongside that, it is also worth mentioning that the European Investment Bank (2023) has put together data on climate adaptation investment for EU countries from 2014 to 2021.

[7] Corrado et al. (2005, 19–20).

[8] Notice that these policies are more effective in a context of strong international cooperation aimed at minimizing carbon leakages (Babiker 2005).

[9] The database covers all G7 countries (Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States) plus Austria, Belgium, Denmark, Finland, Greece, Hungary, Netherlands, Poland, Portugal, Spain, and Sweden.

[10] The category of electrified transport includes only investment in the sector and does not account for consumption, for example, households' purchase of EVs.

[11] Investment in sustainable materials is available only from 2019, CCS and hydrogen from 2018, nuclear from 2015, and electrified heat from 2014. Therefore, the totals represent a conservative estimate of global energy transition investment.

[12] Hydrogen projects—not tracked for G7 countries in our database—are excluded.

[13] For an in-depth description of the methodology, see Frankfurt School-UNEP Centre and BloombergNEF (2020).

[14] Data are standardized by gross value added (GVA), retrieved from the EUKLEMS & INTANProd database (see next subsection).

[15] For further details, see Bontadini et al. (2023).

[16] For further information about the methodology, see Kruse et al. (2022).

[17] Kruse et al. (2022), Table 4) report that, for the full sample of 40 countries, the index increased by 15% over the period 2010–2020.

[18] There is not a clear guidance in the literature nor in official statistics to identify the best prices for deflating green renewable investment. In this paper we use the price index of communications equipment (2020 = 100) to compute green renewable investment in real terms. The rationale for this choice is that communication equipment plays a crucial role in the deployment and operation of many green technologies, especially renewable energy management systems, but also environmental monitoring sensors, smart grids and sustainable transportation all relying heavily on communication infrastructure.

[19] The summary statistics are reported in delta log for the independent and explanatory variables and in levels for total EPS index and subindexes to better get the sense of the extent of growth rates but also of the intensities of the policy indicators. Canada is excluded from the estimation because it is not included in the EUKLEMS & INTANProd database, which prevented the calculation of capital intensities for this country.

[20] The latter aspect has already been explored in the literature—with empirical studies (e.g., De Santis and Jona Lasinio 2016; De Santis et al. 2021) providing support to the Porter hypothesis. As discussed in section 2, the literature on the empirical effects of green investment is instead relatively newer and the theme has been less explored.

[21] *F* tests on the first-stage regressions and the Cragg–Donald test reject the null hypothesis of weak instruments for the specifications underlying Columns 2, 4, and 10. See Appendix C.

[22] Given that the regression results might be biased by the assumptions made regarding the calculation of the renewable green capital stock—particularly, the choice of the depreciation rate—we conduct some sensitivity analysis by rerunning the PIM with different depreciation rates. We show that the results are robust to variations in the depreciation rate in Appendix B.

[23] However, one might notice that the subindex *TECHSUP* groups together two sets of policies which have arguably different effects (Becker 2015), that is, public R&D expenditures on low-carbon energy technologies and renewable energy support measures. Therefore, further research should aim at increasing further the level of granularity, by testing the effect of each policy in each subgroup, using the most disaggregated data provided in Kruse et al. (2022).

[24] During the last decade the OECD carried out several studies on competitiveness and environmental effects—covering different samples, time periods and methods—which support this finding. Effects may differ across countries depending on country-specific policy contexts, macroeconomic effects and the time horizon but, overall, the economic

impact of a 10% increase in industry energy prices on manufacturing sectors has found to be much smaller than its environmental impact. While producing significant decline in energy use and carbon intensity of 5–10%, it brings small decreases in employment and productivity, small increases in FDI ratio and productivity and has no impact on net manufacturing exports. For further discussion, OECD (2021).

