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Socioeconomic impact of environmental product and process innovation in the context of global trade

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ABSTRACT

Environmental innovation is presented in the public debate as a tool to mitigate climate change, while promoting growth and employment. However, the empirical evidence on its socioeconomic impact is limited to specific types of innovation, sectors, and countries. In this paper, we investigate the direct and indirect effects of environmental product and process innovation in the context of global trade. To conduct our investigation, we build and empirically calibrate a model of the world economy on environmental accounts, socioeconomic accounts, and world input-output tables. We use it to simulate the effects of environmental product and process innovation in different sectors over the period 2020–2040. Our findings point to positive and significant effects in most sectors. However, they confirm the importance of substitution effects between more and less polluting products, imported and domestic. Furthermore, significant trade-offs emerge between promoting growth and supporting employment. These effects vary substantially depending on the type of innovation and sector. The main implication is that industrial policies to promote innovation should be calibrated to the specific policy goal and patterns of innovation prevailing in each sector.

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1. Introduction

The European Union achieved a 31 percent reduction in greenhouse gas emissions over the period 1990–2020, well above the targets set in the climate and energy package (EEA 2021; UNFCCC 2008). However, keeping the global average temperature increase within the limit of 1.5 degrees Celsius requires further efforts (IPCC 2018). Furthermore, the impact of climate change could be catastrophic in some European regions, due to the extremity of climate events and low responsiveness of socioeconomic systems

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(Kelemen et al. 2009). The effects are expected to be particularly severe in the Southern regions, affecting vital sectors like agriculture, tourism and infrastructure (IPCC 2014). The costs of climate change mitigation and adaptation add to the structural problems that have plagued these economies over the past decades, in particular slowing growth and persistent unemployment (Fagerberg and Verspagen 2015; Storm and Naastepad 2006).

Environmental innovation is presented in EU policies as an crucial tool to address these challenges, through reducing polluting emissions, fostering economic growth and creating employment (Akcigit et al. 2022; Al-Ajlani et al. 2022). However, a clear and comprehensive assessment of the socioeconomic effects of environmental innovation is still missing. The extensive literature on general technical change identifies mostly positive and persistent effects on output and employment (Becker and Egger 2013; Calvino and Virgillito 2018; Harrison et al. 2014). Furthermore, it suggests that product and process innovation have distinctive effects on prices, productivity and demand, which vary depending on the level of analysis (Benavente and Lauterbach 2008; Harrison et al. 2014; Jaumandreu and Mairesse 2017). In particular, it points to the existence of compensation and substitution effects between products, firms and sectors, which can influence their impact on output and employment at the macroeconomic level (Pianta 2003; Vivarelli 2007).

In contrast, empirical evidence on the specific effects of environmental innovation on output and employment is scarce and mainly at the firm level (Barbieri et al. 2016). While business studies investigate the willingness to pay for green product quality, economic literature focuses on the relationship between environmental regulations, determinants of innovation and productivity (Borghesi, Cainelli, and Mazzanti 2015; Costantini and Mazzanti 2012; Drozdenko, Jensen, and Coelho 2011). The limited empirical evidence comparing different types of environmental innovation highlights important variations in socioeconomic effects between clean and end-of-pipe technologies (Horbach 2010; Horbach and Rennings 2013; Pfeiffer and Rennings 2001). Furthermore, it suggests that environmental innovation has specific determinants and characteristics, which can influence its effects on demand, productivity, growth and employment (Horbach 2008; Töbelmann and Wendler 2020).

Despite the relevance of these effects, the paucity of panel data and direct indicators of environmental innovation has so far limited the scope of empirical analysis to specific sectors and countries (Barbieri et al. 2016; Licht and Peters 2013). Recent developments in modelling and simulation techniques have enabled the representation of complex interactions between natural and socioeconomic systems in Integrated Assessment Models (IAMs) (van Beek et al. 2020; Weyant 2017). In addition to the large number of variables that hinders the identification of causal relationships, these models lack an explicit representation of green product quality and the propensity to pay for environmental attributes (de Cian, Bosetti, and Tavoni 2012; Fuss et al. 2014; Nordhaus 1993). Furthermore, they focus primarily on negative emissions technologies and supply-side solutions, underestimating the role of demand in shaping green economic restructuring. Therefore, they are not well suited for exploring the direct and indirect effects of environmental innovation on demand, output and employment. Therefore, we incorporate insights from the literature on the socioeconomic effects of innovation into specifically designed modelling and simulation tools to explore these effects in the context of European economies vulnerable to climate change and international competitiveness.

In this paper, we investigate the distinctive effects of environmental product and process innovation on output and employment in the context of global trade, including indirect demand effects and substitution effects between more and less polluting products across sectors and regions. The aim is to understand whether and to what extent environmental product and process innovation can contribute to the green restructuring of vulnerable European economies and to identify potential synergies and trade-offs between increasing output and supporting employment in different sectors. Given the lack of direct indicators of environmental innovation comparable across countries, we conduct this investigation through the construction, empirical calibration and simulation of a multi-regional and multi-sector model of the world economy.

The model is specifically built to represent the distinctive effects of different types of environmental innovation on demand, growth and employment. Rather than focusing on a few green sectors, we assume that environmental innovation can occur in all sectors of the economy to varying degrees. Environmental process innovation involves an increase in productivity and a reduction in the prices of green products in line with the literature. Environmental product innovation is typically represented as an increase in the cost-effectiveness of new technologies. Instead, we explicitly model it as a change in the quality of green products in line with business studies. We therefore acknowledge the importance of demand and substitution effects between more and less polluting products.

The model also incorporates the distinctive features of low-growth European economies and their interactions with other regions of the world. We can therefore explore substitution effects across regions, while accounting for structural problems like slowing demand and fragmented markets. We empirically calibrate and test the model over the period 1995–2009, combining data from environmental accounts, socioeconomic accounts, world input-output tables, and additional sources. The purpose of this extensive data collection is to overcome the uncertainties of base year calibration and improve the empirical realism of the model. The calibrated model is used to simulate alternative scenarios over the period 2020–2040, comparing the effects of an increase in green product quality and productivity in different sectors.

Our findings suggest that the structural changes required to cope with climate change do not occur over the period considered. However, environmental innovation could accelerate this restructuring process, supporting growth and employment in the long term. The results of the simulations confirm the importance of compensation mechanisms and substitution effects between products and regions. Environmental process innovation expands production and reduces labour demand for green products in most sectors. However, it has indirect effects on prices and demand, which offset most of the initial labour loss and further increase green production over time. Environmental product innovation raises consumption and hours worked for green products. However, it causes important substitution effects between green and brown products, domestic and imported. Both types of innovation have positive effects on output in most sectors, while the effects on employment are more ambiguous. The most interesting aspect of our findings is that the direction and intensity of the effects described above varies significantly based on the prevailing patterns in each sector. Furthermore, important synergies and trade-offs emerge between the aim of supporting growth and promoting employment.

The paper is structured as follows. Section 2 reviews the theoretical and empirical literature on the direct and indirect effects of environmental innovation. Section 3 illustrates the effects of environmental product and process innovation on the main model variables. Section 4 explains the main steps of model implementation, including time series construction, parameter identification, and empirical validation of the model. Section 5 presents the results of the simulations over the period 2020–2040, comparing the effects of environmental product and process innovation across sectors. Sections 6 provides some concluding remarks and policy recommendations.

2. Literature review

2.1. Direct and indirect effects of innovation

From the Luddite protests against the mechanisation of the textile industry to the most recent technological revolutions, the effects of innovation on growth and employment have been widely debated in the public arena and in the scientific community (Mokyr, Vickers, and Ziebarth 2015; Mondolo 2022). The breadth of the debate stems from the complexity of the interactions between innovation, productivity, demand, output and employment, which have been conceptualised in the so-called 'Compensation Theory' (Fagerberg, Guerrieri, and Verspagen 1999; Vivarelli 2007). The theory postulates the existence of positive indirect effects of innovation through demand, income and prices that counterbalance the depressive effects of productivity increases on employment at the sector and macroeconomic levels (Mondolo 2022; Pianta 2003). The demand for labour can come from an increase in production in the machinery sector (new machines), from a reduction in prices that stimulates consumption (decrease in prices), from a reduction in wages that increases the substitutability of labour (decrease in wages), from the reinvestment of profits in the expansion of production capacity (new investments) (Piva and Vivarelli 2005; Vivarelli 2014). In addition to these classic compensation mechanisms, innovation can result in the creation of new products that stimulate consumption, thereby generating further demand for labour (Calvino and Virgillito 2018; Vivarelli 2014).

At the same time, the creation of new products can be considered as a specific form of innovation, which produces distinctive effects on demand, output and employment (Montobbio et al. 2023; Vivarelli 1995). Numerous empirical studies underline the distinctive effects of product and process innovation on demand, output, and employment (Benavente and Lauterbach 2008; Hall, Lotti, and Mairesse 2008; Harrison et al. 2014). Product innovation fosters the expansion of domestic demand, while opening new niches in international markets (Antonucci and Pianta 2002; Bogliacino and Pianta 2010; Calvino and Virgillito 2018; Harrison et al. 2014). However, it causes indirect substitution effects between products, firms and sectors (Benavente and Lauterbach 2008; Harrison et al. 2014). Process innovation expands production and depresses labour demand. However, it can indirectly stimulate demand through price reductions, new machinery and investments (Becker and Egger 2013; Garcia, Jaumandreu, and Rodriguez 2004; Pianta 2003). The combined introduction of product and process innovation can also generate complementary returns and preserve employment during recessions (Cowling et al. 2024; Ortiz and Salas Fumás 2020).

