Demand or Supply? An empirical exploration of the effects of climate change on the macroeconomy*

Matteo Ciccarelli[1] and Fulvia Marotta[2]

[1]European Central Bank
[2]Queen Mary University of London

This version: May 24, 2022.

* *We would like to thank Marek Jarocinski, Michele Lenza, Haroon Mumtaz, Miles Parker, and ECB's seminar participants for useful comments and suggestions. The views expressed in this paper are of the authors only and do not necessarily reflect those of the European Central Bank or the Eurosystem.*

Abstract

Using an original panel data set for 24 OECD countries over the sample 1990-2019 and a multivariate empirical macroeconomic framework for business cycle analysis, the paper tests the combined macroeconomic effects of climate change, environmental policies and technology. Overall, we find evidence of significant macroeconomic effects over the business cycle: physical risks act as negative demand shocks while transition risks as downward supply movements. The disruptive effects on the economy are exacerbated for countries without carbon tax or with a high exposure to natural disasters. In general, results support the need for a uniform policy mix to counteract climate change with a balance between demand-pull and technology-push policies.

JEL Classification: C11, C33, E32, E58, Q5
Keywords: Environmental policy, Environment-related technologies, Physical risks, Business cycle, SVAR

1 Introduction

The rise in human and economic activity since the industrial revolution – and the subsequent increase in carbon and other greenhouse gas (GHG) emissions, deforestation and air pollution – has already had a substantial and quantifiable impact on our planet's climate. Scientists of the Intergovernmental Panel on Climate Change (IPCC) estimate that global temperatures have risen by around 1°C since 1850 and could exceed 4°C by the end of this century if no action to limit emissions is taken (IPCC (2018)). Under this business-as-usual scenario, climate change will adversely affect ecosystems, water resources, food production, human settlements and the frequency and magnitude of extreme natural events, resulting in great risks for our economy and financial system (IPCC (2022)).

The severity of climate change's direct effects (such as rising sea levels and more frequent severe natural disasters) as well as the transition to a net-zero economy (through changes in government climate policy, technology and consumer preferences), will generate financial risks and economic consequences, involving unprecedented structural changes to our economies, countries and sectors. Therefore, when it comes to understanding the impact of climate change on economic activity it is important to distinguish between the impacts of what the literature identifies as physical and transition risks. Both types of risks (or shocks) affect the economy from both the supply and demand side through many channels.

As such, climate change is relevant to the central banks' mission to maintaining monetary and financial stability. From a central bank perspective this implies that researchers need to investigate two fundamental aspects: first of all, we need to provide evidence that these effects materialize over a horizon that is relevant for monetary policy. Once this is supported, then modelling the interaction between climate change and the economy requires empirically validated assumptions (NGFS (2020b), McKibbin et al. (2021)).

This paper sheds light on these issues by answering three main questions: Are the economic effects of climate-related shocks significant enough over the business cycle (2 to 8 years horizon)? Do climate change and efforts to counteract those changes differ in their effects on the macroeconomy? And, if that is the case, can we determine if those effects resemble more demand- or more supply-type of shocks? Our main contribution is twofold: (i) we start filling the gap in the empirical macroeconomic literature about the effects of climate-related shocks over the short-to-medium term using an empirical framework that is otherwise standard for business cycle analysis; (ii) we provide important preliminary evidence on the interrelated effects of physical and transition risks which could turn useful to inform the assumptions of theoretical models. By carefully selecting the variables that proxy for adaptation, mitigation and damage, and interacting them with macroeconomic variables in a panel of 24 OECD countries over the period 1990-2019, the paper shows that climate changes and policies to counteract them can have a significant and persistent effect on output and price levels. In particular, we find that the impact on output and prices of physical risks is overall negative, whereas policies and technologies affect positively prices and negatively output. We interpret this result as supporting the view that on average for physical risks (downward) demand adjustments play a bigger role than for transition risks, for which supply-type adjustments are stronger. Results differ significantly across countries according to several institutional and economic characteristics. Overall, countries that have introduced carbon tax and revenue recycling tend to suffer less negative consequences in the transition to a low-carbon economy (or after a climate shock) than countries without carbon tax or with a higher exposure to risks.

The paper is structured as follows: In Section 2 we selectively survey the literature on the macro impacts of climate-related events or policies and on the main transmission channels. In Section 3 we illustrate the data and the methodology, including the proposed identification strategy. In Section 4 we present the results. Section 5 explores the transmission channels of climate shocks and countries' heterogeneity. Section 6 concludes.

2 Channels and literature

Several organizations and academic researchers have attempted to estimate the impact of climate change on the global economy. The focus of the literature is scattered across specific regions, characteristics and effects of climate change. Furthermore, these estimates are subject to considerable uncertainty, given the fact that the pace of climate change remains unclear to scientists and its impacts will most likely become more significant over the long horizon. There is an increasing number of reports and reviews that are key to understand the taxonomy and the transmission channels of climate change-related risks. In most of these reports, conclusions have either been based on standard macroeconomic considerations (e.g., Andersson et al. (2020), Batten et al. (2020)), or on model-based simulations (e.g. NGFS (2020a), IMF (2020)).

Our work relates closely to the growing empirical literature that aims at testing these channels and their macroeconomic consequences. However, given the uncertainty involved in the frequency and damages caused by these events and the difficulties in directly attributing such events to climate change, the available evidence on how the economy will be affected is still hazy. The impact of physical risks on prices and inflation is found to vary substantially by type, severity, location and sector of the economy (e.g., Parker (2018), Kim et al. (2021), Heinen et al. (2018), Cavallo et al. (2014), Baldauf and Lorenzo Garlappi (2020), Canova and Pappa (2021)). With respect to the consequences of global warming, namely, the slow increase in average temperature, the literature agrees that an average temperature increase has adverse effects on the economy, even though this result is very sensitive to countries' differences (Burke and Tanutama (2019)). Extreme temperatures are found to reduce output (Burke and Hsiang (2015)), labour productivity (Donadelli et al. (2017)), agricultural production (Winne and Peersman (2019)) and food security (Bandara and Cai (2014), Schaub and Finger (2020), Kamber et al. (2013))

and in general economic growth (see Mumtaz and Alessandri (2021), Kahn et al. (2019), Deryugina and Hsiang (2014)). Most of the evidence examines the effects on the supply side, while still scarce is the literature concerning the threats on the demand side. These are generated by disruption to income, consumption patterns, investments, exports, infrastructures and changes of consumers behavior, potentially related to migration and climate awareness. In fact, climate change is likely to exacerbate not only the frequency and intensity of natural disasters but also the gradual process of environmental degradation (i.e., air and water pollution, global warming, smog, acid rain, deforestation, wildfires), hence leading to premature deaths and injuries, forcing people to leave their homes and temporarily or permanently move to other places, and affecting well-being and welfare.

