Productivity and Environmental Decoupling

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February 27, 2023

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Abstract

We study the effects of productivity on CO2 emissions at the sector-level in EU countries. Therefore, we develop a methodology of "Emission function estimation", as an extension of production function in which we model CO2 emission as a by-product. When we estimate the emission functions of European country-sectors, we find that only six EU economies show decreasing CO2 emissions with productivity growth, a process called *decoupling*. We then investigate the relationship between environmental policies aimed at fostering "green growth" and deduce policy recommendations for efficient decarbonisation strategies for European countries.

JEL Classifications: E00, O13, O33, O4, O52, Q4, Q5, Q54

Keywords: Environmental Decoupling, Productivity Growth, European Green Deal

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1. Introduction

In response to the threats of climate change, the European Commission has pushed forward its "European Green Deal", a set of policy measures designed to transition the European economies to net-zero emissions, all while boosting competitiveness and productivity through investments in research and development. In fact, the term "European Green Deal", set as an allusion to Roosevelt's New Deal policies implies a large social policy dimension of the agenda - in this case, the goal is an increase in wages through higher productivity. The same is true of the European Green Deal, which describes its mission to "transform the EU into a modern, resource-efficient and competitive economy, ensuring no net greenhouse gas emissions by 2050, economic growth decoupled from resource use, and no place and no person left behind. Especially the last of these points is strongly correlated with productivity developments in those places.

The premise behind this agenda is that there is no trade-off between productivity increases and decarbonisation. Historically, however, there has been such a trade-off: productivity increases led to increasing carbon emissions. The overcoming of this trade-off is called "environmental decoupling". The crux is: If the investments lead to growth in total factor productivity (TFP) that is faster than growth in CO2 productivity (output per unit of CO2 emissions), total emissions will rise even when CO2 productivity increases. This is because the economy produces more output overall. For a decarbonisation of the economy, we require that the benefits of per-unit efficiency are not overcompensated by the emissions from additional units that can be produced, the so-called rebound effect. The measure that describes whether the net effect of the invention on CO2 emissions is positive or negative is an environmental decoupling elasticity.

Whether an economy is decoupling has direct implications for the optimality of decarbonisation policies, which we categorize into “growth-based decarbonisation” and “substitution-based” decarbonisation strategies. The former bets that productivity growth will come in the form of technologies that are cheaper and cleaner, and therefore it encourages the development of technologies through large investments into research and development. The latter strategy is based on replacing current dirty technologies with cleaner technologies, even in the absence of growth. Such a replacement can can be incentivized through environmental taxes or subsidies. In other words, while a growth-based strategy is concerned with the development of greener technologies, the substitution-based strategy is concerned with their adoption. A purely growth-based strategy will only decarbonise the economy if productivity growth and CO2 emissions are decoupled. For policy makers, the resulting economic challenge is then to find policy mix that takes into account the decoupling behaviour of their economy to decarbonise the economy as quickly as possible. In sectors which are environmentally decoupled, all incentives are aligned - improvements in productivity (which come with higher real wages and therefore usually find widespread political support) automatically also lead to reductions in CO2 emission. In this case, a growth-based strategy that boosts productivity also lowers emissions. In context of the European Green Deal, decoupling implies that there are synergies between the different objectives. In sectors that are not decoupled, the objectives of policy are conflicting. Hence, such sectors need to be decarbonised by investing in the adoption of greener technologies.

In this paper, we propose a methodology to estimate the relationship between total factor productivity and CO2 emissions. This methodology which we call “Emission function estimation” is constructed on top of the classic production function estimation. In particular, we postulate a general emissions function in which emissions are a by-product of production. We show how two parameters that govern slope and curvature of the emission function can be estimated from the data. The curvature parameter of this emissions function is the decoupling elasticity and it shows how quickly the economy will decarbonize (*dynamically*) with TFP growth. The slope parameter is a reflection of the level of emissions and a change in its magnitude corresponds to a *static* decarbonization (in the absence of growth).

We use this approach to survey EU economies at the country-sector level with respect to their decoupling behaviour. Therefore, we calculate the environmental decoupling elasticities and recover the emissions functions of 16 sectors in 25 countries. Based on this exercise, we project and compare the evolution of CO2 emissions between different country-sectors as a function of productivity improvements. We then investigate the relationship of classes of policy tools with environmental decoupling.

Related Literature: The first implicit introduction of environmental decoupling in economics was the framework of environmental Kuznets curves (Auty (1985)), the crossing of whose peak is the process of decoupling. While Kuznets curves have been debated extensively in the literature (see for instance Beckerman (1992), Holtz-Eakin and Selden (1995), Schmalensee et al. (1998) and Churchill et al. (2018)), Vehmas et al. (2003) were the first to propose a formal framework to analyse the link between GDP growth and environmental stress. In this context, they find empirical support for the existence of an environmental Kuznets curve[1]. More recently, a fast-growing literature has emerged around the topic of environmental decoupling. Their framework was picked up and refined further by Tapio (2005) who distinguishes between coupling, decoupling and negative decoupling. Tapio-decoupling has since then become the state of the art method of investigating the relationship between CO2 and GDP growth Wu et al. (2018). Wang and Su (2020) survey 192 countries and calculate their decoupling elasticities. Hubacek et al. (2021) investigate the dynamics of decoupling over time for a panel of 132 countries and the drivers thereof, pointing out the need for international cooperation to reduce CO2 intensity along supply chains.

In contrast to the literature, which often calculates Tapio-decoupling, the percentage change in CO2 emissions over the percentage change in GDP, in this paper we focus explicitly on technology, proxied by TFP. Hence, we remain agnostic about developments in the markets for other production factors and their contribution to value creation. The reason is that we want to investigate if growth-based "innovating to zero" is a viable strategy; and if a new deal agenda that wants to solve social and environmental problems at the same time can be successful. We find that between 2008 and 2019, six EU economies have successfully de-coupled productivity from CO2 emissions: Italy, Spain, Greece, Sweden, Czech Republic and France. In all other countries, per-unit emissions decrease, but overall emissions increase with productivity growth. The countries with the lowest decoupling elasticities are Poland, Luxembourg, Finland and Belgium. In case of Poland, the estimate implies that a 1% increase in productivity is associated with a 0.7% increase in emissions while in Italy, a 1% increase in productivity entails a 1% reduction in CO2 emission. All other countries fall in between these extremes. We further find that there is substantial heterogeneity across sectors in the extent to which productivity improvement increase CO2 emissions. For example, we find that while emissions growth is decoupled from productivity growth among others in the construction sector, the hospitality sector and the manufacturing of wood and paper product, chemical products, machinery and equipment, increasing productivity still comes with increasing emissions in the agricultural sector, mining and quarrying, the transportation sector and the trade sector. This implies that technical change in the latter sectors is not directed sufficiently towards greening the economy.