Important differences emerge depending on the level of analysis. Firm-level studies find mostly positive effects for product innovation and more ambiguous for process innovation, with significant variations based on sector, time frame, and innovation indicators (Arenas Díaz, Guerrero, and Heijs 2024; Bogliacino, Piva, and Vivarelli 2012; Harrison et al. 2014). Sector-level studies confirm that the greatest benefits are concentrated in science- and technology-based sectors oriented toward product innovation, while weaker or even negative effects are associated with the reorganisation of production processes (Antonucci and Pianta 2002; Evangelista 2000; Evangelista and Savona 2002). However, these studies cannot account for indirect compensation through prices and demand, nor for substitution effects across firms and sectors. The few studies available at the macroeconomic level suggest that the strength of compensation mechanisms and substitution effects varies depending on institutional context, labour market characteristics, and demand elasticity (Arenas Díaz, Guerrero, and Heijs 2024; Montobbio et al. 2023; Vivarelli 2015). The need to compete in increasingly integrated international markets may also influence their extent and effectiveness (Ambec et al. 2013; Costantini and Mazzanti 2012; van Leeuwen and Mohnen 2017). However, the lack of comparable indicators prevents a clear assessment of the direct and indirect effects of product and process innovation on an international scale.

2.2. Socioeconomic effects of environmental innovation

While compensation and substitution effects have been widely discussed in the general literature on technical change, it is unclear how and to what extent such effects occur in the case of environmental innovation. Several studies suggest that its determinants and characteristics are different from general innovation and that this may influence the strength and effectiveness of compensation and substitution effects (Horbach 2008; Horbach and Rennings 2013; Töbelmann and Wendler 2020). Empirical evidence on the effects of environmental innovation on economic performance is mainly conducted at the firm level, using available indicators such as profits, sales, and return on investment (Cheng, Yang, and Sheu 2014; Lanoie et al. 2011; Liao 2018). These studies identify mostly positive and significant effects for both environmental product and process innovation (El-Kassar and Singh 2019; Hojnik and Ruzzier 2017; Huang and Li 2017). However, they underline their distinctive effects on competitive strategy and economic performance.

Environmental product innovation supports retention and differentiation strategies, stimulating qualitative changes in output and creating customer value through environmental attributes (Chen and Liu 2018; Hojnik and Ruzzier 2017; Huang and Li 2017). Therefore, it can create new market niches, stimulating demand, production and employment (direct demand effects) (Arenas Díaz, Guerrero, and Heijs 2024; Fernández, Torrecillas, and Díaz 2024; Rennings, Ziegler, and Zwick 2004). However, new or substantially improved green products can replace other domestic or imported, more or less polluting products (indirect substitution effects) (Aldieri and Vinci 2018; Arenas Díaz, Guerrero, and Heijs 2024; Horbach and Rennings 2013). Environmental process innovation supports cost leadership strategies, transforming production processes to increase efficiency, reduce input demand, and contain environmental spillovers (Chen and Liu 2018; Hojnik, Ruzzier, and Konečnik Ruzzier 2019; Liao 2018). Therefore, environmental process innovation can foster growth and competitiveness, while reducing costs and labour demand (direct productivity effects) (Arenas Díaz, Guerrero, and Heijs 2024; Fernández, Torrecillas, and Díaz 2024; Rennings, Ziegler, and Zwick 2004). However, the reduction in costs and prices can further stimulate consumption and production, creating new demand for labour (indirect demand effects) (Arenas Díaz, Guerrero, and Heijs 2024; Fernández, Torrecillas, and Díaz 2024; Triguero, Cuerva, and Álvarez-Aledo 2017).

Empirical analysis of the employment effects of environmental innovation is more limited, due to the paucity of panel data and direct indicators (Barbieri et al. 2016; Licht and Peters 2013). The investigation is mostly based on green patent data and some waves of community innovation surveys (Aldieri and Vinci 2018; Triguero, Cuerva, and Álvarez-Aledo 2017). Although valuable, these data do not allow for intertemporal analysis and usually do not include the share of sales related to environmental product innovations (Kunapatarawong and Martínez-Ros 2016; Licht and Peters 2013). Few studies compare the effects of different types of environmental innovation on employment based on more detailed data available for specific sectors and countries (Horbach and Rennings 2013; Licht and Peters 2013; Rennings and Zwick 2002). These findings point to generally positive effects, with significant differences based on the type of innovation (Fernández, Torrecillas, and Díaz 2024; García-Marco, Zouaghi, and Sánchez 2020). Environmental product innovation expands demand and creates new markets, therefore the direct effects on employment are mostly positive and significant (Horbach 2010; Pfeiffer and Rennings 2001; Rennings and Zwick 2002). Environmental process innovation increases efficiency and improves competitive positioning, therefore the effects on employment are moderately positive and indirect (Horbach and Rennings 2013; Triguero, Cuerva, and Álvarez-Aledo 2017). However, the magnitude and direction of these effects also depend on the contribution of innovation to value creation, the structure of the labour market, and global trade (Pfeiffer and Rennings 2001; Rennings and Zwick 2002).

Finally, important differences emerge between sectors, as environmental pressures from markets, regulations and public opinion influence the prevailing innovation patterns (Fernández, Torrecillas, and Díaz 2024; García-Marco, Zouaghi, and Sánchez 2020). In particular, sectors such as chemicals, transportation, rubber and plastics are considered more polluting than clothing, machinery, and equipment, and are therefore exposed to greater environmental pressures (Al-Ayouty, Hassaballa, and Rizk 2017; Kunapatarawong and Martínez-Ros 2016; Shan and Wang 2019). The latter can influence the adoption and effectiveness of environmental product and process innovations, altering their impact on output and employment (Fernández, Torrecillas, and Díaz 2024; Horbach and Rammer 2018; Kunapatarawong and Martínez-Ros 2016). Therefore, these effects should be explored across different types of innovation, sectors and countries. However, the lack of uniform indicators has so far limited the scope of the analysis and hindered the comparison of results. The use of modelling, empirical calibration, and simulation techniques can address the lack of comparable indicators and support the analysis of the direct and indirect effects of environmental innovation in the context of global trade.

2.3. Recent developments in modelling the effects of technical change

Recent developments in modelling and simulation techniques have supported the development of Integrated Assessment Models (IAMs) to investigate the complex interactions between natural and socioeconomic systems, including the role of technical change

(Stanton, Ackerman, and Kartha 2009; van Beek et al. 2020). In particular, the detailed process-based IAMs explore pathways for transforming economic, energy and land use systems to meet climate targets, while the cost–benefit IAMs focus on economic impacts and optimal levels of mitigation (van Beek et al. 2020; Weyant 2017). The representation of technical change has evolved in these models to include the role of innovation policies and processes of technological learning and diffusion. For examples, the Dynamic Integrated Climate and Economy (DICE) model was based on increases in total factor productivity and automatic reduction of emissions, while the World Induced Technical Change Hybrid (WITCH) model includes an explicit representation of energy sources, the role of R&D investments and the diffusion of technological knowledge across regions (Bosetti et al. 2006; de Cian, Bosetti, and Tavoni 2012; Nordhaus 1993). Some recent models such as E3ME-FTT represent bottom-up technology diffusion processes, including decision-making and investment constraints in key sectors like energy, transport, and heating (Mercure, Lam, et al. 2018; Mercure, Pollitt, et al. 2018). Despite these advances, the modelling of technological change in IAMs remains strongly oriented towards supply-side solutions and negative emissions technologies, whereby the attractiveness of new products is linked to energy efficiency and cost reduction (Fuss et al. 2014; van Beek et al. 2020). Therefore, we build on the literature on the direct and indirect effects of innovation to explicitly model the role of demand and qualitative changes in product environmental attributes.

This overview of the literature suggests that product and process environmental innovation have distinctive effects on output and employment, which vary significantly across sectors and regions (Horbach 2010; Horbach and Rennings 2013; Pfeiffer and Rennings 2001). Furthermore, the need to compete in increasingly integrated markets and benefit from international knowledge spillovers influence the direction of technological change and its impact on growth and employment (Akcigit et al. 2022; Antonelli and Feder 2020). Therefore, the direct and indirect effects of environmental innovation may vary in the context of global competitiveness. Finally, the structural characteristics of the regional context shape the complex interaction between technical and socioeconomic variables, influencing the direction and magnitude of these effects (Costantini, Delgado, and Presno 2023; Mazzanti and Zoboli 2009; Wu et al. 2024). There is a clear need to extend the empirical analysis to different types of environmental innovation, incorporating further sector and geographical specificities (Barbieri et al. 2016; Clausen and Fichter 2019). However, the lack of panel data and comparable indicators has so far limited the scope of the analysis to specific types of innovation, sectors, and countries (Barbieri et al. 2016; Licht and Peters 2013). Therefore, we employ modelling and simulation techniques to investigate the direct and indirect effects of environmental product and process innovation in the context of structurally vulnerable European economies, exposed to global trade and climate impacts.

3. Model structure

The multiregional and multi-sector model introduced in this section is specifically built to investigate the direct and indirect effects of environmental innovation on growth and employment in the context of international trade. Firstly, the complex and simultaneous effects of a change in productivity on demand, growth and employment are analysed in the context of international competitiveness. For this purpose, the world economy is divided into five main regions. Each region includes twenty sectors, which produce more polluting or *brown* (b) products and less polluting or *green* (g) products. Therefore, compensation mechanisms through demand, prices and capital goods across countries are accounted for. Secondly, a specific parameter (v) is introduced in the demand functions to model a change in the quality of less polluting products. Therefore, the substitution effects between more and less polluting products across sectors and regions are also explored. Finally, the model is calibrated on world economy data and used to simulate an increase in productivity and an improvement in the quality of less polluting products over the period 2020–2040, as detailed in Sections 4 and 5. The main equations that represent the causal structure of the model and the related variables are reported in Appendix A. Each equation corresponds to a set of equations in the complete model (n = 4975). The complete model code and results are available in the Supplementary Materials.