To mitigate and to adapt to climate change substantial changes to the economy are needed, implying significant policy intervention, investment and innovation (Gillingham and Stock (2018)). Unfortunately, while protecting our climate, environmental policies could alter economic activity substantially, having an impact on the demand and supply mix that affects output and prices. As well, the roll-out of new green technologies would encompass significant government expenditure, investment and innovation that could result in wide-ranging economic risks (see Andersson et al. (2020) for a review). Nevertheless, the empirical literature seem to point to the result that environmental policy and investments in climate mitigation can have positive effects on the economy (Metcalf and Stock (2020), Braennlund and Gren (1999), Batini et al. (2021), Sokolov-Mladenović and Mladenović (2016), Wong et al. (2013)). However, in order for these effects to be optimal, the blend between environmental policy and technological innovation has to be carefully planned, together with the potential risks connected with the wrong mix of the two. Generally, environmental policy intervention is necessary when facing two two types of market failures: (1) environmental externalities (e.g., pollution is not priced by the market, firms and consumers have no incentive to reduce emissions without policy interventions) (2) knowledge failures concerning environmental R&D. The public good nature of innovations creates knowledge spillover and, as a result, firms do not have incentives to provide the socially optimal level of research activity. As a result, when the policy mix is characterised by a more balanced use of demand-pull and technology-push instruments facing these two types of externalities, its effects on environmental innovation tend to be greater, mitigating the occurrence of market failures negatively affecting the economy (Costantini et al. (2017)).[1]

To the best of our knowledge, we propose the first empirical exercise that includes the interrelated effects of both physical and transition risks on the economy. Our paper tries to

[1]In the literature, policies addressing the first type of externalities are typically referred to as demand-pull policies. They foster technological change by stimulating their demand, increasing the market size for environmental innovation through regulation, carbon tax, financial incentives, standard-setting instruments or information campaigns (Popp (2019)). Policies that address knowledge market failures instead are called technology-push policies. This type of policies aim to foster socio-technical change by reducing the private cost of research and development from the supply side (Nemet (2009)). Typical technology-push policies are non-market based instruments such as public R&D funding or tax reductions for R&D investments.

fill this gap in the literature using standard macroeconomic tools such as Structural Vector Autoregressive (SVAR) models to test the combined effect of (1) exposure and vulnerability to climate change and, specifically, environmental degradation, (2) environmental policies and (3) environment-related technologies on the macroeconomy. Such a setup differs from the standard literature that applies (dynamic) panel methods to examine how weather and climate-related events influence economic outcomes in a single equation framework (e.g. Dell et al. (2014)). By using a multivariate setup, we also aim at providing some additional evidence that could be relevant for the structural modelling of climate and economics. An increasing number of papers that develop structural models often make use of too restrictive assumptions on the effects of climate change, e.g. modelling it as a supply shock (such as Economides and Xepapadeas (2018) or Keen and Pakko (2009)), or just simplifying on some relevant channels (Niu et al. (2018)). Furthermore, this paper takes a business cycle perspective and focuses on a medium-term gradual impact of climate-related risks instead of considering either the secular effects of climate change based on the temperature increase or the immediate impacts due to natural disasters possibly caused by it.

3 Data and Methodology

In order to cast the analysis into standard macroeconometric tools for business cycle, the (available) data to proxy for both physical and transition risks requires a careful selection. In what follows, therefore, we first illustrate with much detail the climate data set – that covers almost 30 years of annual observations (1990-2019) for 24 OECD countries[2] – and then we describe the econometric approach. To proxy for the macroeconomy we use standard concepts and variables that measure real activity – industrial production, investment, employment, value added, business confidence – or prices – consumer price index (CPI), total, energy and food.

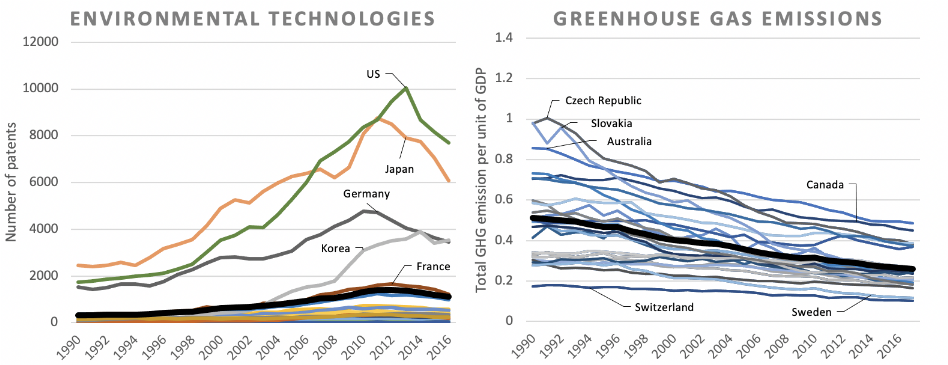
3.1 Measuring physical and transition risks

The database used for the analysis combines several variables coming from different sources. Climate related variables are downloaded from the OECD.stat Environment database.[3] To proxy for climate change and environmental risks, we use two main variables: (1) total Greenhouse gases (GHG) per unit of GDP; and (2) welfare costs of premature deaths due to exposures to climate-related events. To measure environmental policy and technological development, we use two general proxies, namely: (1) the OECD Environmental Policy Stringency index (EPSI); and (2) the number of patents for each country for selected environment-related inventions and technologies.