To issue policy recommendations on how to direct TFP growth towards greening the economy, we first investigate if the share of green innovation is informative of the direction of TFP growth. We find no evidence that this is the case. We then analyse if an increase share of renewable energies in the national energy mix, higher environmentally related taxes or public budgets for environmental protection or energy-related R&D correlate with environmental decoupling. While we find that the increase of environmentally-related taxes in European countries correlates strongly with environmental decoupling, there is no evidence that and a higer share of renewable energy, higher environmental protection budget or public budgets for energy R&D are associated with higher environmental decoupling.

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[1] It should be noted however, that the existence of an inverse U-shaped environmental Kuznets curve is not a scientific consensus: In particular, Aldy (2006) and Wagner (2008) question prior methodologies and present evidence to the contrary)

The light of this, we recommend that policy makers should focus on substitution-based strategies, i.e. decarbonize their economies with existing technologies rather than by betting on green innovations that can deliver both productivity growth and decarbonization. In particular, increases in the share of renewable energies in the national energy mixes is a straightforward way for policy makers to reduce CO2 emissions (statically). Even when productivity growth and emission are still coupled, such a measure can help decouple overall GDP growth from emissions and thereby achieve the objectives of the European Green Deal.

Additionally, based on our results and their country-sector disaggregation, the message for policy makers is therefore that policies that aim towards general improvements in productivity can be counterproductive from an environmental point of view, except in those countries that have decoupled productivity and emissions. Instead, an optimal policy mix targets specific industries that are decoupling with for growth (with R&D investments) and incentivises the substitution of dirty technologies for green technologies in other sectors. This report is structured as follows: In section 2, we present the methodology of emission function estimation and its relationship with growth- and substitution-based decarbonisation strategies. Section 3 describes the data. Section 4 presents the results of the empirical exercises, analyses determinants of decoupling and discusses the role of policy. Section 5 concludes.

2. Methodology

This section presents the methodological approach to CO2 emission functions and shows how they can be estimated. We propose a simple approach of how to measure the relationship between technological progress, proxied by TFP, and CO2 emissions. Two parameters that control slope and curvature of an emission function govern this relationship. Both parameters can be recovered from the data, where the curvature parameter is the *decoupling elasticity*. The basic assumption is that CO2 emissions are a by-product of production in the following way:

$$\Gamma_t = \gamma A_t^{-\xi} Y_t \tag{1}$$

CO2 emissions Γ depend linearly on the overall level of output Y_t. Slope parameter $\gamma > 0$, technology A_t and curvature parameter, ξ, the "decoupling elasticity" determine *CO2 emissions per unit of output*. For any production function $Y_t = A_t f(K_t, L_t)$ we get that

$$\Gamma_t = \gamma A_t^{1-\xi} f(K_t, L_t) \tag{2}$$

For a given level of labour input L_t and capital stock K_t, we get the following result:

- If $\xi > 1$, total CO2 emissions are decreasing with technological progress, i.e. there is "absolute environmental decoupling". This implies that the savings in CO2 emissions due to better technologies are greater than the new CO2 emissions from increased production - driven by the lower cost of output.

- If $0 < \xi < 1$, CO2 emissions per unit of output are decreasing with technological progress, but overall emissions increase as more output is produced. This is called "relative environmental decoupling". In other words, the increased production overcompensates the savings in CO2 from better technology.

- If $\xi < 0$, emissions per unit of output are increasing with technological progress. Such could be the case when technological progress leads to increased automation.

Rearranging the first equation implies:

$$\frac{Y_t}{\Gamma_t} = \frac{1}{\gamma_t} A_t^{\xi} \tag{3}$$

By taking logs, we obtain the following regression equation

$$log\left(\frac{Y}{\Gamma}\right)_{i,t} = \underbrace{log\left(\frac{1}{\gamma_i}\right)}_{\beta_i} + \xi\, log(A_t) \tag{4}$$

which allows us to recover $\gamma = exp(\beta)^{-1}$ and ξ from the data. The CO2 production function can then be backed out from equation 4 as:

$$\Gamma_t = exp(\beta_i)^{-1} A_t^{-\xi} Y_t \tag{5}$$

We emphasise that for overall emissions, decoupling elasticity and scale parameter are both extremely important. While the decoupling parameter is a more dynamic measure that indicates how CO2 will likely evolve, the scale parameter speaks to the current level of CO2 emissions.

Figure 1 sketches an emissions function plotted in black. Here, the decoupling elasticity is greater than one, hence, emissions are decreasing with TFP. Figure 1 shows two stylized examples of innovations that affect the emissions function in different ways. In the left panel, an innovation affects the slope parameter of the emission function, thereby leading to a downward shift of the curve. The right panel shows the effect of an innovation that affects the decoupling elasticity. This this affects the curvature of the emissions function - here leading to a steeper decline of emissions with future TFP increases. Finally, innovations can lead to increases in TFP - rightward along the emissions function. This decomposition also enables us to test whether slope and curvature parameter of the emission function respond to policy changes, spanning a two-dimensional space of decarbonisation policies. On the one side, we have policies that reduce the slope parameter decarbonize the economy even in the absence of TFP growth. This "static" decarbonisation relies on the substitution of high-emission technologies by lower-emission technologies. At the other end, we have policies that promote decoupling elasticities, leading to steeper declines of emissions with growth. This "dynamic" decarbonisation relies on high productivity growth to have any effect on carbon emissions. The effects of policy on both parameters - and thereby its effectiveness - can be tested econometrically. Finally, the framework can also be used to address the question whether carbon Kuznets curves exist. The existence of such a curve in total factor productivity conjectures a bell-shaped relationship between TFP and CO2 emissions. For low levels of TFP, CO2 emissions are increasing in TFP, before reaching a maximum and decreasing thereafter if TFP rises further. This has clear implications for the decoupling elasticities, as can be seen in Figure 2. The decoupling elasticity as defined above is directly related to the slope of the Kuznets curve. If we then estimate decoupling elasticities for a panel of countries, we can check if the TFP-decoupling relationship follows the Kuznets-curve pattern.