Figure 1 illustrates the main variables and parameters for a specific region A and green product i in our model. The demand functions for private household consumption are structured on three levels to incorporate substitution effects across regions, sectors, and product types. Firstly, labour and capital income in region A contribute to household consumption expenditures (1,2) based on the propensity to consume out of labour (c_L) and capital (c_K). Secondly, households allocate their expenditures to the main sectors (3) based on their preferences and sector prices, regardless of the region of origin and the specific type of product. Finally, households allocate the sector budget between products of different type and origin (4) based on respective prices and attributes. Therefore, they decide whether to purchase a domestic or foreign product, a green or brown product.

Environmental product and process innovation cause numerous direct and indirect effects on the main variables of the model. An improvement in the quality of green product i produced in region A raises domestic consumption of the same product (5) at equal relative prices. The qualitative improvement also stimulates foreign consumption and exports of the same product (6). Both effects contribute to increasing production and hours worked for green product i. However, an increase in green quality may cause important indirect substitution effects between regions and products, depending on the elasticity of substitution (σ). If green products primarily replace imported brown products, the effects on output and hours worked in the sector are largely positive. If they cause a decline in domestic brown consumption, the effects at the sector level could be weak or even negative. Conversely, an increase in green productivity expands production, with depressive effects on hours worked and labour income (7,8). However, it causes a decrease in the price of the same product (9). The decline in price can stimulate consumption (10) and improve the competitiveness of the green product i on foreign markets (6). These indirect effects on demand through prices can further increase output and create new demand for labour (7). The impact on output and employment in the sector also depends on the extent of the substitution effects between domestic green and brown products compared to the replacement of imported products.

In both cases, the increase in the production of green product i produces several cascading effects on the other real and nominal variables in the model. The first is an increase in the utilisation rate (11), which fosters both investment and capital accumulation (12,13). A significant change in the utilisation rate can also be transmitted to the markup rate (14),

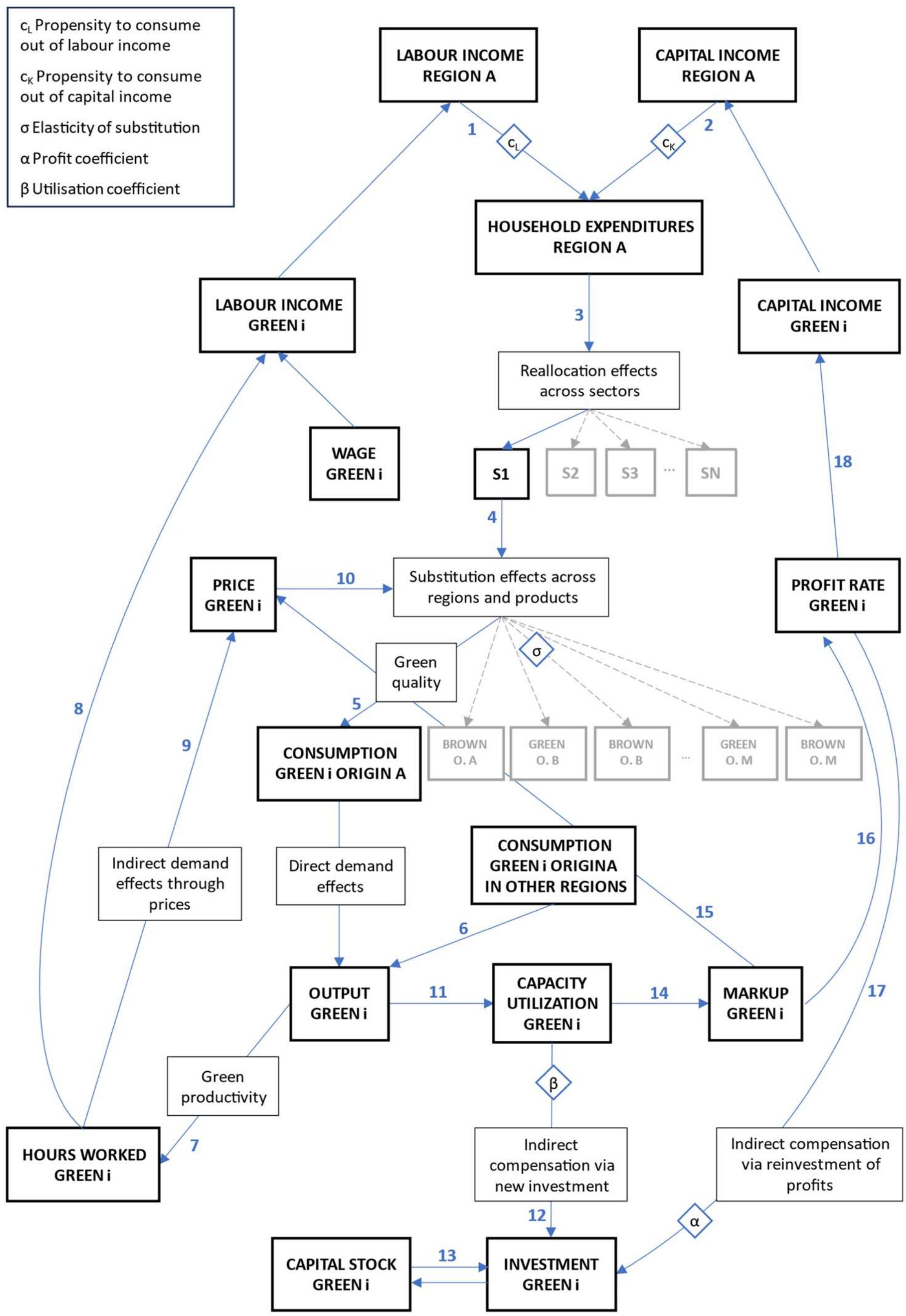

Figure 1. Main effects of environmental product and process innovation for region A and green product i.

causing an increase in the profit rate and price of product i (15,16). The higher profit rate supports investment (17) and expands capital income (18), with potential redistributive effects in the region. The price increase may have depressive effects on consumption.

However, the transmission mechanism from utilisation to markup is assumed to be too weak to counterweight the initial expansion in consumption.

4. Model implementation

The model implementation is carried out in several phases and combines various techniques, including literature analysis, time series construction, origin-destination matrix estimation, and assessment of deviations between historical and simulated series. The aim of this extensive data collection and analysis is to improve the accuracy, reliability, and empirical realism of the model, addressing the main criticisms of empirical calibration techniques found in the literature.

Our more detailed calibration procedure introduces three fundamental improvements compared to standard practice. First, we depart from the conventional practice of identifying and testing parameter values only for the base year and instead construct historical time series for all model variables over the period 1995–2009. For this purpose, we combine different data sources including world input-output tables (WIOTs) in current and previous year's prices, socioeconomic accounts (SEAs), environmental satellite accounts, Business and Consumer Surveys (BCS), Penn World Tables (PWT). Second, we depart from the prevailing practice of identifying the value of key parameters based on specific studies and instead conduct specific reviews of the empirical literature to compare different estimates of the same parameter. Since these key parameters may influence the direct and indirect effects we investigate, the more extensive literature review improves the reliability of the selected values. Third, we apply the RAS method to estimate the time series of origin-destination investment matrices from the origin and destination vectors. The construction of investment matrices allows to represent all investment flows between sectors and regions, improving the empirical realism of the model. Finally, we introduce a specific metric to assess deviations between historical and simulated time series, calculating the Mean Absolute Percentage Error (MAPE) for each type of variable and for the entire model. The aim is to address the criticisms that have emerged in the literature regarding the lack of reference metrics for testing the validity of simulation models. The main steps of the model implementation are introduced in this section. For the sub-steps related to the construction of the time series and the origin-destination investment matrices, we refer the reader to Appendix C and D.

The first main step is to define the geographical and sector classification of the model, which will serve as a reference for the construction of the time series. The main source of data is the World Input-Output Database (WIOD) (Timmer et al. 2015), which includes world input-output tables (WIOTs) in current and previous year's prices, socioeconomic accounts (SEAs) and environmental satellite accounts. Therefore, the forty countries represented in the WIOD are reclassified into five main areas with a specific focus on the European Union: North-Eastern (N), Western (W), and Southern (S) Eurozone, other European Union countries (O), and the Rest of the World (R). Each country is attributed to the selected areas based on the UN Geo Scheme (UNSD 1999), which is used for statistical purposes and does not consider affiliations of a political or other nature. The WIOD is based on the NACE 1.1 industrial classification with 35 sectors, further aggregated into 20 sectors for each region. Both sector and geographical classifications are included in Appendix B.

The second step is to construct time series for all nominal and real variables in the model. First, we use WIOTs in current prices for the period 1995–2009 to construct matrices of intermediate inputs, value added, and final uses based on our regional and sector classification. We also use WIOTs in previous-year prices to construct the corresponding regional and sector matrices and chain-link them to derive sector- and region-specific price indices. These indices are used to convert the intermediate input, value added, and final uses matrices into real terms. The time series of regional and sector matrices are used to derive the time series of the main real variables of the model. Second, we construct emissions vectors by sector and region from environmental satellite accounts for the period 1995–2009. We combine emissions vector, intermediate input matrix, and final uses vector to estimate emissions demanded in each sector and region. The degree of greening of each sector is determined on the basis of its contribution to emissions over contribution to value added (EMVAC), as detailed in Appendix C.

The third step is to identify the key model parameters that govern the causal relationships in Figure 1. Rather than selecting parameter values based on individual studies, we first review the relevant empirical literature for each of the key model parameters and identify the average estimated value across studies. Figure 1 identifies profitability and demand as two fundamental drivers of consumption and investment. In particular, the propensities to consume out of capital (c_k) and labour (c_w) determine the relative contribution of income flows to consumption expenditures, while the profit (α) and utilisation (β) coefficients determine the relative importance of demand and profitability in stimulating investment. To identify the values of these parameters, we refer to the vast empirical literature investigating the effects of income redistribution on consumption and investment (Bowles and Boyer 1995; Hein and Vogel 2007, 2009; Stockhammer 2009; Stockhammer, Hein, and Grafl 2011; Stockhammer and Ederer 2008; Storm and Naastepad 2006). The positive and significant value of the consumption differential between wages and profit (0.4) and of the ratio between demand and profit coefficients (2.3) suggests that a redistribution of income toward labour can stimulate consumption and investment.