[2] Australia, Austria, Belgium, Canada, Czech republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Netherlands, Norway, Portugal, Slovakia, Spain, Sweden, Switzerland, United Kingdom, and USA.

[3] See https://www.oecd.org/environment/environment-at-a-glance

Figure 1: Measuring GHG emissions and environmental-related technologies



Sources: OECD; Sample: 1990-2019.

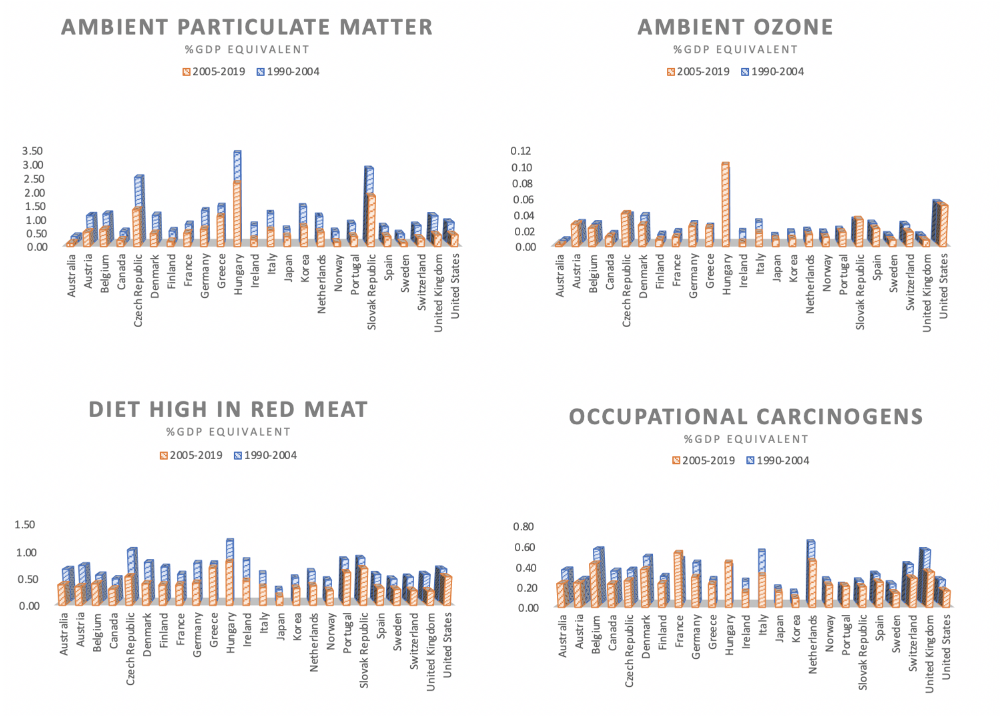
GHG emissions The data on emissions refers to man-made emissions of major greenhouse gases and emissions by gas (the time series is reported in the right panel of Figure 1).[4] We use the intensities (i.e. GHG per unit of GDP) which are calculated on gross direct emissions excluding emissions or removals from land-use, land-use change and forestry (LULUCF). The GDP used to calculate intensities is expressed in USD at 2015 prices and purchasing power parities (PPPs). The main reason to use intensities as opposed to GHG total emissions is that emissions intensities, at least with respect to energy and industrial emissions, are influenced primarily by shifts in energy intensity, economic structure, and fuel mix. It follows that emission intensities are not directly correlated with changes in activity levels (such as Industrial Production or GDP). Even in the event of major GDP changes, changes in intensity levels may be modest. Absolute emission levels, on the other hand, are strongly pro-cyclical and influenced by GDP shifts (Doda (2014) and Herzog et al. (2005)).

Overall, GHG emissions intensities have been reducing for all countries in the sample at an average rate of 1%. The data also show a sort of beta-convergence across countries, namely, countries with a higher initial level of GHG are also those with a higher emission reduction rate (not shown). However this convergence process is far from over and countries generally maintain their initial position with respect to the average.

Environmental degradation The second proxy for physical risks refers to the cost of premature deaths from exposure to environment-related risks and we use it as a damage function to measure environmental degradation (i.e. depletion of resources such as quality of air, water

[4]It includes total emissions of CO_2 (emissions from energy use and industrial processes, e.g. cement production), CH_4 (methane emissions from solid waste, livestock, mining of hard coal and lignite, rice paddies, agriculture and leaks from natural gas pipelines), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6) and nitrogen trifluoride (NF_3). Data exclude indirect CO_2.

Figure 2: Welfare cost of premature deaths from exposure to environmental-related risks



Sources: OECD; Sample: 1990-2019.

and soil; the destruction of habitat and ecosystems; the extinction of wildlife; and pollution).[5] The measure is build by OECD using epidemiological data taken from Global Burden of Disease Study 2019 (GBD (2019)) while the welfare costs are calculated using a methodology adapted from Roy and Braathen (2017). The core idea of this indicator, conceptually very close to a damage function, is that environment-related risks, such as air pollution, carry a significant economic costs to society through the premature deaths and disabilities that they cause (OECD (2016)). The cost of premature deaths at the society level is measured through the so-called Value of Statistical Life (VSL). In essence, it represents the individuals' willingness to pay (WTP) to secure a marginal reduction in the risk of premature deaths.