Figure 1: Emissions Decoupling Examples

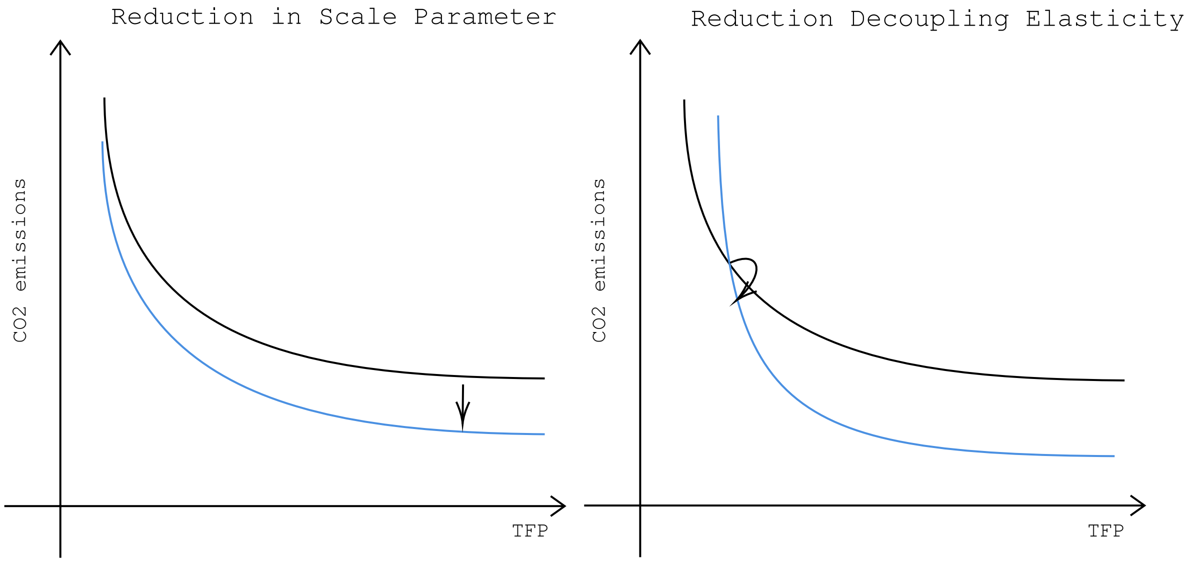
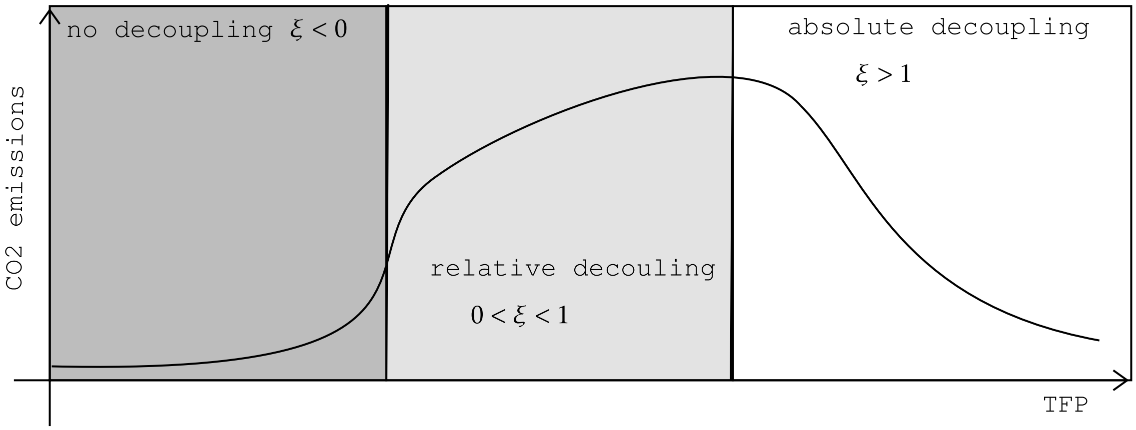


Figure 2: TFP Kuznets Curve



3. Data and Estimation

This section describes the sourcing and construction of the data used in this analysis, and explains the estimation of the emission functions described in the previous section. We base the main exercise on data from three sources. Firstly, we obtain socio-economic data from the EUKLEMS database. This provides data on value added, labour supply (hours), capital stock and capital formation for all EU countries at the sector-level. We use a separate dataset from Eurostat to adjust the values of output and capital stock for purchasing power parity. Additionally, we obtain country-level estimates of capacity utilization from Eurostat. Secondly, we obtain data of sector-level energy consumption from the Enerdata Odyssee project. The advantage of this data compared to energy use data from Eurostat is that it covers energy consumption back to 1995 for most sectors. The downside is that it covers many fewer sectors than data from Eurostat. However, we feel that the advantages outweigh the disadvantages, as the high-emission sectors agriculture, mining, manufacturing, construction and transport are included in the Enerdata database, and mainly less important service sectors are missing. Thirdly, Eurostat also provides data on CO2 emissions per sector. These emissions are only the direct emissions that each sector causes with its activities, i.e. they do not account for the indirect emissions economic activity causes through its usage of energy. This allows us to calculate CO2 productivities, as the ratio of value added over CO2 emissions for each sector[2]. Finally, we pair the energy use data with data on the carbon intensity of energy. This data stems from the European Energy Agency and is available at the country-level[3]. The combination of these data sources allows us to study the effects both on direct and indirect CO2 emissions. This is important as energy consumption accounts for the majority of industrial emissions[4].

From this data, we estimate the production functions of each sector.

$$Y_t = A_t U_t L_t^{\alpha} K_t^{\beta} E_t^{1-\alpha-\beta}$$

In practice, the estimation of productivity proceeds as follows. First, we divide the entire equation by the labour supply. Hence, we need to only estimate the production function coefficients of $\frac{K}{L}$ and $\frac{E}{L}$. This comes with the hidden assumption of constant returns to scale of the production function. Secondly, we take logs of the production function to obtain the following regression equation:

$$log\left(\frac{Y_t}{L_t}\right) = log(A_t U_t) + \beta log\left(\frac{K_t}{L_t}\right) + (1-\alpha-\beta) log\left(\frac{E_t}{L_t}\right) + controls$$

In line with the literature Hsieh and Klenow (2009), we assume that the same sector-specific production functions are optimal in each country, and that any deviation is a form of misallocation. The extra controls variables serve the purpose of accounting for the distance of each country-industry to the technology frontier. Following Pablo-Romero et al. (2019), we measure the difference in labour productivity, between

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[2] The sectoral breakdown of the merged database is described in Table A.4.

[3] We obtain this data from https://ourworldindata.org/grapher/carbon-intensity-electricity (11.10.2022), which sources its data from the Ember Global Electricity review, the European Environmental Agency and the EIA.

[4] On average across countries and sectors, indirect emissions make up 59.6% of total emissions.

each country-industry and the country with the highest labour productivity in the same industry. We include two equivalently constructed regressors for capital and energy productivity. The inclusion of such distance measures is necessary to ensure that the heterogenous levels of technology between EU member countries do no distort the estimate of the production factor elasticities. We estimate this equation with a two-step GMM procedure, in which we instrument the factors with their lagged values to account for the endogeneity of factor inputs to productivity (see De Ridder et al. (2021) for details). This yields estimates for the parameters of the production function, which we then use to calculate total factor productivity (net of utilization). The results of the production function estimation for each sector are presented in Table A.5, which is relegated to the appendix for expositional purposes.