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Appendix A

Permanent Inventory Method

We apply the permanent inventory method (PIM) to the series of renewable green investment in real terms. Accordingly, we first need to choose an appropriate price level to deflate the series. In absence of reliable data sources, we adopt the average of the price deflators of two similar fixed assets, for example, communications equipment and other machinery and equipment. The data are gathered from the EUKLEMS & INTANProd database and both deflators are harmonized (quality adjusted). The second important element necessary to applying the PIM is the identification of a depreciation rate for renewable green capital stock. As there is no evidence on its depreciation rate, we compute the average of the depreciation rates of the two fixed assets mentioned above following the so-called geometric model, considering that they have a similar vintage of renewable green capital stock (mostly constituted by machinery and equipment). In particular, the total industry depreciation rates in EUKLEMS & INTANProd for assets in “Other machinery” and “Communication technologies” (CT) are, respectively, 12.9% and 11.5% (Bontadini et al. 2023), resulting in a depreciation rate of 12.2%. Third, the capital stock in the starting year is initialized using the steady-state approach (Berlemann and Wesselhöft 2014). Specifically, the initial capital stock is computed according to the formula $K_{\text{green},0} = I_{\text{green},0}/(g + \delta)$, where $I_{\text{green},0}$ denotes the initial value of renewable green investment, g is the average annual growth rate of investment over the period 2004–2020, and δ is the depreciation rate. Both investment and estimated capital stock are expressed in constant 2020 US dollars.

Appendix B

Estimation Results With Different Depreciation Rates of the Renewable Green Capital Stock

As illustrated above, the choice of the depreciation rate used to estimate the renewable green capital stock is crucial for the resulting series. Given the inherent difficulty in identifying an appropriate depreciation rate, we conduct a sensitivity analysis around the baseline rate ($\delta = 12.2\%$). Specifically, we rerun the PIM to calculate the renewable green capital stock

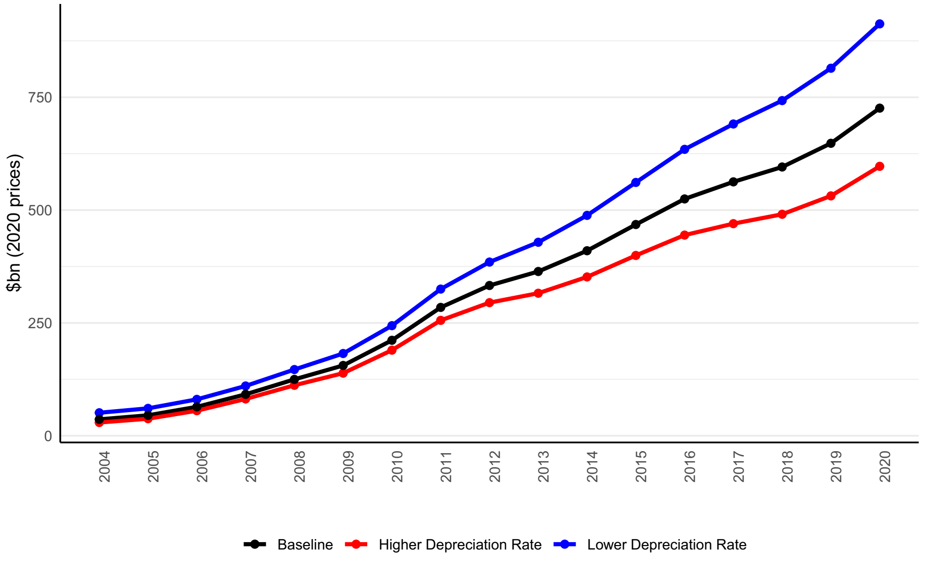

FIGURE B1 | Renewable green capital stock with different depreciation rates, total. *Source:* Authors' elaboration on BloombergNEF and EUKLEMS & INTANProd data.