The calculation of the VSL, as described in great detail in Roy and Braathen (2017) can be summarised as follows. Suppose that each individual has an expected utility function, EU, relating the utility of consumption over a period $U(y)$ and the risk of dying in that period r:

$$EU(y,r) = (1-r)U(y) \tag{1}$$

then, the individual's WTP to mantain the same expected utility in the case of a reduction of

[5]Environmental degradation is one of the ten threats officially cautioned by the high-level PaneI on Threats, Challenges and Change of the United Nations.

risk from r to r_1 is the solution to

$$EU(Y - WTP, r_1) = EU(y, r). \tag{2}$$

Thus the VSL is the marginal rate of substitution between the value of consumption and the reduction of risk of dying, such that:

$$VSL = \frac{\delta WTP}{\delta r}. \tag{3}$$

The WTP, which is derived from surveys (OECD (2012)) is eventually multiplied by the total number of premature deaths, becoming a measure of the economic cost of the impact of environment-related risks. In the model we use three measures of costs due in particular to (i) air pollution (ambient particulate matter, ambient ozone), (ii) environment-related occupational risks (occupational carcinogens), and (iii) environment-related behavioural risks (diet high in processed meat). Figure 2 illustrates the welfare cost of premature deaths from exposure to the selected risks (expressed in % of GDP equivalent).[6] The figure reports in blue averages in the first part of our sample (1990-2004) and in orange the averages in the second 15 years (2005-2019). We believe that the welfare costs of deaths related to exposures to environmental risks are a reasonable and tangible measure of the damages caused by physical risks related to climate change. By construction, the variable does not capture the consequences of extreme weather events but is a good proxy for the medium-to-long term effects that gradual climate changes and environmental degradation have on our everyday life. In the empirical analysis we take a simple average over the three welfare costs. This measure shows a decreasing trend not only of the mean – which has been reducing at an approximate rate of 0.8% between 1990 and 2017 across countries – but also of cross-country dispersion – the standard deviation has gone from 0.7 in 1990 to 0.5 in 2017.

It is important to notice here that we choose not to include in the baseline specification a variable that proxies for natural disasters for three main reasons. First, for all the countries in the analysis there is not a sufficient set of information about their nature and costs. This implies that we don't have data to build a long enough macroeconomic series to analyse their dynamic repercussions. Second, the concomitant happening of other events occurring either as triggers or as consequences of the disasters and the higher frequency of disasters in specific areas, would make it difficult to discern among the drivers of the effects on the macroeconomic variable when a disaster occurs. Finally, we adopt a business cycle perspective and do not focus on the immediate economic impact of natural disasters. However, we have performed some robustness check by including also temperature anomalies in the specification without any notable value

[6]The dataset includes the following types of risks: Air pollution; Climate risks; Unsafe water, sanitation and handwashing; Environment-related occupational risks; Environment-related behavioral risks. We selected the risks with the higher cost, but results with all the risks included do not differ in sign and magnitudes.

added, and we use the available data on exposure to natural disasters in Section 5, where we test country heterogeneity in their responses to certain shocks.

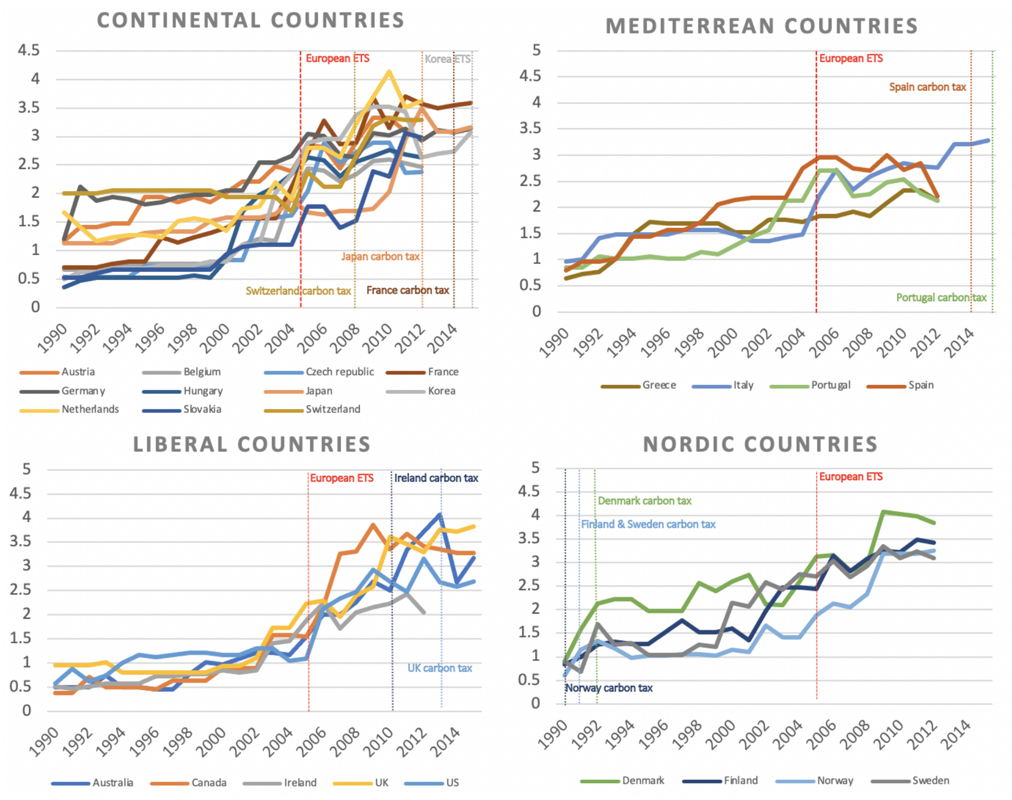
Environmental technology The proxy for technology (see left panel Figure 1) counts the number of patents related to developments in environment related technologies. The statistics are constructed using data extracted from the Worldwide Patent Statistical Database (PATSTAT) of the European Patent Office (EPO) using algorithms developed by the OECD. We use an aggregate category labelled "selected environment-related technologies" which includes all of the environmental domains considered by the OECD. The number of inventions developed by country's inventors are independent of the jurisdictions where patent protection is sought (i.e. all known patent families worldwide are considered). Cross-country comparability is ensured by the use of indicators based on patent family size which are flexible and can be adapted to various applications (see Haščič et al. (2015)). This variable provides therefore a good approximation of the innovation suitable for tracking developments in environment-related technologies for two reasons. Firstly, patents themselves are a direct measure of countries' and firms' innovative performance; secondly, since patents applications are usually filled early in the research process they are also an indicator of the level of R&D activity itself. This variable, on average, shows an initial (almost) exponential number of innovations and a subsequent inversion of the initial trend which has started well after the great recession.