Next, we estimate the emission functions. We face the choice between two options: We can choose either to use sector fixed effects and estimate country-specific decoupling elasticities, or to use country fixed-effects and estimate sector-specific decoupling elasticities. We follow both approaches, and present the results in Tables B.6 and B.7. Neither measure is foolproof: when we estimate sector-level decoupling elasticities it is possible that the sectoral response to TFP growth in a subset of countries drives the decoupling elasticity, misleading about the effect in a sector of another country. Conversely, a subset of sectors may drive a country-level decoupling elasticity, obscuring individual sector-level responses of CO2 productivity from TFP growth. We argue that in light of this, country-specific decoupling elasticities are more useful to policy makers because they accurately predict the effects of TFP increases that are uniform across industries in the respective country[5]. We therefore recommend a dual approach to using these results. Primarily, the country-level decoupling elasticity shows how fruitful a growth-based decarbonisation strategy can be. If the decoupling elasticity of a country is above one, investment in general TFP growth will lower carbon emissions. The associated slope parameter shows the extent to which the economy can still be decarbonized by substituting out dirty technologies. If the country-level decoupling elasticity is below one, the policy maker can use the sector-level decoupling elasticity to understand in which sector TFP growth yields the largest reductions in CO2 emissions. In spirit, this is a similar exercise as the production function estimation, as we are effectively estimating the “production” of CO2. Hence, we rely on a similar procedure, in which we instrument productivity by its once-lagged value in order to ensure that that the estimates are endogeneity-proof. De-facto, this models total factor productivity as an AR(1) process, which is a common assumption in macroeconomics. Additionally, we include a dummy and interaction effect for all periods in which productivity was growing. The process of decoupling assumes (at least in the medium run) productivity growth, so we do not want our results to be driven by periods in which productivity shrank. However, we generally find that the interaction effect is statistically insignificant.

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[5] In contrast, knowledge of the effect of uniform TFP growth in a specific industry in all countries is not useful for country-level policy making.

Table 1: Benchmark Decoupling Elasticities by Country

Austria	Belgium	Czechia	Denmark	Finland	France	Germany	Greece	Hungary	Ireland
0.61	0.50	1.18	0.88	0.43	1.14	0.66	1.47	0.55	0.64
Italy	Luxembourg	Netherlands	Poland	Portugal	Romania	Slovakia	Spain	Sweden	UK
1.98	0.40	0.96	0.30	0.78	0.73	0.92	1.43	1.32	0.51

This table shows the decoupling elasticites by country backed out from the benchmark exercise of emission function estimation.

Table 2: Benchmark Decoupling Elasticities by Sector

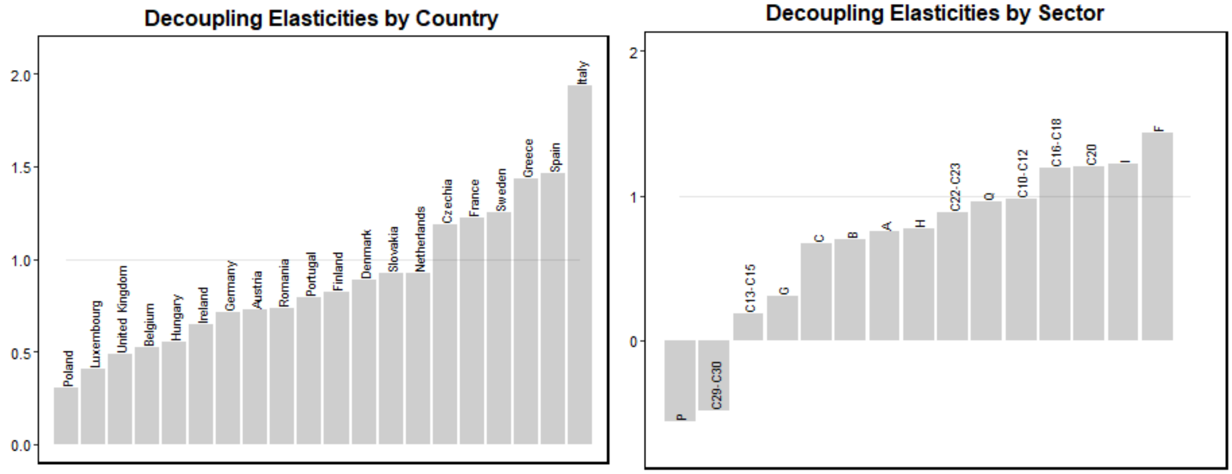
A	B	F	G	H	I	P	Q
0.75	0.69	1.43	0.30	0.77	1.21	-0.55	0.96
C (aggregate)	C10-C12	C13-C15	C16-C18	C20	C22-C23	C25-C28	C (other)
0.66	0.97	0.18	1.19	1.20	0.88	1.05	-0.48

4. Results

This section presents the results of the empirical analysis, above all the estimated decoupling elasticities. We estimate the decoupling elasticities both for the sectors as well as for countries. Figure 3 and Tables B.6 and B.7 shows the estimated decoupling elasticities for countries and sectors. Herein, we have removed the countries for which we have fewer than 5 years of data.

As we can see, there are six countries that have decoupling elasticities above one: Italy, Greece, Spain, Sweden, Czechia and France. All other countries have not absolutely decoupled productivity growth from emissions yet. For policy makers, this implies that using these estimates as reference values, there are currently no synergies between the productivity and environmental policy goals of the European Green Deal (no net GHG emissions by 2050, no place and no person left behind.) Alternatively to looking at decoupling elasticities by country, we can look at the sector-specific decoupling behaviour across countries. The results of this exercise are shown in Table 3 and in the right panel of Figure 2: The sectors in which CO2 emissions and productivity growth are decoupled are construction (=F), hospitality (=I), manufacturing of Chemical Products (C20), manufacturing of wood and paper products, including printing and production of recorded media (C16-C18), and the manufacturing of machinery and equipment (C28). Notably, there are also two sectors in which emissions are estimated to rise per-unit of value added (negative coupling). These sectors are the manufacturing of motor vehicles and other transport equipment (C29-C30), as well as the education sector. An alternative way to gain insight in to the CO2 response to increases in total factor productivity comes from local projections. Following Jordà (2005), we can estimate impulse response functions without the need to specify the underlying dynamic system by regressing the dependent variable and its leads on the dependent variable and its lags. This framework also takes into account the 2SLS structure that we used in the emission functions estimation. Thereby, it is a natural extension, that provides

Figure 3: Benchmark Decoupling Elasticities for Countries and Sectors



more details on the evolution of the effect over time. We implement this exercise, which sheds light on the different persistences that the response of CO2 productivity has in each NACE-1 sector when hit with a TFP shock. Figure 4 compares as an example the impulse responses in the agricultural and manufacturing sector. We can clearly see that both the initial response, as well as the persistence of the effect is larger in the agricultural sector, in which the effect is still significant after 8 year. At the same time, the effect of a TFP shock fades out within 5 years in the manufacturing sector. Figures C.6 and C.7 in the appendix show the impulse response functions of the remaining NACE-1 sectors.