Another key parameter of the model is the elasticity of substitution between more or less polluting products (σ) in the CES demand function. A review of the limited empirical studies that estimate this parameter on the basis of the same functional form indicates high sensitivity to relative price changes, with values significantly above unity (2) (Lanzi and Sue Wing 2010; Malikov, Sun, and Kumbhakar 2018; Papageorgiou, Saam, and Schulte 2017; Popp 2004). Finally, we draw on the extensive business literature on green price premium to identify the markup rate of price functions for less polluting products. Green price premia vary significantly across consumer goods, ranging from about 6 percent for deodorant aerosol cans to 9–10 percent for music players and refrigerators (Drozdenko, Jensen, and Coelho 2011; Galarraga, Heres, and Gonzalez-Eguino 2011; Kapelianis and Strachan 1996; Kotchen and Moore 2008). The willingness to pay for green services such as transportation, real estate and lodging appears to be lower, between 3 and 6 percent over base price (Achtnicht 2012; Brouwer, Brander, and Van Beukering 2008; Dastrup et al. 2012; Fuerst and McAllister 2011; Kang et al. 2012; Krishnamurthy and Kriström 2016; Manaktola and Jauhari 2007; Zheng et al. 2012). However, estimates vary significantly according to the income and geographical origin of the consumers and the type and quality of the service offered. These studies point to a positive and significant willingness to pay, with an estimated average green price premium around 6 percent.

Starting from the key values estimated in previous empirical studies, we proceed to identify and validate all model parameters. The time series constructed in the second step are first used to calculate the growth rates of all lagged variables in the model to increase its empirical realism. Based on the same growth rates, we also calculate the initial value of all lagged variables at t-1. All remaining model parameters are then estimated on the base year values of the time series. However, the parameters are identified and tested separately for each set of equations corresponding to a specific variable to improve their accuracy. More importantly, we conduct a replication exercise to test the validity of the calibrated model, in which we run simulations for all model variables and compare them to the historical series. Specifically, we introduce a standardised metric (MAPE) to assess the deviations between simulated and historical series for each type of variable and for the entire model. The aim of the exercise is to verify that the simulated results reproduce the real trends for all industries, addressing the main criticisms to calibration on a single equilibrium observation and lack of reference metrics emerged in the literature (Dawkins, Srinivasan, and Whalley 2001; Hoover 1995; Watson 1993). The exercise produces consistent results, with a mean absolute percentage error (MAPE) close to zero and within the 10 percent limit for all variables and the entire model.

The calibrated model is then run over the period 1995–2040 to identify the main patterns at the region and sector level, which are discussed in Section 5.1. Starting from this baseline, we simulate the introduction of an environmental product and process innovation in different sectors in the Southern Eurozone over the period 2020–2040 to investigate the direct and indirect effects on output and employment. The results of the simulations are presented in Sections 5.2 and 5.3, while substitution effects and potential synergies and trade-offs between policy goals are discussed in Sections 5.4 and 5.5.

5. Main results

5.1. Baseline

The simulation results indicate that, in the absence of innovation, the distribution of more and less polluting products across regions and sectors remains rather stable over time. The production of brown products dominates in all regions, with the only exception of the Western Eurozone. In particular, they represent the main share of output in the North-Eastern Eurozone and the Rest of the World. The distribution between green and brown products is more balanced in the Southern Eurozone and in the other EU countries. The regional differences are more evident in some sectors, where a specialisation in different productive activities is observed. The 'Agriculture, Forestry, and Fishing' (1) sector is greener in the Southern Eurozone, thanks to the specialisation in fresh produce and wine and the lower intensity of capital use (Eurostat 2019). Conversely, the sector is mostly polluting in the North-Eastern Eurozone and the other EU countries, where forestry and cattle-related activities prevail (EEA 2015; Eurostat 2019). The regional disparities may also reflect the different role of institutions and green public procurement as in the 'Education' (19) and 'Public administration' (18) sectors (Canfora et al. 2019).

Some specific sector patterns emerge across regions. The sectors 'Coke, refined petroleum and nuclear fuel' (6), 'Electricity, Gas and Water Supply' (11), and 'Basic metal and fabricated metal products' (8) rely on traditional sources and imported ores and minerals which are highly polluting (Emep and European Environment Agency 2019; Nakajima et al. 2017). The 'Food, beverages, and tobacco' (3), 'Hotels and restaurants' (14) and 'Health and social work' (20) sectors are also main contributors to emissions, due to the massive consumption of water, energy, materials and machinery (Batini 2019; Eurostat 2009). The increase in the length and complexity of supply chains counterweights efficiency gains in the 'Wholesale and retail trade' (13) and 'Transport, storage, and communication' (15) sectors, which remain highly polluted (Rizet et al. 2010). Thanks to improvements in energy performance and automation, a greening pattern emerges in the 'Textile, leather and footwear' (4), 'Machinery and equipment' (9), 'Construction' (12) and 'Financial intermediation' (16) sectors (Al-Hawari 2006; European Commission 2016). The distribution of more and less polluting firms is more varied in the remaining sectors.

The next sections introduce alternative scenarios compared to the baseline. The main aim is to understand whether environmental innovation can accelerate the redistribution of production towards less polluting products and promote growth and employment in a context of slowing demand. The first scenario is the introduction of an environmental process innovation, which is simulated through a 100 percent increase in the productivity parameter ($gb_{r\_s\_g}$) for green products in each sector s. The second scenario is the introduction of an environmental product innovation, which is modelled through a 100 percent increase in the quality parameter ($v_{r\_s\_g}$) for green products in each sector s. The increase is simulated in one sector at a time, to identify the distinctive effects on output and hours worked. The key results of the simulations are reported in Tables 1 and 2 and discussed in the following sections. In particular, Section 5.2 and 5.3 introduce the alternative scenarios and summarise the main effects on output and employment at the sector level. Section 5.4 and 5.5 discuss substitution effects between green and brown products and trade-offs between policy goals. Detailed results and model code are available in the Supplementary Materials.

Table 1. Main effects of environmental innovation on output (percentage changes).

	gb		*v*	
Sector	Variation	Impact*	Variation	Impact*
Agriculture, forestry, and fishing (1)	17 (+)	high	15 (+)	high
Mining and quarrying (2)	3 (+)	moderate	4 (+)	moderate
Textile, leather and footwear (4)	6 (+)	moderate	17 (+)	high
Wood, paper, and printing (5)	15 (+)	high	7 (+)	moderate
Chemical, plastics, and non-metallic minerals (7)	5 (+)	moderate	4 (+)	moderate
Basic metals and fabricated metals (8)	18 (+)	high	15 (+)	high
Machinery and equipment (9)	50 (+)	very high	81 (+)	very high
Manufacturing, nec, and recycling (10)	19 (+)	high	42 (+)	very high
Construction (12)	0.1 (+)	low	3 (+)	moderate
Wholesale and retail trade (13)	3 (+)	moderate	1 (+)	low
Hotels and restaurants (14)	0.5 (+)	low	3 (-)	moderate
Transport, storage and communication (15)	100 (+)	very high	14 (+)	high
Financial intermediation (16)	55 (+)	very high	11 (+)	high
Real estate, renting, and business activities (17)	3 (+)	moderate	26 (-)	very high
Public administration (18)	18 (+)	high	0.4 (+)	low
Education (19)	7 (+)	moderate	1 (+)	low
Health and social work (20)	6 (+)	moderate	7 (-)	moderate

*Note: Impact = *low:* var < 1%, *moderate:* 1% ≤ var < 10%, *high:* 10%≤ var < 20%, *very high:* var ≥ 20%.

Table 2. Main effects of environmental innovation on employment (percentage changes).

	gb		*v*	
Sector	Variation	Impact*	Variation	Impact*
Agriculture, forestry, and fishing (1)	28 (-)	very high	15 (+)	high
Mining and quarrying (2)	18 (-)	high	4 (+)	moderate
Textile, leather and footwear (4)	1 (-)	low	17 (+)	high
Wood, paper, and printing (5)	13 (-)	high	7 (+)	moderate
Chemical, plastics, and non-metallic minerals (7)	5 (-)	moderate	4 (+)	moderate
Basic metals and fabricated metals (8)	7 (-)	moderate	15 (+)	high
Machinery and equipment (9)	8 (+)	moderate	81 (+)	very high
Manufacturing, nec, and recycling (10)	1 (+)	low	42 (+)	very high
Construction (12)	1 (-)	low	3 (+)	moderate
Wholesale and retail trade (13)	1 (-)	low	1 (+)	low
Hotels and restaurants (14)	1 (-)	low	3 (-)	high
Transport, storage and communication (15)	26 (-)	very high	14 (+)	high
Financial intermediation (16)	16 (-)	high	11 (+)	high
Real estate, renting, and business activities (17)	10 (-)	high	26 (-)	very high
Public administration (18)	3 (-)	moderate	0.4 (+)	low
Education (19)	0.5 (-)	low	1 (+)	low
Health and social work (20)	2 (-)	moderate	7 (-)	moderate

*Note: Impact = *low:* var < 1%, *moderate:* 1% ≤ var < 10%, *high:* 10%≤ var < 20%, *very high:* var ≥ 20%.