Environmental policy The EPSI is a newly developed OECD composite indicator of environmental policy stringency which records increasingly stringent environmental policies in all countries. It is a country-specific and internationally-comparable measure of the stringency of environmental policy, where stringency is defined as 'the degree to which environmental policies put an explicit or implicit price on polluting or environmentally harmful behaviour'. The EPSI includes therefore the explicit and implicit, policy-induced cost of environmental externalities that polluters have to pay.[7] The index ranges from 0 (not stringent) to 6 (highest degree of stringency) and is based on the degree of stringency of 14 environmental policy instruments (market and non-market based, that is, inclusive of demand-pull and technology push policies), primarily related to climate and air pollution (OECD) (for further details see Botta and Kozluk (2014)). The main limitation of this index is that it only covers countries for the period 1990-2012, with data reaching 2015 only for a limited number of countries.[8]

The index is a good proxy to measure the effects that environmental policies, addressing well-being and sustainability objectives, could introduce for firms and household behaviour. Figure 3 shows the EPSI time series for different groups of countries and the years of adoption of carbon tax or emission trading schemes (ETS). Even though there are differences in timing in

[7]See Figure A.1, in Appendix for more details on the composition of the index
[8]Australia, Canada, France, Germany, Italy, Japan, Korea, Turkey, UK and US

Figure 3: Evolution of Environmental Policy Stringency Index



Sources: OECD; Sample: 1990-2019.

terms of adoption of carbon tax, the EPSI has registered increasingly stringent environmental policies in all countries. However, after an initial exponential increase at an average rate of 3.1% between 1990 and 2006, the average growth rate of the EPSI has only been 0.89% between 2007 and 2015. There are also some notable differences in the levels which seem to persist: the standard deviation across countries has been stable around 0.5 with notable spikes around and in the aftermath of the financial crisis. Interestingly enough, notwithstanding the lack of a sort of σ-convergence, a regression of the average cross-country growth rate on the initial stringency level gives a beta coefficient of -1.6, implying not only that all countries have been increasingly stringent in their environmental policies but also that they are converging fast to a steady state. Given that countries tend to opt for similar types of main policy instruments, it remains to be seen to which steady state they are converging and whether that steady state is enough to implement a sustainable change. Overall, the unconditional correlation (not shown) between environmental policies and environment-related technologies confirms that there are some relevant countries' differences. It appears that, not only the technological development is driven by just a few countries (US, Japan, Korea, Germany and France) with more or less low levels of policy (except for Germany), but there are several countries (such as Denmark, Sweden, Switzerland) that have high levels of policy and a limited amount of environment-related technologies.

3.2 The econometric model

We investigate the dynamic relationship between measurements of physical and transition risks, and macroeconomic variables in a SVAR model estimated with panel data. For each country, the model can be written as:

$$A_{i0}Y_{it} = \mu_i + A_i\left(L\right)Y_{it-1} + \nu_{it} \tag{4}$$

where the As are coefficient matrices, μ_i is a vector of country-specific constants, and ν_{ti} is a zero-mean vector of orthogonal structural shocks with diagonal variance-covariance matrix D_i. The vector Y_{it} consists of two sets of variables, the climate-related variables and the macroeconomic ones. Our analysis is based on two main specifications, depending on the size and composition of the macroeconomic block. The climate block, instead, is unchanged throughout the analysis and consists of four variables as illustrated in the previous section, namely (i) the Environmental Policy Stringency index, (ii) the Environment-related Technologies, (iii) the Greenhouse Gas emissions; and (iv) the Welfare cost of premature deaths due to exposure to environmental risks (damage function). The macroeconomic set of variables of the baseline exercise contains (i) industrial production (or GDP) as a measure of activity; (ii) energy prices; (iii) food prices; and (iv) core prices (i.e. total prices excluding energy and food). The macroeconomic block will be subsequently enlarged in Section 5 when we discuss the role that some channels play in the transmission of climate-related shocks, the heterogeneous response across groups of countries that differ in several dimensions, and the differential effects across the various sectors of the economy.

In the empirical analysis, all variables are in log levels multiplied by 100. The estimation period spans from 1990 to 2019. However, the panel is unbalanced and for some countries data are not always available over the full sample.[9]

We make the following general assumptions for the reduced-form estimation of the model:

1. The data generating process features dynamic and static homogeneity, namely that $A_i\left(L\right) = A\left(L\right)$, and that $D_i = I$ and $A_{i0} = A_0$. The latter implies that the variance-covariance matrix of the reduced form shocks, $A_{i0}^{-1}A_{i0}^{-1\prime} = \Sigma_i$, is also common across countries ($\Sigma_i = \Sigma$).

2. The reduced-form shocks (ϵ_{it}) are serially and sectionally uncorrelated.

3. A linear deterministic trend is used in the estimation to account for the non-stationarity of most variables.

[9] For instance for the stringency index the most recent update of the variable covers until 2015 for some countries with many of them having data only until 2012.

Under these assumptions, pooled estimation with fixed effects – potentially capturing idiosyncratic but constant heterogeneity across variables and countries – is the standard approach to estimate the parameters of the model (Canova and Ciccarelli (2013)).

Let's discuss the assumptions in turn. The homogeneity assumption is probably the strongest one because if the slope parameters differ across countries, a (frequentist) fixed effect-type estimator is biased and inconsistent (Pesaran and Smith (1995)) even when N (the cross section dimension) and T (the time series dimension) are large enough, which is anyway not the case in our analysis. We therefore only use this assumption as a first approximation because we are constrained by the available data which covers too short of a time span to fully account for country heterogeneity (even for a mean group estimation). This assumption will however be partially relaxed in Section 5 when we discuss the heterogeneous responses of different groups of countries to climate-related shocks. In that case, we split the countries in various groups according to country-specific characteristics (such as their level of income, their adoption and use of a carbon tax, or their degree of exposure to natural disasters or other risks) and pool the data for estimation separately by groups.