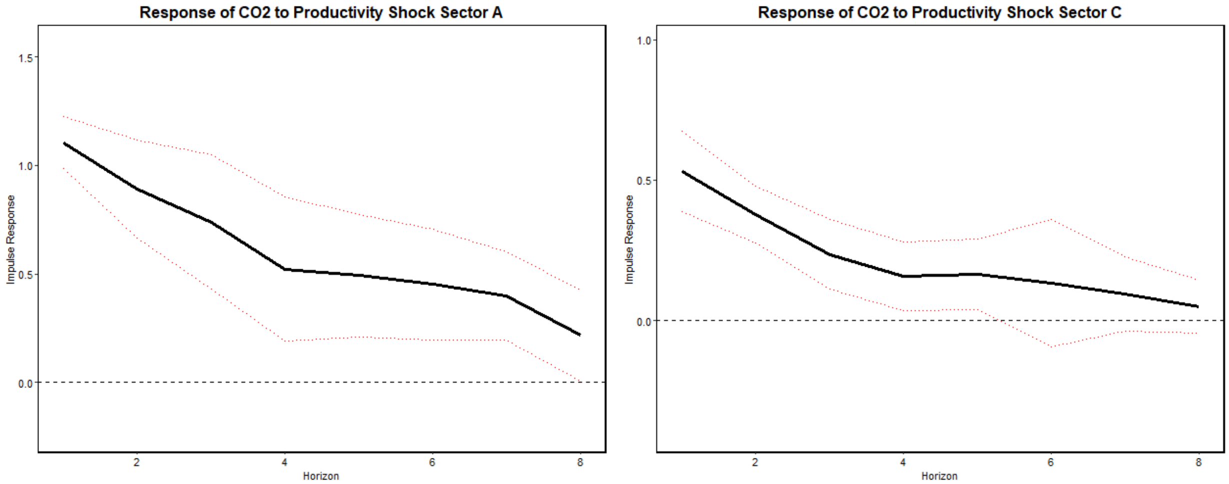
4.1. Robustness

The results are qualitatively robust to slight changes to the assumptions of the production function estimation. In particular, they do not change qualitatively for various combinations of instruments for the production factors and the distance-to-technology-frontier variables included in the production function estimation. We further find similar results when we restrict attention to direct CO2 emissions and omit energy as a factor of production. The accounting for capacity utilization also only has mild effects on the estimates. However, the estimates of decoupling elasticities still suffer from a weak point, which is the variability of estimates of decoupling elasticities over different periods of time. Splitting the sample into two subperiods of equal length produces country-level estimates that change both quantitatively and qualitatively between the two subperiods. We currently judge that the variability of the decoupling elasticities is too great to use the estimates as "sufficient statistics", based on which policy choices can be made. While we can excuse this variability with the very short time frame for which sector-level data on CO2 emissions exist, it is not clear that future revisions with more data will produce more stable estimates.

4.2. Innovation and the direction of TFP growth

One of the most frequent mentions for drivers of total factor productivity is innovation – on which the literature of endogenous growth builds (see among others Romer (1990), Aghion and Howitt (1990), Comin

Figure 4: Responses of CO2 Productivity to TFP shock in Agriculture and Manufacturing Sector



This figure shows the impulse responses estimated through local projections as described above. The x-axis measures the horizon, the y-axis measures the response of CO2 productivity to a shock in total factor productivity. The dashed lines are the 95% confidence bands of the estimated IRF.

(2010)). Especially when the measures of TFP are cleared of capacity utilization, improvements in production technology that are ultimately driven by innovations could have an important impact on growth. As argued earlier, when productivity growth and emissions growth are decoupled, this implies that there is sufficient direction of productivity growth toward decarbonization. In light of that, we check if the magnitude “Green Innovation” is a good measure of this directedness of productivity growth. Therefore, we match patent data from the PATSTAT database of the European Patent Office (EPO), which is classified into “green” and “non-green” patents to our estimates of decoupling. The patent data is available at NUTS2 levels, but since our decoupling estimates are at the national level, we aggregate over all regions within a country. We compute the share of “green” patent applications in overall patenting. However, we find that there is no significant correlation between higher patenting activity and higher decoupling elasticities. This absence of correlation is surprisingly robust: it holds both for the patents that were filed during the same period as the decoupling elasticities (2008-2019) as well as for the patents that were filed in the 2000s (2000-2009). It also holds for several subcategories of patents that exclusively protect innovations in the fields of manufacturing, transport and energy efficiency. To further corroborate this result, we also use and OECD measure of environmentally-related innovations as a share of overall technological innovations – and again find no significant correlation between the two. This suggests that green innovation alone is not a determinant of the directedness of TFP growth alone.

Can policy target the environmental decoupling behaviour of an economy directly? To answer this question, we access the Green Growth Dataset by the OECD. It provides information on 150 environmental indicators, ranging from CO2 productivity to exposure to pollution, available biomass, degradation of ecosystems and particles of industrial-emitted gases in the atmosphere. While this data set is now updated on a yearly

Table 3: Policy Tools Summary Statistics

	Envir. Taxes to GDP	Envir. Protection to GDP	Renewables in Energy Mix	Public Energy R&D to GDP
25% quantile	2.206	1.706	9.333	0.0019
mean	2.732	1.951	17.216	0.0037
75% quantile	3.308	2.224	23.231	0.0039
standard deviation	0.714	0.549	10.092	0.0034

basis, it only reports statistics once every five years until 2015. Most importantly for our purposes, they provide information on classes of environmental policy tools for European countries. We identify four policy tools[6] that characterize different aspects of decarbonisation strategies: These four tools are: 1) the share of environmentally-related tax revenue to GDP. This category includes taxes on energy products, as well as taxes on purchase and registration and road use of motor vehicles. Additionally, the category also includes taxes on waste disposal, packaging or other waste-related taxes. 2) The overall environmental protection budget of a country, relative to GDP. 3) The share of renewable energies (wind, water, solar, tidal and geothermic power, as well as biofuels) in the national energy mix. 4) The public budget for research and development for energy, as a a share of GDP. Table 3 presents summary statistics of the different classes of policy tools. All values are expressed in percent. As we can see, environmental tax revenue as well as the governmental environmental protection budget only amount to a small fraction of GDP. The average share of renewables in the national energy mix sits at just 17 %. The share of renewables is also the policy tool that exhibits the highest amount of variation between different countries.

The policy tools here relate to the decarbonisation strategies as follows. Investments into research and development are part of a growth-based decarbonisation strategy[7] if the developed technologies are both more productive and cleaner. On the contrary, the share of renewables in the national energy mix is an important part of both substitution-based and growth-based strategy. Their installation reduces the carbon intensity of the current energy mix. At the same time, more installed capacities of renewable energies also help capture the increasing energy demand that often follows productivity growth – thereby enabling growth without any additional emissions. Environmental Protection Budget are also part of a substitution-based strategy, as the preservation of lands and biomass can facilitate natural capture of CO2 and does not affect total factor productivity. Finally, environmentally related taxes are also important for both growth- and substitution-based decarbonisation strategies. The underlying idea for environmental taxes to promote decoupling is simply that higher taxes penalize non-green growth at the margin and therefore push economic agents to pursue green productivity growth. At the same time, environmentally-related taxes also affect the behaviour of agents for any given level of productivity, encouraging static decarbonization.