5.2. Environmental process innovation

The first alternative scenario is the introduction of an environmental process innovation in the Southern Eurozone. The main direct effects are an increase in output and a simultaneous decline in hours worked for green products. However, indirect effects are more complex. On the one hand, the initial rise in productivity is transferred to the consumers through lower prices, stimulating additional demand for less polluting products and labour. Thanks to this expansion in demand, the initial decline in employment is partially compensated. Therefore, the average loss of hours worked at the sector level is modest (7 percent). On the other hand, the increase in demand for green products displaces the consumption of more polluting products, causing a reduction in output and labour demand. The substitution effects between green and brown products contain the increase in output at the sector level, which however remains significant (19 percent).

The strength of these compensation and substitution effects differs widely across sectors, determining the final impact on output and employment in each sector. The greatest benefits occur in the 'Machinery and Equipment' (9), 'Transport, storage and communication' (15) and 'Financial intermediation' (16) sectors, with a remarkable increase in output (50–100 percent). The benefits are also significant in the 'Agriculture, Forestry, and Fishing' (1), 'Wood, Paper, Printing and Publishing' (5), 'Basic Metals and Fabricated Metals' (8), 'Manufacturing Nec and Recycling' (10), and 'Public Administration' (18) sectors (15–19 percent). The effects are modest (3–7 percent) or unimportant in the remaining sectors.

The impact on hours worked is more ambiguous. The effect is positive and moderate only in the 'Machinery and Equipment' sector (9) (8 percent), where the remarkable rise in output compensates for the loss of labour demand. The effect is negative but modest (2–7 percent) in the 'Chemicals, Plastics and other Non-Metallic Mineral' (7), 'Basic Metals and Fabricated Metals' (8), 'Public administration' (18), and 'Health and social work' (20) sectors. The decline is more significant in the 'Mining and Quarrying' (2), 'Wood, Paper, Printing and Publishing' (5), 'Financial intermediation' (16) and 'Real estate, renting, and business activities' (17) sectors (10–18 percent). Substitution effects between more and less polluting products prevail in some sectors, causing an important decline in hours worked. The greatest losses occur in the 'Agriculture, Forestry, and Fishing' (1) sector (28 percent) and the 'Transport, storage and communication' sector (15) (26 percent). The effect is minimal in the remaining sectors.

5.3. Environmental product innovation

The second alternative scenario is the introduction of an environmental product innovation in the Southern Eurozone. The main direct effect is an increase in the consumption of less polluting products, with positive effects on output and hours worked. However, green products can replace more polluting domestic or imported products, depending on the distribution of preferences and substitution effects in the same sector. If domestic replacement effects prevail, the decline in brown output and hours worked contains the positive effects of innovation. As detailed in Section 5.4, these effects occur in most sectors. However, their importance vary significantly. The average increase in output and hours worked at the sector level is 11 percent.

The most important effects occur in the 'Machinery and Equipment' (9) and the 'Manufacturing NEC and Recycling' (10) sectors, with an outstanding increase in output and employment over the baseline (42–81 percent). The increase is also significant in the 'Agriculture, Forestry, and Fishing' (1), 'Textile, Leather and Footwear' (4), 'Base Metals and Fabricated Metals' (8), 'Transport, storage and communication' (15) and 'Financial intermediation' (16) sectors (11–17 percent). Conversely, domestic substitution effects are significant in the 'Mining and Quarrying' (2), 'Wood, Paper, Printing, and Publishing' (5), 'Chemicals, Plastics and other Non-Metallic Mineral' (7), 'Construction' (12), resulting in a modest increment in output and hours worked (3–7 percent). These effects are more important in the 'Hotels and restaurants' (14) and 'Health and social work' (20) sectors, with a 3–7 reduction in output and employment at the sector level. The greatest losses occur in the 'Real estate, renting and business activities' (17) (26 percent). The effects are negligible in the remaining sectors.

5.4. Substitution effects

An improvement in the quality of green products causes an immediate increase in consumption of the same products. The increase can occur through an expansion of overall demand in the sector. The expansion of demand in turn fosters investment and capital accumulation, strengthening the positive effects on growth and employment. In this case, the variation in total output and hours worked is positive and largely depends on initial green share and reinforcement effects between consumption, investment and capital. The increase can also occur through the replacement of other products of different type and origin. In particular, higher quality green domestic products can replace products imported from other European regions and the rest of the world. In this case, substitution effects are positive and contribute to increasing output and employment in the region. However, they can replace less polluting products from other regions, slowing down green restructuring in the rest of the world. Finally, they can replace more polluting products from the same region. In this case, the decline in

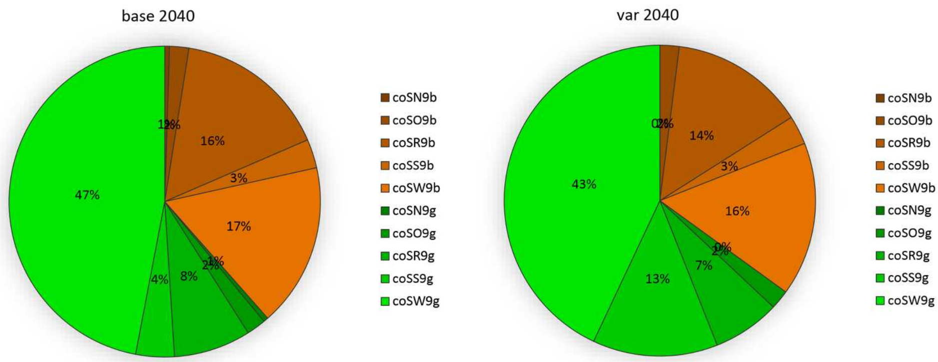

Figure 2. Effects on the quantities consumed of brown and green products, domestic and imported (var v, sector 9)

*Note: The graph represents the quantities consumed (co) of products of different origins (N = North-Eastern Eurozone, O = Other Europea countries, R = Rest of the World, S = Southern Eurozone, W = Western Eurozone) and type (b = brown, g = green) within the region (S = Southern Europe) and sector (9 = Machinery and Equipment), in the base scenario (base) and the alternative scenario (var).

output and hours worked for the most polluting products partially offsets the initial increase, containing the positive effects of environmental innovation. The final impact on output and hours worked depends on the balance between demand expansion and substitution effects.

In some sectors, demand effects prevail. For example, in the 'Machinery and Equipment' (9) sector the extraordinary rise in green domestic consumption contains the influx of green products from the Western Eurozone and, to a lesser extent, of brown products from the North-Eastern Eurozone and the Rest of the World (Figure 2). The share of green domestic consumption triples, from 4 to 13 percent, while the share of brown domestic products remains constant. The redistribution of output towards green products fundamentally reflects the expansion of demand. Therefore, the increase in output and hours worked is notable. Similarly, in the 'Manufacturing NEC and Recycling' (10) sector, the share of green domestic products rises from 10 to 27 percent, replacing products imported from the North-Eastern Eurozone and other EU countries (Figure 3). The extraordinary increase in green products offsets the partial decline in brown products, with important positive effects on growth and employment. The redistributive effects on output are evident in both sectors, with a share of green products of over 80 percent (Figures 5 and 6). In other sectors, substitution effects prevail. For example, in the 'Real estate, renting and business activities' (17) sector the share of green domestic products consumed increases significantly, from 64 to 84 percent (Figure 4). However, the share of brown domestic products halves, from 33 to 16 percent. The result is a significant loss of output and hours worked compared to the base scenario and an important redistribution towards green products (Figure 7).

In the 'Wholesale and retail trade' (13) sector, the decline in the production of brown domestic products completely offsets the increase in green output (Appendix E). The final impact on growth and employment is negligible. In the 'Hotels and restaurants'

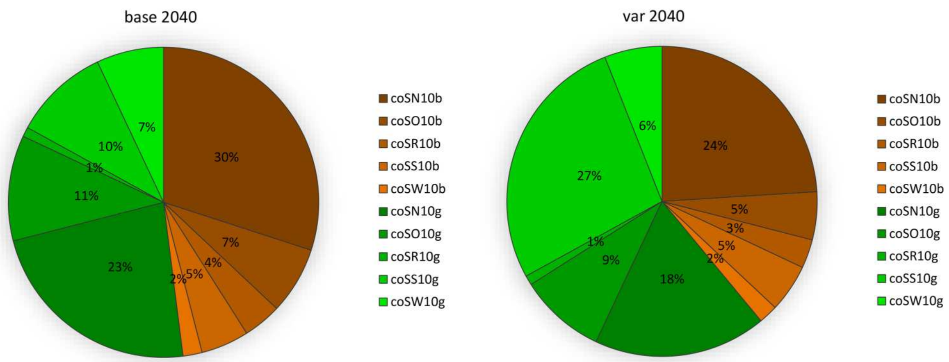

Figure 3. Effects on the quantities consumed of brown and green products, domestic and imported (var v, sector 10)

*Note: The graph represents the quantities consumed (co) of products of different origins (N = North-Eastern Eurozone, O = Other Europea countries, R = Rest of the World, S = Southern Eurozone, W = Western Eurozone) and type (b = brown, g = green) within the region (S = Southern Europe) and sector (10 = Manufacturing NEC and Recycling), in the base scenario (base) and the alternative scenario (var).

(14) and 'Health and social work' (20) sectors, the increase in the production of green domestic products partially offsets the decline of brown products. The result is a modest increase in output and hours worked at the sector level. These substitution effects are also important in the 'Wood, Paper, Printing, and Publishing' (5), 'Base Metals and Fabricated Metals' (8), 'Transport, storage and communication' (15) and 'Financial intermediation' (16) sectors. However, the increase in output remains significant.