The serial and sectional uncorrelation assumptions are standard when estimating a panel of dynamic simultaneous equation models (see e.g Rebucci (2010)). However, while the serial uncorrelation is a standard practice in VAR models, the sectional uncorrelation can be stronger than usually discussed with panel data, especially in a macroeconomic setup where international spillovers are the norm rather than the exception. In one of the robustness check we will modify the main VAR specifications to include a measure of the country interdependencies similarly to the Global VAR approach (e.g. Chudik and Pesaran (2016)), that is by adding in a country VAR the cross country average of national GDP growth rates (calculated over the other countries).

Finally, the deterministic trend is an empirically convenient way to account for non-stationary data (based on the assumption that the data is indeed trend-stationary), to partially compensate for the low lag order of the VAR, and to condition the estimation on initial values of the endogenous variables which are in levels. A sum-of-coefficient prior will also be used to complement this assumption.

3.2.1 Reduced-form estimation

The reduced-form of model (4) is

$$Y_{it_i} = C_i + B\left(L\right) Y_{it_i-1} + \epsilon_{it_i} \tag{5}$$

where $C_i = A_0^{-1}\mu_i$, $B\left(L\right) = A_0^{-1}A\left(L\right)$, and $\epsilon_{it_i} = A_0^{-1}\nu_{it_i}$. We estimate this model using Bayesian techniques, which require specifying a prior information for the unknown, in terms of a functional form for the distribution of the error term and for the parameters.

We re-write the model in matrix format stacking first by t for each country and then by i

as:

$$\boldsymbol{Y} = \boldsymbol{X}\boldsymbol{B} + \boldsymbol{E} \tag{6}$$

where $\boldsymbol{Y}$ is a matrix of $NT \times m$, $NT = \sum_{i=1}^{N} T_i$, m is the number of variables in the VAR for each country, $\boldsymbol{X}$ is the re-arranged matrix of lagged $\boldsymbol{Y}$ and of dummy variables for the country "fixed-effects" and $\boldsymbol{B}$ is the matrix of the coefficients which contains the common $B(L)\,s$ and the loadings of the country specific constants.

We assume that the errors are normally distributed and we use a conjugate Normal-Inverse Wishart prior distribution for the parameters, such that:

$$p(\boldsymbol{B}, \Sigma) = p(\boldsymbol{B} \mid \Sigma) p(\Sigma) \tag{7}$$

with

$$p(\Sigma) = iW(S, \nu) \tag{8}$$

and

$$p(\boldsymbol{B} \mid \Sigma) = N(\boldsymbol{B}_0, \Sigma \otimes \Omega_0) \tag{9}$$

Under this prior, the posterior distribution has the same functional form and is easy to simulate from. To elicit the prior hyperparameters we use a standard Minnesota prior for the prior hyperparamters $\boldsymbol{B}_0$ and $\bar{\Omega}$, with the mean for the own lag equal to 1, the general tightness (λ) equal to 1 and the tightness for the constant is diffuse. As for the covariance matrix of the residuals it is assumed to be diagonal and its elements are estimated from univariate AR(p) model. Finally, we use a sum-of-coefficient prior with shrinkage parameter $\tau = 10 * \lambda$. We implement the priors adding dummy observations. The posterior distribution is simulated 10000 times and the VAR is estimated with one lag.

3.2.2 Empirical strategy

Let us recall that the purpose of our paper is to analyse to what extent shocks to climate-related variables have meaningful effects on the macroeconomy over a business cycle horizon.[10]

Impulse response functions to shocks to climate variables are obtained using a block triangular (Choleski) factorization of the variance-covariance matrix of the reduced form errors, with the climate block ordered before the macro block. This assumption – in line with similar empirical studies, such as Mumtaz and Alessandri (2021) and Kim et al. (2021) – implies assuming that the shocks hitting the macroeconomic variables will not impact the climate variables contemporaneously, and therefore the possible consequences on climate or climate policy of macro shocks can

[10]We are less interested in the effects of the typical macroeconomic shocks (say demand and supply) on climate variables, although their (relatively more standard) identification can allow us both to understand if physical and transition shocks can be classified as demand or supply, and to help us gauge the size and persistence of the effects of climate related shocks in a comparative manner (see robustness Subsection 4.1 and Appendix, Figure A.10).

be appreciated only after one year. On the other hand, shocks hitting climate-related variables are more likely to have effect on the macroeconomy during the same year. This assumption may seem somewhat unconventional for, in the loop between the climate and the economic systems, emissions are usually a consequence of the economic activity while the economy gets hit by the damage that generates after emissions affect the climate system. However, we are not using total emissions but emission intensities which, because their main drivers are energy intensity and the fuel mix, are not directly correlated with changes in economic activity (Herzog et al. (2005)).

In line with the same argument, even with low frequency data, it makes sense to assume that environmental policy-making or the patenting of a new green technology in a given year are likely to affect the economy in the same year, whereas macroeconomic shocks take relatively longer to reach the climate block. Environmental policy is the most exogenous variable in the system, being the results of public interventions due to political shifts and social and environmental pressures. Furthermore, while absolute technological development can respond quickly to economic activity (Dechezleprêtre et al. (2021)), specific environmental technologies aimed to mitigate, and adapt to, climate change, have very high costs, represent a small portion of the market, and are currently mostly driven by technology push policies and R&D expenditure or incentives. For this reason, even in times of economic crisis, it is reasonable to think that the effect on environmental specific patenting activity will unfold relatively slowly.

In the climate block we shock each of the four variables. We will therefore speak of two transition risk shocks – policy and technology – and two physical risk shocks – GHG emissions' intensities and (welfare cost of) environmental degradation. The variable ordering in the VAR is such that a policy shock increases the stringency index at time 0 while a technology shock increases the number of climate-friendly innovations without affecting at time 0 the policy index, which can react to it only after one year. Both shocks can affect contemporaneously the emissions' intensities and the welfare cost of premature deaths but do not react contemporaneously to their movements.

In the baseline specification we leave the macroeconomic shocks unidentified. In robustness checks we also experiment by identifying standard demand, supply and monetary policy shocks with the typical assumptions that the former have positive signs on both output, prices and interest rates, whereas the second is a negative technological shock or a type of cost-push shock that reduces output and increases prices and interest rates. The monetary policy shock instead is identified with the assumption of a negative effect on both output and prices (see Appendix, Table (6) for more details on the sign identification).