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[6] for which sufficient data is available

[7] We assume throughout that R&D is a driver of TFP growth.

Figure 5: Correlation of Decoupling Elasticities with Policy

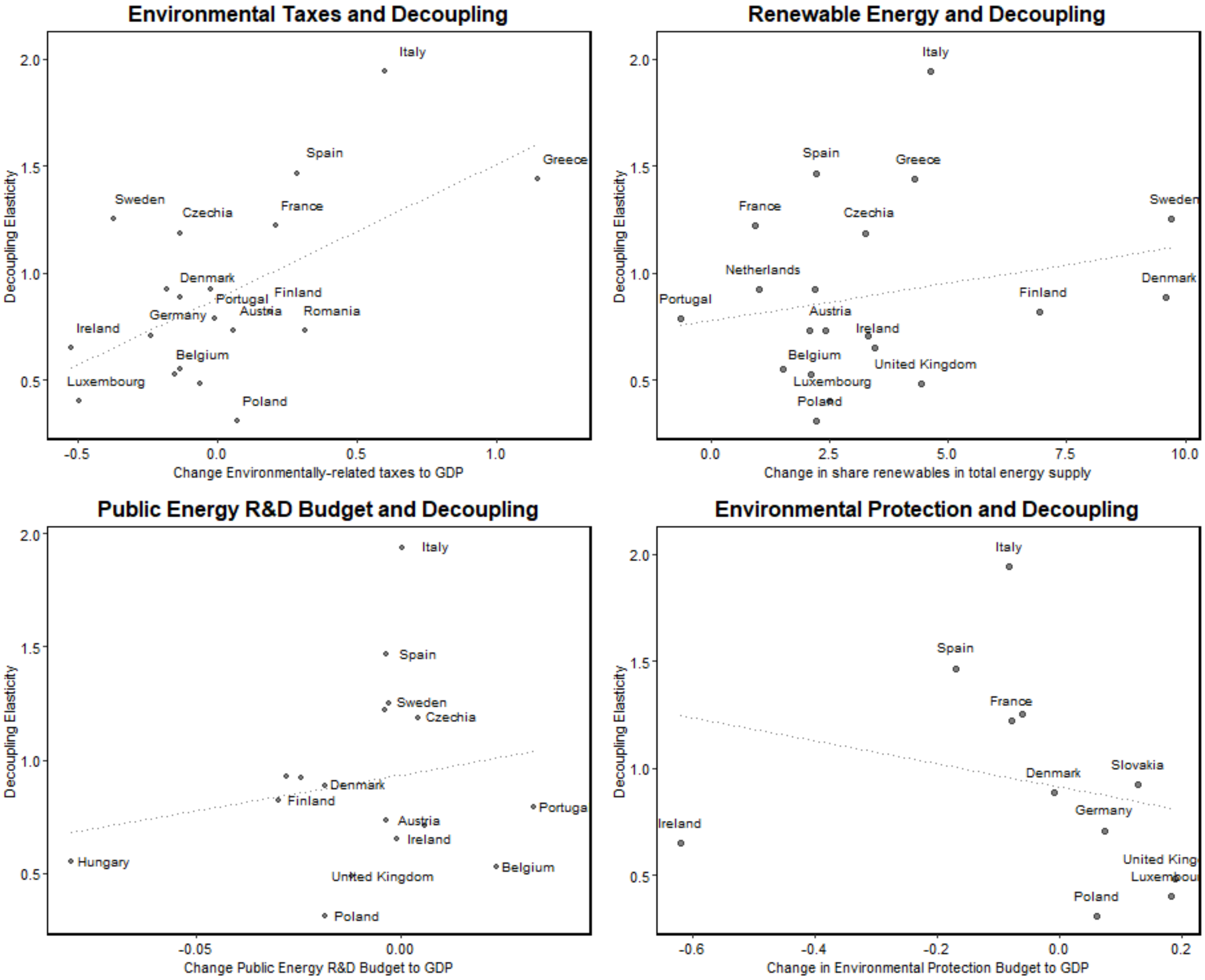

Figure 5 above show the correlation of these four policy tools with the environmental decoupling elasticity. On the top-left see with see the change in environmentally-related tax revenue between 2010 and 2015 on the x-axis, while the y-axis measures the decoupling elasticity. As we can see, the relationship is positive, and the correlation coefficient of 0.53 confirms this. The lack of data coverage prevents an proper identification of the effect of environmental taxes on decoupling. The negative takeaway from the left panel in this figure is that roughly half the countries have witnessed reductions in their environmentally-related tax revenue between 2010 and 2015. This goes against the recommendations of many economists to shift the tax burden away from labour towards environmental damages, most importantly to emissions. In the top-right panel, we see the relationship of the decoupling elasticity with the change in the share of renewable energies in the national energy mix between 2010 and 2015. The correlation is again positive and amounts to 0.18. All countries except for Portugal have increased the share of renewables in their energy mix over this period. The correlations of the decoupling elasticities with the change in government R&D budget that is allocated to energy-related matter (bottom-left), and the change in environmental protection budget

amount to 0.22 and -0.25, respectively. Neither correlation is statistically significantly different from zero. This holds both for the change in the variables between 2010 and 2015, as well as for their levels.
The weakness of the relationship between policy and decoupling behaviour make it impossible to issue clear policy recommendations. However, it is clear that optimal combination of policy tools ultimately depends on the necessary speed of decarbonisation of the economy, the costs associated substituting dirty technologies for zero-carbon technologies and the tax revenues that can be raised (and are palatable to the population) from increased environmental taxation. Such a strategy could only be calculated properly in a structural model which takes full account of the interactions of different tools and the magnitudes of the synergies, rather than merely pointing out where synergies can be found. Such an exercise is beyond the scope of this paper but can be an interesting task for future research.

5. Conclusion

In this paper, we have outlined a methodology of estimating emission functions – which describe CO2 emission as by-products of the production process. The estimation of the emission functions yields estimates of decoupling elasticities, that describe to what extend CO2 emissions increase or decrease with productivity growth. Similarly to production function estimation, we estimated a two stage least squares model, in which we control for the endogeneity of productivity with its lagged values. We showed that only decoupling elasticities larger than one imply the existence of synergies between policy goals of decarbonization and productivity improvements and all the welfare-improvements that productivity growth entails. We have then estimated decoupling elasticities for 20 countries and 16 sectors of the European Union. We found that six economies and five sectors (across countries) have decoupled productivity growth from emissions. In those countries and sectors, there may therefore be synergies between productivity- and environmental goals of the European Green Deal. Finally, the evidence that policy can affect the decoupling behaviour of the economy is very weak. While there is a positive correlation between decoupling elasticities and the revenue from environmentally-related taxes, there is no evidence that increase innovation, increased green innovation or higher public spending on RD is associated with faster decoupling of productivity and CO2 emissions. We hence conclude that research has a long way to go to inform policy on how to direct productivity to foster a green transition. In light of these results and the urgency of the climate crisis, it is better to decarbonize without relying on productivity growth.