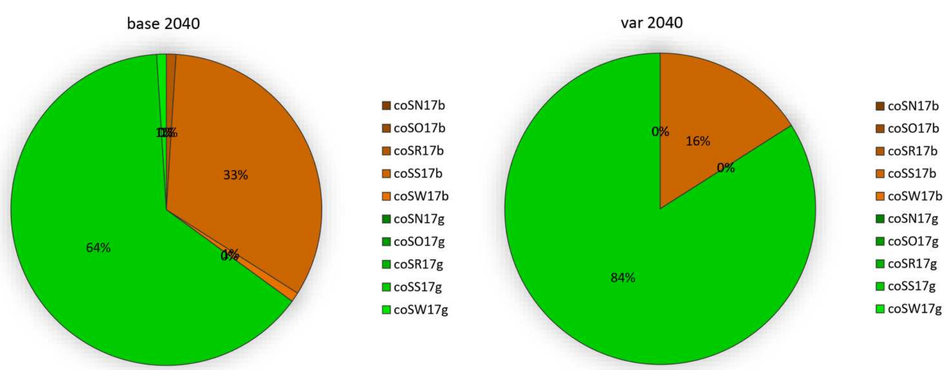

Figure 4. Effects on the quantities consumed of brown and green products, domestic and imported (var v, sector 17)

*Note: The graph represents the quantities consumed (co) of products of different origins (N = North-Eastern Eurozone, O = Other European countries, R = Rest of the World, S = Southern Eurozone, W = Western Eurozone) and type (b = brown, g = green) within the region (S = Southern Europe) and sector (17 = Real estate, renting and business activities), in the base scenario (base) and the alternative scenario (var).

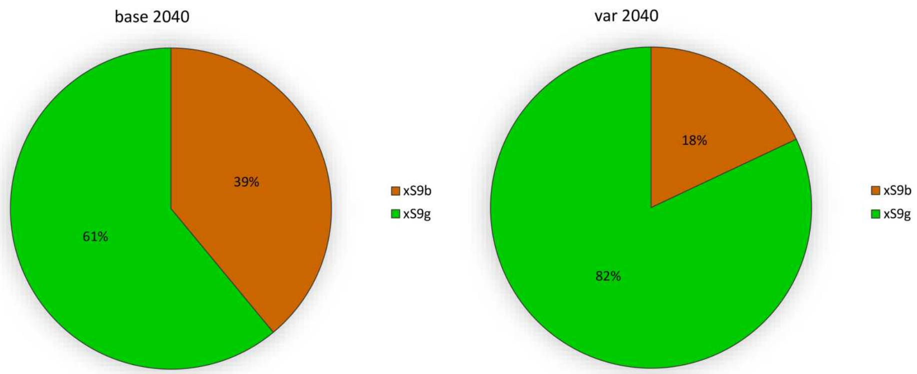

Figure 5. Redistributive effects on output for green and brown products (var v, sector 9)

*Note: The graph represents the distribution of output (x) between brown (b) and green (g) products within the region (S = Southern Europe) and sector (9 = Machinery and Equipment), in the base scenario (base) and the alternative scenario (var).

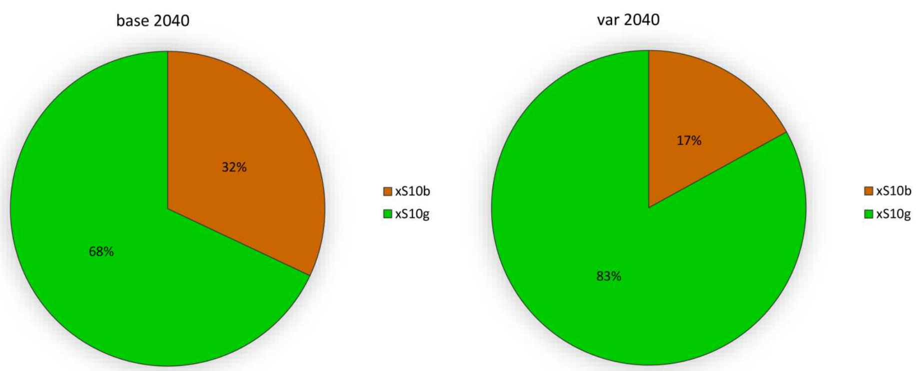

Figure 6. Redistributive effects on output for green and brown products (var v, sector 10)

*Note: The graph represents the distribution of output (x) between brown (b) and green (g) products within the region (S = Southern Europe) and sector (10 = Manufacturing NEC and Recycling), in the base scenario (base) and the alternative scenario (var).

5.5. Trade-offs

An increase in the productivity of green products causes important synergies and trade-offs between the goals of supporting growth and promoting employment. The collapse of employment in the 'Agriculture, Forestry, and Fishing' (1) sector erodes most of the positive effects on output (Tables 1 and 2). The decline in employment is more contained in the 'Mining and Quarrying' (2), 'Chemicals, Plastics and other Non-Metallic Mineral' (7) and 'Real estate, renting and business activities' (17) sectors, but still exceeds the modest increases in output. The moderate increase in output in the 'Wood, Paper, Printing and Publishing' (5) and 'Basic Metals and Fabricated Metals' (8) sectors corresponds to a significant loss of hours worked. Conversely, in the 'Textile, leather and footwear' (4), 'Transport, storage and communication' (15), 'Financial intermediation' (16), 'Public administration' (18), 'Education' (19) and 'Health and social work' (20) sectors, the increase

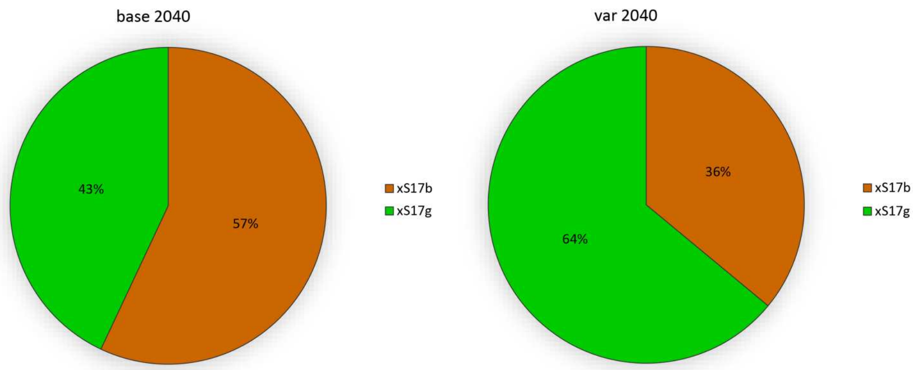

Figure 7. Redistributive effects on output for green and brown products (var v, sector 17)

*Note: The graph represents the distribution of output (x) between brown (b) and green (g) products within the region (S = Southern Europe) and sector (17 = Real estate, renting and business activities), in the base scenario (base) and the alternative scenario (var).

in output is more than triple compared to the loss of hours worked. An interesting synergy occurs in the 'Machinery and Equipment' (9) sector, with an important rise in output and a significant increase in hours worked. The increase in productivity can also cause indirect substitution effects. When the productivity increase is transferred to the consumer through a price reduction, green products become more competitive and replace brown ones. The decline in the production of brown products is more important in the 'Transport, storage and communication' (15) and 'Financial intermediation' (16) sectors. However, the extraordinary rise in green production contains such negative effects. Therefore, the final increase in output is notable. The detailed variations in brown and green output and hours worked are reported in Appendix E.

6. Conclusions

The results of the base simulation indicate a very stable regional distribution, suggesting that green structural transformations are too slow to address the urgency of the climate challenge. Western and Southern Eurozone are relatively green, while the remaining regions remain highly polluted. The simulation of alternative scenarios suggests that environmental innovation can reduce polluting emissions and foster growth and employment. However, it highlights the importance of indirect demand effects and substitution effects between green and brown, domestic and imported products. The intensity and balance of these effects determines the final impact on growth and employment.

Our analysis supports the main findings from the general literature on technical change and the emergent line of studies on the socioeconomic effects of environmental innovation, while providing insights for further research. Firstly, both product and process environmental innovation have mostly positive and significant effects on output, in line with previous empirical studies (El-Kassar and Singh 2019; Hojnik and Ruzzier 2017; Huang and Li 2017). However, our findings reveal marked differences in the magnitude of these effects across sectors. The benefits of environmental innovation are largely concentrated in specific sectors such as machinery, recycling, transport, and finance, and to a lesser extent agriculture and metals. Conversely, modest or even negative effects occur in few sectors such as real estate, construction, health, hotels and restaurants. These findings underline the importance of industry-level innovation patterns and competitive strategies in shaping the socioeconomic outcomes of environmental innovation and are consistent with the general innovation literature, which suggests that user requirements influence the direction and type of innovation (Bogliacino and Pianta 2010; Evangelista and Savona 2003). Further research could explore the emergence of sector regimes for environmental innovation across different regions.

Secondly, environmental products and process innovation have specific direct and indirect effects on output and employment. However, the latter vary significantly across sectors, depending on the strengths of indirect demand effects and substitution effects. Environmental process innovation is much more effective in sectors such as transportation, finance, public administration, education, wood, paper, and printing, while the benefits of environmental product innovation are most significant in the machinery, recycling, and textile sectors. Both types of innovation produce similar effects in agriculture, mining, metals, and chemicals. Therefore, the combined use of policies in favour of environmental product and process innovation is effective in most sectors. However, providing differentiated incentives could strengthen the final effects on output. These findings suggest that the general mechanisms identified in the compensation theory may also be relevant for environmental innovation (Calvino and Virgillito 2018; Mondolo 2022; Vivarelli 2014). However, their extent and effectiveness depend on the characteristics of demand, the valorisation of environmental attributes and the degree of substitutability between more or less polluting products.

Finally, the potential synergies and trade-offs between increasing output and supporting employment must be considered in order to design appropriate incentives. Environmental process innovation can foster output expansion and international competitiveness. However, it can substantially reduce the demand for hours worked. The positive effects on output more than compensate for the losses in hours worked, in the textile, transport, financial, public administration, education and healthcare sectors. In contrast, the decline in employment outweighs the increases in output in the agricultural, mining, chemical, and real estate sectors. Environmental product innovation has positive effects on the hours worked in most sectors, in particular machinery, recycling, metals, and agriculture. However, it can induce important substitution effects between green and brown local products, causing a decline in production and hours worked. These negative effects occur in the hotels and restaurants, health and real estate sectors.