Finally, it is important to notice that the results we report in what follows based on the Choleski orthogonalisation are qualitatively and quantitatively similar to those obtained using Generalised Impulse Response functions, which do not require orthogonalization of shocks and are invariant to the ordering of the variables in the VAR (Pesaran and Shin (1998)).[11]

3.3 Physical risks policy scenarios

Following a similar approach as in Mountford and Uhlig (2009), we can use the basic shocks defined in the previous section to analyze the effects of the physical risks shocks under selected policy scenarios. More specifically, we extend the assumption implied by the Choleski identification, that the two transition risk variables – environmental policy and technology – do not react to the physical risk shocks only contemporaneously. In a counterfactual scenario-type of experiment we also leave the subsequent impulse response functions of stringency and technology muted for the whole forecast horizon, so that for the shocks that increase emissions or the damage function the endogenous response of the policy or technology is silent for a long period of time. Furthermore, for the shock to welfare cost of environmental degradation (our damage function) we extend the scenario above leaving unresponsive also the response of the GHG emissions, so that we can interpret this final shock as one that increases only the welfare costs independently of an increase in emissions. This latter works as a worsening of the damage from other sources than GHG emissions. Beyond a pure triangular identification, therefore, this experiment implies defining a climate shock by assuming an increase in GHG (or the damage) and, at the same time, by generating a sequence of shocks to the stringency and technology (and GHG) variables that leave their IRFs unresponsive.[12] For the two "physical risk shocks" we will only report results based on these scenarios.

4 Baseline results

In this section we report a first set of results based on the baseline ("small") VAR with the four climate-related variables and four macroeconomic variables, namely the industrial production and the price levels (energy, food, and total excluding energy and food).

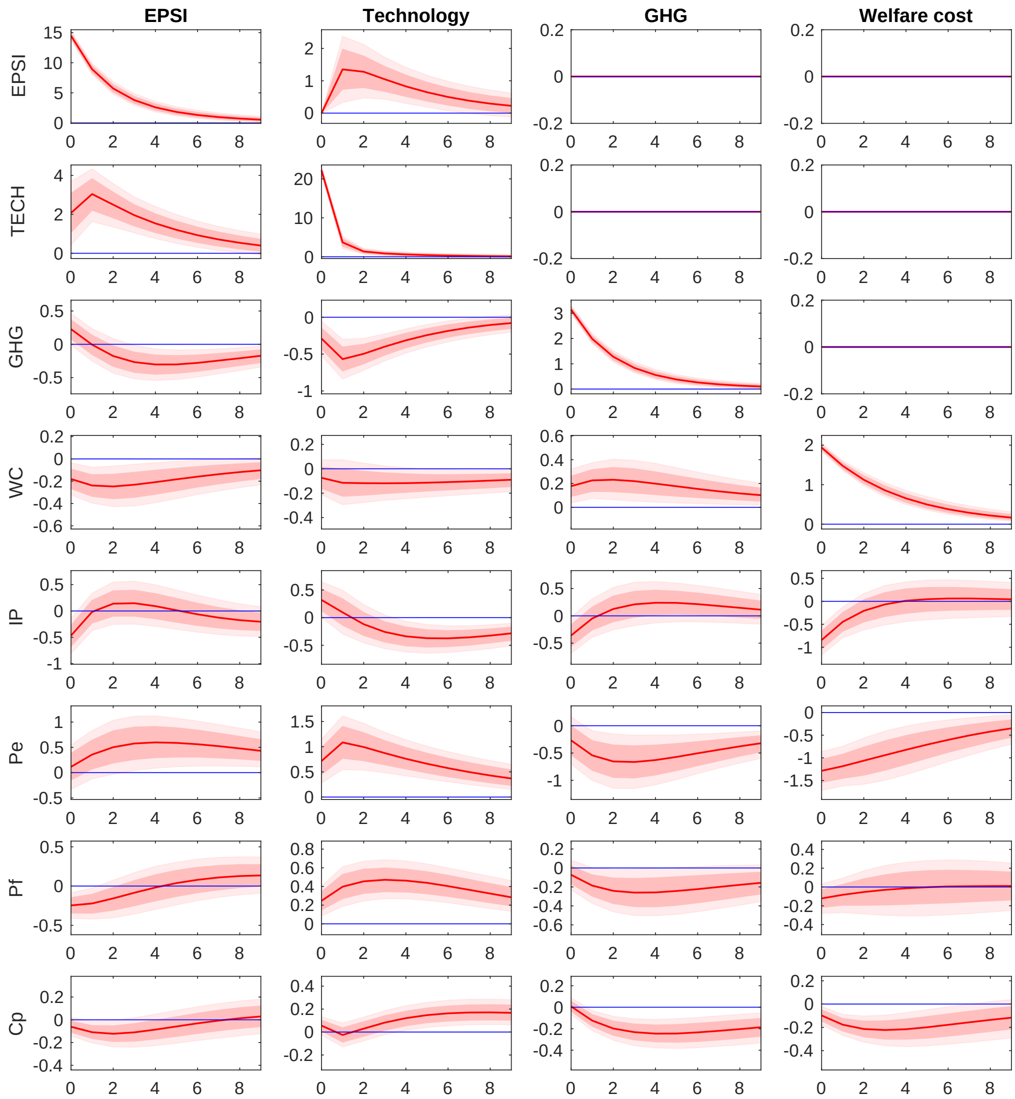
We report impulse response functions – to check how much macro variables move when physical or transition risks rise by one-standard deviation – and the forecast error variance decomposition – to check the relative importance of the climate shocks for the macro variables. Results are shown only for the four climate shocks. Because the variables are transformed in log multiplied by 100, the unit scale of the IRFs is directly expressed in percentages.

Baseline results are reported in Figure 4 where in each column we plot the responses of all variables to one-standard-deviation increases in the innovation of the four climate variables heading the columns, namely environmental policy stringency index, environment-related technology, GHG emissions and welfare costs of premature deaths. The red line represents the median re-

[11] See Section 4.1 and Figure A.8 in Appendix.