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Appendix A. Sector Classifications and Production Function Estimation

Table A.4: Sector Classifications and Descriptions

Description	Code	Description	Code
Crop and animal production and hunting	A01	Wholesale and retail trade and repair of motor vehicles	G45
Forestry and logging	A02	Wholesale trade, except of motor vehicles	G46
Fishing and aquaculture	A03	Retail trade, except of motor vehicles	G47
Mining and quarrying	B	Land transport and transport via pipelines	H49
Manuf. of food products, beverages and tobacco prod.	C10-C12	Water transport	H50
Manuf. of textiles, wearing apparel and leather prod.	C13-C15	Air transport	H51
Manuf. of wood and cork products, except furniture;	C16	Warehousing and support activ. for transportation	H52
Manuf. of paper and paper products	C17	Postal and courier activ.	H53
Printing and reproduction of recorded media	C18	Accommodation and food service activities	I
Manuf. of coke and refined petroleum products	C19	Publishing activities	J58
Manuf. of chemicals and chemical products	C20	Recording, publishing activ. and broadcasting	J59_J60
Manuf. of basic pharmaceutical products	C21	Telecommunications	J61
Manuf. of rubber and plastic products	C22	Computer programming and information service activ.	J62_J63
Manuf. of other non-metallic mineral products	C23	Financial service activ., except insurance	K64
Manuf. of basic metals	C24	Insurance, except compulsory social security	K65
Manuf. of fabricated metal products, except machinery	C25	Auxiliary to financial services and insurance	K66
Manuf. of computer, electronic and optical products	C26	Real estate activities	L68
Manuf. of electrical equipment	C27	Legal, accounting and management consulting activ.;	M69_M70
Manuf. of machinery and equipment n.e.c.	C28	Architectural and engineering activ.	M71
Manuf. of motor vehicles, trailers and semi-trailers	C29	Scientific research and development	M72
Manuf. of other transport equipment	C30	Advertising and market research	M73
Manuf. of furniture; other manufacturing	C31_C32	Other scientific, technical and veterinary activities	M74_M75
Repair and installation of machinery and equipment	C33	Administrative and support service activ.	N
Electricity, gas, steam and air conditioning supply	D35	Public administration and defence; social security	O84
Water collection, treatment and supply	E36	Education	P85
Waste collection	E37-E39	Human health and social work activ.	Q
Construction	F	Other service activ.	R_S
		Activities of households as employers;	T
		Activities of extraterritorial organizations	U

This table provides a dictionary for the sector codes used in the graphs throughout the paper. The descriptions are sometimes abbreviated for expositional purposes.

Table A.5: Production Function Estimation

Sector	K/L	E/L
Agriculture (A)	0.44	-0.01
Mining and Quarrying (B)	0.49	0.06
Manufacturing (C, aggregate)	0.60	0.26
Construction (F)	0.61	0.01
Trade (G)	0.75	-0.10
Transportation (H)	0.64	-0.02
Hospitality (I)	0.28	-0.01
Education (P)	0.67	-0.01
Human Health and Social Work (Q)	0.78	-0.02
Manufacturing (C10-C12)	0.47	0.21
Manufacturing (C13-C15)	0.45	-0.06
Manufacturing (C16-C18)	0.37	0.17
Manufacturing (C20)	0.76	0.05
Manufacturing (C22-C23)	0.34	0.44
Manufacturing (C25-C28)	0.75	0.07
Manufacturing (C29-C30)	1.02	-0.10
Manufacturing (other)	0.53	0.34

Appendix B. Counterfactual Direct Emissions

Table B.6: Direct Emissions Decoupling Elasticities by Country

Austria	Belgium	Czechia	Denmark	Finland	France	Germany	Greece	Hungary	Ireland
0.35	0.36	1.17	0.63	0.10	1.41	0.92	0.37	0.42	0.61
Italy	Luxembourg	Netherlands	Poland	Portugal	Romania	Slovakia	Spain	Sweden	UK
1.99	0.34	0.90	0.52	0.37	0.95	0.86	1.37	1.10	0.51

This table shows the decoupling elasticites by country backed out from the counterfacutala exercise of emission function estimation, in which indirect emissions through energy consumption are disregarded.

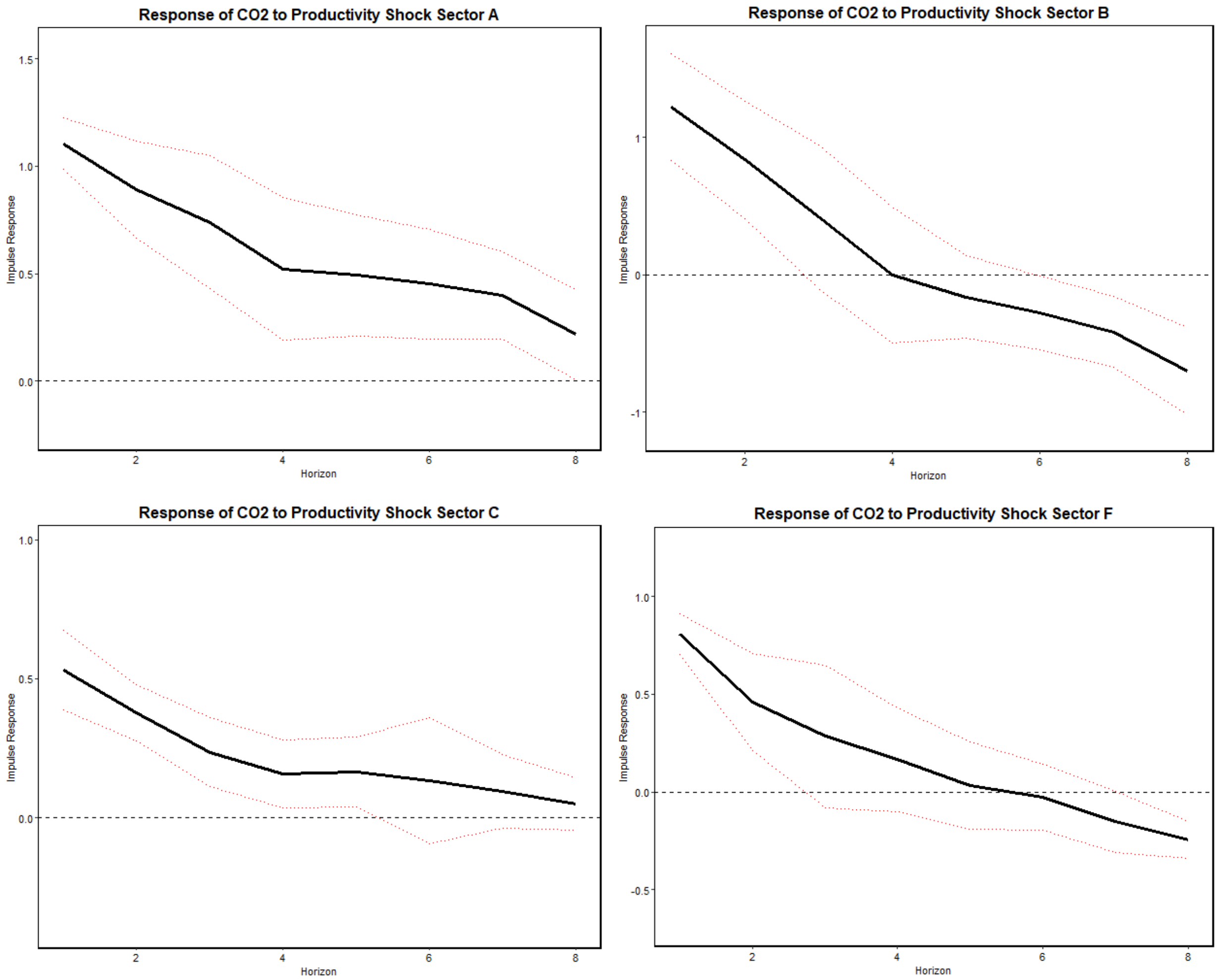
Table B.7: Direct Emissions Decoupling Elasticities by Sector