These patterns have important implications for industrial policies. A policy promoting environmental innovation in the machinery and recycling sectors can have positive and important effects on output and employment, regardless of the type of innovation. This policy is also effective in the agriculture, textiles, and metals sectors, but greater incentives should be dedicated to product innovation to contain labour losses. Conversely, environmental process innovation is more effective in the financial, transportation, and public administration sectors, where the important increase in output compensates for the loss of hours worked. In conclusion, an effective industrial policy should design an appropriate incentive system, according to the distinctive effects of each type of innovation and the prevailing patterns in each sector. In particular, it should take into consideration the substitution effects between more and less polluting goods and the indirect effects on demand. Indeed, substitution and compensation effects vary from one sector to another, determining which type of innovation is most appropriate and for what specific purpose.

While our study offers innovative policy insights, several limitations and future research avenues are identified. As previously highlighted in literature (Gibson and van Seventer 2000; Taylor 1990, 2004), the model structure and macroeconomic closures can influence its results. In particular, the structuralist functions increase the empirical realism of the model, allowing to represent crucial features of the regional context such as resource underutilisation and market fragmentation. However, they assume a fundamental role of demand and investment in driving the expansion of productive capacity. To address this concern, we tested the model through different tools, including a literature review for key parameters, the calculation of growth rates for all variables on real time series and the assessment of the deviations between simulated and real time series for all variables included in the model (MAPE). However, future studies could expand our analysis, comparing the effects across regional contexts with different structural characteristics. Another fundamental limitation concerns the lack of direct indicators of the socioeconomic effects of environmental product and process innovation that are comparable at international level. This lack of data requires the use of proxy indicators (EMVAC) to identify brown and green sectors, limiting the accuracy of our findings. We therefore hope that future studies can benefit from greater availability and comparability of direct indicators to provide more detailed results at product and industry level.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials. https://osf.io/6aqnp/?view_only=50e8dc3d18ac43f68e0cd92713021df6.

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Appendices

Appendix A

Model Structure

(1) $b_{r\_s\_c(t)} = (1 + gb_{r\_s\_c})\, b_{r\_s\_c(t-1)}$

(2) $cg_{rd\_ro\_s\_c(t)} = \dfrac{f_{rd\_ro\_s\_c}\; ncg_{rd(t)}}{p_{ro\_s\_c(t)}}$

(3) $ci_{r\_s\_c(t)} = (iu_{r\_s\_c(t)}\; piu_{r\_s\_c(t)} + h_{r\_s\_c(t)}\; w_{r\_s\_c(t)})\; \tau_{r\_s\_c(t)}$

(4) $ci_{r(t)} = \sum_{s=1}^{m} ci_{r\_s\_b(t)} + \sum_{s=1}^{m} ci_{r\_s\_g(t)}$

(5) $co_{rd\_ro\_s\_c} = \dfrac{co_{rd\_s(t)}\; p_{rd\_s(t)}\; p_{ro\_s\_c(t)}^{\sigma_{rd\_s}-1} s_{rd\_ro\_s\_c}^{1-\sigma_{rd\_s}}\; v_{rd\_ro\_s\_c}^{1-\sigma_{rd\_s}}}{\sum_{ro=1}^{a} p_{ro\_s\_b(t)}^{\sigma_{rd\_s}}\; s_{rd\_ro\_s\_b}^{1-\sigma_{rd\_s}} + \sum_{ro=1}^{a} p_{ro\_s\_g(t)}^{\sigma_{rd\_s}}\; s_{rd\_ro\_s\_g}^{1-\sigma_{rd\_s}}\; v_{rd\_ro\_s\_g}^{1-\sigma_{rd\_s}}}$

(6) $co_{rd\_s(t)} = (nco_{rd(t)}\; \gamma_{rd\_s(t)})/p_{rd\_s(t)}$

(7) $cu_{r\_s\_c(t)} = \dfrac{x_{r\_s\_c(t)}}{q_{r\_s\_c(t)}}$

(8) $did_{r\_s\_c(t)} = g_{r\_s\_c}\; \delta_{r\_s\_c}\; ka_{r\_s\_c(t-1)} + \alpha_{r\_s\_c} \dfrac{ci_{r\_s\_c(t)}}{pk_{r\_s\_c(t)}} + \beta_{r\_s\_c}\; x_{r\_s\_c}$

(9) $dio_{r\_s\_c(t)} = wio_{r\_s\_c}\; did_{r\_s\_c(t)}$

(10) $h_{r\_s\_c(t)} = b_{r\_s\_c(t)}\; x_{r\_s\_c(t)}$

(11) $iu_{r\_s\_c(t)} = au_{r\_s\_c}\; x_{r\_s\_c(t)}$

(12) $ka_{r\_s\_c(t)} = ka_{r\_s\_c(t)(t-1)}(1 - \delta_{r\_s\_c}) + did_{r\_s\_c(t)(t)}$

(13) $li_{r\_s\_c(t)} = h_{r\_s\_c(t)}\; w_{r\_s\_c(t)}$

(14) $li_{r(t)} = \sum_{s=1}^{m} li_{r\_s\_b(t)} + \sum_{s=1}^{m} li_{r\_s\_g(t)}$

(15) $ncg_{r(t)} = (1 + gncg_r)\, ncg_{r(t-1)}$

(16) $nco_{r(t)} = cr_r\; ci_{r(t)} + cw_r\; li_{r(t)}$

(17) $p_{r\_s\_c(t)} = (1 + \tau_{r\_s\_c(t)})(1 + rtm_{r\_s\_c})$

$(au_{r\_s\_c}\; piu_{r\_s\_c(t)} + b_{r\_s\_c(t)}\; w_{r\_s\_c(t)})$

(18) $piu_{r\_s\_c(t)} = p_{r\_s\_c(t)}\; wpiu_{r\_s\_c(t)}$

(19) $pk_{r\_s\_c(t)} = p_{r\_s\_c(t)}\; wpk_{r\_s\_c(t)}$

(20) $p_{rd\_s(t)} = \sum_{ro=1}^{a} \dfrac{p_{ro\_s\_b(t)}\; co_{rd\_ro\_s\_b(t)}}{\left(\sum_{ro=1}^{a} co_{rd\_ro\_s\_b(t)} + \sum_{ro=1}^{a} co_{rd\_ro\_s\_g(t)}\right)}$

$+ \sum_{ro=1}^{a} \dfrac{p_{ro\_s\_b(t)}\; co_{rd\_ro\_s\_g(t)}}{\left(\sum_{ro=1}^{a} co_{rd\_ro\_s\_b(t)} + \sum_{ro=1}^{a} co_{rd\_ro\_s\_g(t)}\right)}$

(21) $q_{r\_s\_c(t)} = did_{r\_s\_c}\; k_{r\_s\_c} + q_{r\_s\_c(t-1)}$

(22) $w_{r\_s\_c(t)} = (1 + gw_{r\_s\_c})\; w_{r\_s\_c(t-1)}$

(23) $x_{r\_s\_c(t)} = dio_{r\_s\_c(t)} + \sum_{rd=1}^{a} is_{rd\_ro\_s\_c(t)}$

$+ \sum_{rd=1}^{a} cg_{rd\_ro\_s\_c(t)} + \sum_{rd=1}^{a} co_{rd\_ro\_s\_c(t)}$

(24) $\tau_{r\_s\_c(t)} = \phi_{r\_s\_c}\; cu_{r\_s\_c(t)}$

Definitions

au technical coefficient	*v* quality parameter
b unit labour requirements	*w* nominal wage
cg real consumption by government and non-profit organisations	*wio* weight investment of origin
ci capital income	*wpiu* proportionality coefficient of the price of inputs
cr propensity to consume out of capital income	*wpk* proportionality coefficient of the price of capital
cu capacity utilisation	*x* gross output
cw propensity to consume out of labour income	α profit coefficient
did investment of destination	β output coefficient
dio investment of origin	γ sector share parameter of the household demand function
g investment coefficient	δ depreciation rate
gb growth rate of unit labour requirements	*f* share parameter of the demand function of government and non-profit organisations

(*Continued*)

Continued.

Definitions	
gncg growth rate of government consumption expenditure	τ markup rate
gw growth rate of the nominal wage	ϕ coefficient of markup function
h hours worked	**Subscripts**
is intermediate inputs supplied	
iu intermediate inputs used	*b* brown
k coefficient of capacity function	*c* classification (b, g)
ka capital stock	*g* green
li labour income	*i* industry
ncg government consumption expenditure	*r* region
nco household consumption expenditure	*rd* region of destination
p price of output	*ro* region of origin
piu price of intermediate inputs	*t* current period
pk price of capital	
q capacity output	
rtm tax and transportation margins	
s industry share parameter of the household demand function	

Appendix B

N	Sector
1	Agriculture, forestry, and fishing
2	Mining and quarrying
3	Food, beverages, and tobacco
4	Textile, leather and footwear
5	Wood, paper, and printing
6	Coke, refined petroleum, and nuclear fuel
7	Chemical, plastics, and non-metallic minerals
8	Basic metals and fabricated metals
9	Machinery and equipment
10	Manufacturing, nec, and recycling
11	Electricity, gas, and water supply
12	Construction
13	Wholesale and retail trade
14	Hotels and restaurants
15	Transport, storage and communication
16	Financial intermediation
17	Real estate, renting, and business activities
18	Public administration
19	Education
20	Health and social work

Code	Country	Region
AUS	Australia	R
AUT	Austria	W
BEL	Belgium	W
BRA	Brazil	R
BGR	Bulgaria	O
CAN	Canada	R
CHN	China	R
CYP	Cyprus	S
CZE	Czech Republic	O
DNK	Denmark	O
EST	Estonia	N
FIN	Finland	N

(*Continued*)

Continued.