TABLE B1 | Regression results—lower depreciation rate ($\delta_{\text{low}} = 7.2\%$).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Variables	**GLS**	**GMM**	**GLS**	**GMM**	**GLS**	**GLS**	**GLS**	**GLS**	**GLS**	**GMM**
$\Delta \ln(k)$	0.449***	0.436***	0.442***	0.494***	0.441***	0.443***	0.445***	0.444***	0.412***	0.426***
	(11.294)	(3.867)	(11.288)	(4.603)	(11.193)	(11.352)	(11.471)	(10.784)	(9.806)	(7.712)
$\Delta \ln(k_{\text{Green}})$			0.007***	0.010*	0.007***	0.006***	0.007***	0.007***	0.010**	0.012**
			(2.993)	(1.878)	(2.992)	(2.752)	(2.957)	(2.905)	(2.160)	(2.246)
$\ln(EPS)$					0.002					
					(0.215)					
$\ln(EPS_{MKT})$						−0.005				
						(−1.394)				
$\ln(EPS_{NMKT})$							0.020**			
							(2.299)			
$\ln(TECHSUP)$								−0.001		
								(−0.628)		
$\ln(RD_{GOV}) \times \ln(k_{Green})$									0.015**	0.014**
									(2.334)	(2.203)
										(−0.939)
Observations	272	240	272	240	272	272	272	269	238	224
R^2		0.539		0.558						0.583

Note: Labor productivity growth as dependent variable; annual data; z statistics in parentheses; all specifications are estimated with year and country fixed effects.
$^{*}p < 0.1$. $^{**}p < 0.05$. $^{***}p < 0.01$.

assuming alternative depreciation rates of ±5% compared to the baseline, resulting in $\delta_{low} = 7.2\%$ and $\delta_{high} = 17.2\%$.

Figure B1 plots the aggregate series of renewable green capital stock (in constant 2020 prices) under different assumptions regarding the depreciation rate. The figure shows that the trajectory of the estimated series is significantly affected by the choice of the depreciation rate, highlighting the need for a deeper econometric investigation to assess the robustness of the results under alternative assumptions.

We then reestimate our econometric framework using the new series of renewable green capital per hour worked. Regression results are reported in Tables B1 and B2. As can be observed, the econometric results remain broadly robust to variations in the depreciation rate. Differences relative to the baseline estimates (Table 4) are minimal: for some specifications the coefficient of $\Delta \ln(k_{\text{Green}})$ tends to be slightly higher (lower) when the depreciation rate is lower (higher), as would be expected, but the magnitude of the difference is negligible.

TABLE B2 | Regression results—higher depreciation rate ($\delta_{\text{high}} = 17.2\%$).

Variables	(1) GLS	(2) GMM	(3) GLS	(4) GMM	(5) GLS	(6) GLS	(7) GLS	(8) GLS	(9) GLS	(10) GMM
$\Delta \ln(k)$	0.449***	0.436***	0.445***	0.501***	0.443***	0.445***	0.448***	0.446***	0.415***	0.431***
	(11.294)	(3.867)	(11.354)	(4.639)	(11.254)	(11.416)	(11.541)	(10.830)	(9.823)	(7.742)
$\Delta \ln(k_{\text{Green}})$			0.006***	0.009*	0.006***	0.006***	0.006***	0.006***	0.007*	0.008**
			(2.913)	(1.876)	(2.915)	(2.679)	(2.906)	(2.802)	(1.942)	(2.075)
$\ln(EPS)$					0.002					
					(0.251)					
$\ln(EPS_{MKT})$						−0.005				
						(−1.420)				
$\ln(EPS_{NMKT})$							0.020**			
							(2.335)			
$\ln(TECHSUP)$								−0.001		
								(−0.589)		
$\ln(RD_{GOV}) \times \ln(k_{Green})$									0.016**	0.014**
									(2.505)	(2.152)
										(−0.726)
Observations	272	240	272	240	272	272	272	269	238	224
R^2		0.539		0.556						0.582

Note: Labor productivity growth as dependent variable; annual data; z statistics in parentheses; all specifications are estimated with year and country fixed effects.
$^{*}p < 0.1$. $^{**}p < 0.05$. $^{***}p < 0.01$.

Appendix C

Weak Instrument Tests

See Table C1

TABLE C1 | Weak instrument tests for IV specifications.

Statistic	Column 2	Column 4	Column 10
Cragg–Donald F	12.41	11.42	12.59
Kleibergen–Paap F	10.54	9.33	12.33
10% Max IV bias threshold	10.83	8.78	11.12

Note: Stock–Yogo 10% critical values shown for relevant comparisons.