A	B	F	G	H	I	P	Q
0.68	0.66	1.07	0.63	0.85	1.89	0.21	0.83
C (aggregate)	C10-C12	C13-C15	C16-C18	C20	C22-C23	C25-C28	C (other)
0.48	1.22	0.40	1.33	0.92	0.02	0.34	-0.02

This table shows the decoupling elasticites by country backed out from the counterfacutala exercise of emission function estimation, in which indirect emissions through energy consumption are disregarded.

Appendix C. Local Projections

Figure C.6: Responses of CO2 Productivity to TFP shock in Sectors A, B, C, and F


Response of CO2 to Productivity Shock Sector A

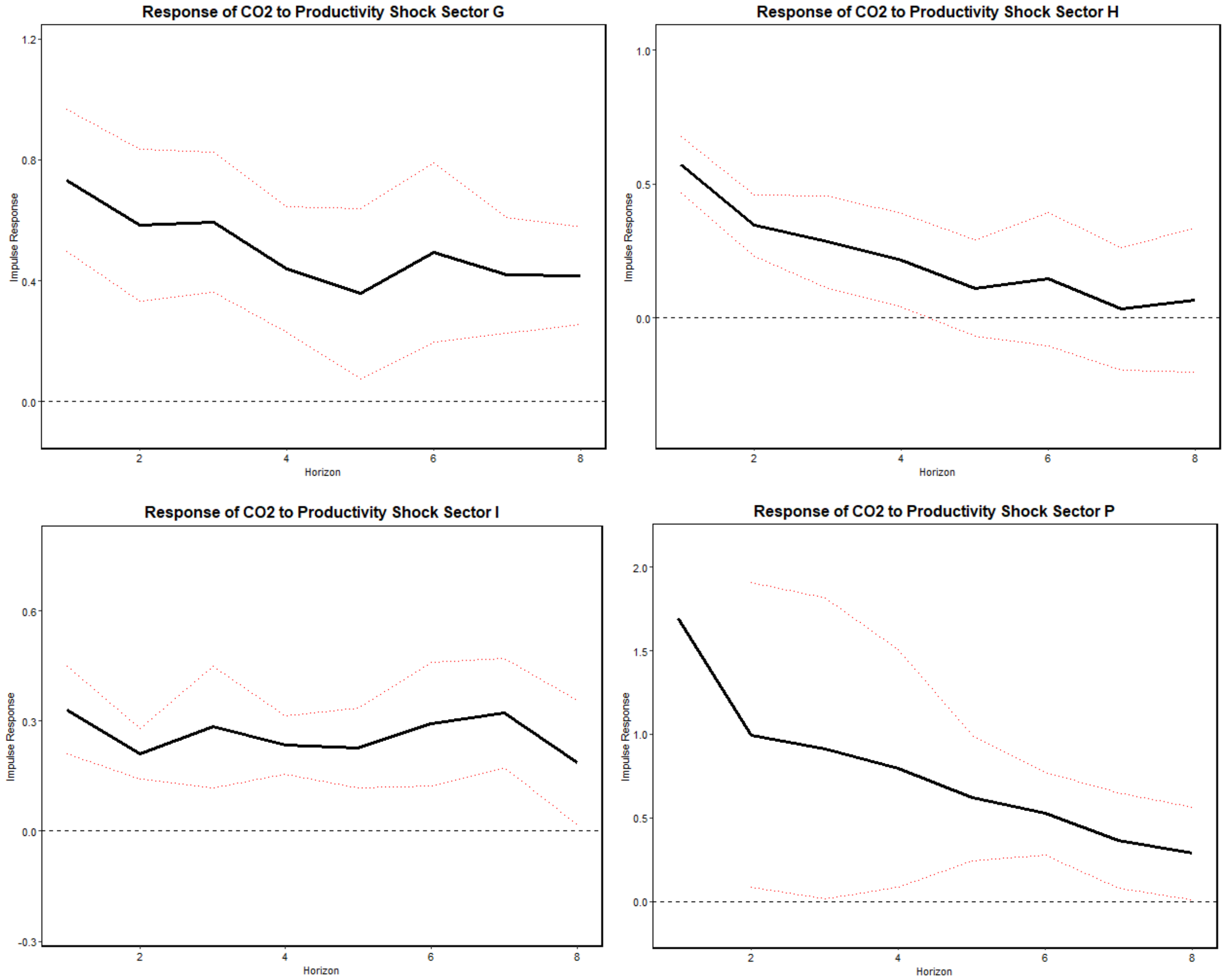
Response of CO2 to Productivity Shock Sector B

Response of CO2 to Productivity Shock Sector C

Response of CO2 to Productivity Shock Sector F

This figure shows the impulse responses estimated through local projections as described above. The x-axis measures the horizon, the y-axis measures the response of CO2 productivity to a shock in total factor productivity. The dashed lines are the 95% confidence bands of the estimated IRF.

Figure C.7: Responses of CO2 Productivity to TFP shock in Sectors G, H, I, and P



This figure shows the impulse responses estimated through local projections as described above. The x-axis measures the horizon, the y-axis measures the response of CO2 productivity to a shock in total factor productivity. The dashed lines are the 95% confidence bands of the estimated IRF.