Code	Country	Region
FRA	France	W
DEU	Germany	W
GRC	Greece	S
HUN	Hungary	O
IND	India	R
IDN	Indonesia	R
IRL	Ireland	N
ITA	Italy	S
JPN	Japan	R
KOR	Korea, Republic of	R
LVA	Latvia	N
LTU	Lithuania	N
LUX	Luxembourg	W
MLT	Malta	S
MEX	Mexico	R
NLD	Netherlands	W
POL	Poland	O
PRT	Portugal	S
ROU	Romania	O
RUS	Russia	R
SVK	Slovak Republic	N
SVN	Slovenia	S
ESP	Spain	S
SWE	Sweden	O
TWN	Taiwan	R
TUR	Turkey	R
GBR	United Kingdom	O
USA	United States	R
RoW	Rest of the World	R

Appendix C

To calibrate the model and test its performance over the period 1995–2009, the values of the real and nominal variables for all sectors and industries must be identified for the same period. The time series for the main real variables are derived from the environmental satellite accounts and the WIOTs in four main steps. The first main step is the construction of the time series of regional matrices of intermediate and final uses, starting from the WIOTs. The regional matrices of intermediate uses in current prices for the period 1995–2009 are built through the summation along columns and rows of the inputs used and supplied within the same region and sector. Similarly, the regional matrices of final uses and value added for the period 1995–2009 are constructed from the corresponding WIOTs. The time series of price indexes for each region and sector is derived from the output matrices in current and previous year's prices over the same period. The regional time series are converted in real terms using these sector price indexes.

The second main step is the determination of the effective contribution to emissions for each sector. The environmental accounts provide the polluting emissions produced in each sector and country. However, many sectors rely on polluting inputs from other countries. To estimate the net contribution of each sector, the polluting emissions associated with intermediate inputs must be reallocated from the sector of production to the sector of use. The purpose is to calculate the effective contribution to emissions of each sector, including the component associated to the inputs used and produced in different regions and sectors. For this purpose, the emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) produced in the same sector and region in a specific year are first summed up and converted into kilotons of carbon dioxide equivalent using their global warming potential (IPCC 2007). The demand-side emission vector for each year (de_y) is calculated as the matrix product between the supply-side emission vector (se_y), the inverse diagonal output matrix (Dx_y), and the regional input matrix in real terms (RRI_y) (Eq. 10).

$$de_{y(1x100)} = se'_{y(1x100)} x Dx_{y(100x100)} x RRI_{y(100x100)} \tag{C1}$$

Each vector (de_y) can be divided by the total emissions produced in the same year y to identify the contribution to emissions of each sector for the period 1995–2009. The contribution to the total value added for manufacturing or services is calculated for each sector over the same period. Finally, the contribution to emissions over contribution to value added (EMVAC) indicator is used as a proxy for the degree of greening of each sector (Krabbe et al. 2015; Randers 2012; Rubiconto 2023). The average value of this indicator over the period 1995–2009 is considered. The value of this indicator can vary from 0 for sectors producing only green products up to 1 for sectors producing only brown products.

The third main step is the derivation of time series for the nominal variables from the SEAs. The capital and labour income are available for each sector and country. However, the capital income time series count several missing or negative values. Therefore, the series for both income sources at the industry level are recalculated from the real value added, using the share of labour in total income from the SEAs. The time series of wages is calculated based on the hours worked and the labour income in each industry. Since some of the countries classified as the 'Rest of the World' are not included in the SEAs, the amount of hours worked in the same region is corrected based on data from the Penn World Tables (version 9.1). Finally, the nominal wages over the period 1995–2009 are obtained as the ratio between the labour income and the hours worked in a specific year and industry. The average growth rates of the nominal wages over the same period are used to derive the lagged values for the same variables.

The remaining time series are constructed using additional datasets. The availability of data on current capacity utilisation at the sector level is limited. Therefore, the regional series are estimated on the basis of the information available for the 27 countries and 21 industries represented in the Business and Consumer Survey (BCS) archive. The quarterly data for each country and industry are first cleaned and combined into annual data. The annual data are then reorganised to ensure the correspondence with the industrial classification NACE 1.1. For this purpose, the share of supply of each industry within the corresponding NACE 1.1 sector is obtained from the world supply tables for the period 1995–2009. The current utilisation rate of each NACE sector in a specific year is calculated as the average of the p utilisation rates of the BCS industries belonging to the same sector, weighted by their share of supply. Similarly, the regional rates of capacity utilisation for each NACE 1.1 sector in a specific year are calculated as the weighted average of the m national rates in the same sector. The result is a time series of region- and sector-specific capacity utilisation rates for the North-Eastern (N), Western (W), and Southern (S) Eurozone, and other European Union countries (O). The corresponding time series for the Rest of the world (R) are constructed as the weighted average of the sector rates of the other regions.

Appendix D

The world origin-destination investment matrices over the period 1995–2009 are constructed from the investment of origin and destination using the RAS method. The time series of gross fixed capital formation by country and sector of destination are available in the socio economic accounts. The latter are converted in real terms using the specific price indexes provided in the same accounts and aggregated at the regional and sector level. The result is a series of vectors of investment of destination for each region and sector (id_y). The total investment of origin for each region is extracted from the world matrices of final uses derived in the previous section and reallocated to each sector of destination using the annual share of each industry in total fixed capital formation. The result is a series of vectors of investment of origin for each region and sector (io_y). Finally, the RAS method is applied to each pair of vectors of origin (io_y) and destination (id_y) to construct the nxn matrix of investment of origin and destination for the same year. The result is a time series of origin-destination investment matrices over the period 1995–2009.

The time series of gross fixed capital stock in real terms for each sector and country are also extracted from the socioeconomic account. The series are converted into 1995 US dollars based on the exchange rates from the WIOD and aggregated at the regional level. Given the numerous missing entries, the average growth rates over the period 1995–2007 are used to recalculate the values for the years 2008–2009. Since the socioeconomic accounts do not include the gross fixed capital stock for all the countries classified as 'Rest of the world', the time series for the same region is adjusted using the data from the Penn World Tables version 9.1. The countries for which more than half of the series is missing are excluded. The missing values are calculated on the basis of the average growth rate of the available years for the remaining countries. The values are then converted to 1995 million of US dollars and summed up. Finally, the total capital stock obtained from the PWT (TKA_{row_p}) is reallocated to each sector based on its weight in the total capital stock of the same region. Therefore, the real gross capital stock for each industry of the 'Rest of the World' (KA_{row_i}) is calculated as the sum of the value derived from the SEA ($KA_{row\_sea\_i}$) and the share of the additional capital from the PWT (Eq. 11).

$$KA_{row\_i} = KA_{row\_sea\_i} + TKA_{row\_p}\left(KA_{row\_sea\_i} / \sum_{i=1}^{n} KA_{row\_sea\_i}\right) \quad (D1)$$

Appendix E

Table E1. Effects on green and brown output.

	var g = 100%			var v = 100%		
sec	var xg	var xb	var x	var xg	var xb	var x
S1	0,230	−0,018	0,169	0,241	−0,123	0,153
S2	0,046	−0,001	0,032	0,076	−0,028	0,043
S4	0,113	−0,005	0,062	0,363	−0,087	0,168
S5	0,269	−0,034	0,146	0,287	−0,237	0,074
S7	0,211	−0,006	0,045	0,380	−0,067	0,038
S8	0,452	−0,061	0,181	0,651	−0,293	0,152
S9	0,848	−0,035	0,501	1,448	−0,167	0,814
S10	0,295	−0,033	0,189	0,753	−0,262	0,424
S12	0,003	−0,002	0,001	0,113	−0,097	0,033
S13	0,211	−0,019	0,029	1,024	−0,262	0,010
S14	0,124	−0,006	0,005	1,946	−0,218	−0,033
S15	3,213	−0,292	1,003	1,028	−0,386	0,136
S16	0,761	−0,262	0,553	0,282	−0,565	0,110
S17	0,158	−0,074	0,025	0,106	−0,537	−0,262
S18	0,337	−0,003	0,181	0,016	−0,010	0,004
S19	0,090	−0,025	0,070	0,051	−0,177	0,012
S20	0,397	−0,053	0,064	0,569	−0,298	−0,072

Table E2. Effects on green and brown hours worked.

	var g = 100%			var v = 100%		
sec	var hg	var hb	var h	var hg	var hb	var h
S1	−0,020	−0,360	−0,280	0,241	−0,123	0,153
S2	−0,001	−0,270	−0,180	0,076	−0,028	0,043
S4	−0,005	−0,020	−0,010	0,363	−0,087	0,168
S5	−0,030	−0,200	−0,130	0,287	−0,237	0,074
S7	−0,005	−0,180	−0,050	0,380	−0,067	0,038
S8	−0,060	−0,070	−0,070	0,651	−0,293	0,152
S9	−0,040	0,150	0,080	1,448	−0,167	0,814
S10	−0,030	0,020	0,001	0,753	−0,262	0,424
S12	−0,002	−0,020	−0,010	0,113	−0,097	0,033
S13	−0,020	0,020	−0,010	1,024	−0,262	0,010

(*Continued*)

Table E2. Continued.

	var g = 100%			var v = 100%		
sec	var hg	var hb	var h	var hg	var hb	var h
S14	−0,006	0,050	−0,001	1,946	−0,218	−0,033
S15	−0,290	0,120	−0,260	1,028	−0,386	0,136
S16	−0,260	−0,130	−0,160	0,282	−0,565	0,110
S17	−0,070	−0,130	−0,100	0,106	−0,537	−0,262
S18	−0,003	−0,040	−0,030	0,016	−0,010	0,004
S19	−0,030	−0,001	−0,005	0,051	−0,177	0,012
S20	−0,050	0,080	−0,020	0,569	−0,298	−0,072