[12] The technical details to engineer these scenarios in our framework are similar to what explained e.g. in Wong (2015).

Figure 4: Impulse response functions of shocks to transition risks and physical risks



Sources: Authors' calculation; Sample: 1990-2019.

sponses and the shaded areas are the 68 percent (dark) and 95 percent (light) Bayesian credible sets.

Four initial considerations are in order. The first striking result from these impulse responses is that climate-related shocks can have a significant impact on macroeconomic variables over an horizon comprised between 2 and 8 years, i.e. the "typical" range for a business cycle periodicity. Moreover, the impact is quite strong on energy prices and can translate into significant changes in variation in business and consumers sentiment or investments. In turn, this could affect overall spending in the macroeconomy and these shocks could eventually impact the business cycle fluctuations becoming of first order importance also for central banks.

Table 1: Variance decomposition (unit %)

Variance decomposition		EPSI	TECH	GHG	WC	IP	Pe	Pf	Cp
$EPSI_t$	1 y	100.00	0.87	0.52	0.84	1.10	0.11	1.27	0.34
	5 y	91.30	4.41	1.37	2.50	0.87	1.30	0.92	1.09
	10 y	85.21	4.65	2.30	2.89	1.05	2.38	1.17	0.94
$TECH_t$	1 y	0.00	99.13	0.84	0.18	0.52	1.44	1.26	0.28
	5 y	1.41	82.98	4.25	0.67	0.87	4.57	4.53	0.66
	10 y	1.55	77.40	4.09	1.02	1.63	5.02	5.45	1.86
GHG_t	1 y	0.00	0.00	98.46	0.82	0.65	0.22	0.15	0.08
	5 y	0.00	0.00	85.59	2.50	0.79	2.00	1.26	3.54
	10 y	0.00	0.00	77.29	3.09	0.96	2.85	1.64	4.77
WC_t	1 y	0.00	0.00	0.00	97.81	3.58	4.68	0.31	0.82
	5 y	0.00	0.00	0.00	90.28	2.15	6.95	0.39	3.83
	10 y	0.00	0.00	0.00	82.42	2.11	7.51	0.53	3.65

In order to further substantiate this claim, we quantified the effects of these shocks by using a forecast error variance decomposition (FEVD) and a spectral variance decomposition (SVD).[13] Overall, the SVD allows us to disentangle, for each macroeconomic variable, the contributions of each climate shock to the frequencies that are typically associated with business and medium cycle movements. The results are reported in Table 4 that shows indeed the importance of the climate shocks at the business cycle frequency. The FEVD (Table 1) shows that their magnitude is not so sizeable to imply that climate shocks related with either physical or transition risks are to be regarded as strong direct sources of business cycle movements. Nonetheless, the SVD suggests that, even though the effect on the business cycle is small, the importance of the climate shocks becomes more substantial in the medium cycle (10 to 30 years), in line with the idea that climate change economics' implications are bound to become more and more significant in the long run if no mitigation and adaptation action is taken.[14] We will analyse in more detail the transmission mechanism in the next section.

Second, climate change – as identified with shocks to either emissions or the welfare cost of premature deaths due to environmental degradation (our damage function) in absence of policy or technology – have a negative and significant impact on both output and prices. While the effect on production is fast – with a negative sign at impact – and "short-lived", the effects on prices typically pick between 2 and 5 years (with the exception of the response of energy prices after a shock to the damage variable) and are much more persistent.

Third, a shock that increases the technological adaptation to fight climate change is rein-

[13] The spectral variance decomposition, and more in detail the contribution of each shock at any given frequency, is calculated following the procedure described in Rossi and Zubairy (2011).

[14] Figure A.2 in the Appendix, plots the fraction of spectral density of the four main macro variables due to each climate shock at different cycles.

forced by a positive response of the policy index, and reduces both the level of emissions and the economic damage over the business cycle. This combination of results from the climate system has a depressing effect on output between 2 and 10 years (after an initial increase) and a positive effect on all price levels with somewhat different dynamics: The price of energy increases faster and more forcefully with a pick between one and two years; food prices pick after three years and react in a more persistent manner; core prices do not react much in the first two years and become significant and persistent in the medium-to long run.

Finally, the effects of a shock to climate policy as measured by the stringency index have the expected sign on climate variables. In particular, an increase in the price that firms face when polluting is not only followed by an increase in technological investments but has also a clear mitigation effect as represented by a reductions in GHG emissions (after a small initial increase) and in the damage costs. Regarding the effects on the macroeconomic variables, an initial negative effect on industrial production is followed by a positive response over the medium term, and energy prices increase as expected in a sustained manner while food and core prices decrease.

These first results can be interpreted through the lens of the discussion on the channels we have entertained in Section 2. First of all, in our simple set up we do not have extreme weather events or natural disaster associated with climate changes. In fact, the proxies that we use for physical risks are more associated with medium-to-long term effects of global warming or with the exposure and vulnerability of society and natural systems to climate events (in short, environmental degradation). Though different in timing and immediate severity, both risks are dynamically evolving over time and interacting with each other in a complex and non-linear fashion, a feature that our linear model of course cannot capture. But the sign and persistence of the responses we obtain are quite telling of the kind of shocks that they subsume. It has been fairly common to assume that physical risks associated to climate changes act as (negative) supply-side shocks or as a combination of both negative supply and demand shocks through a number of different channels. Therefore the effect of these shocks on production or output is certainly negative at least in the near term. Our results in Figure 4 are consistent with this simple fact.

By contrast, the overall impact on prices (and inflation) is in principle ambiguous, since it depends on the overall balance of supply and demand shocks, which may differ between individual events. Moreover, that balance may itself differ between sectors, such that the overall impact on the economy in general and on prices in particular may depend on its sectoral make-up. Looking at the responses of prices it seems that the effects on prices are significantly negative and persistent in our sample, and indeed show a marked difference between sectors, with the effects on energy prices being much more pronounced than those on food and core prices. In other words, looking at both production and prices these results would be consistent with a predominance of demand (relative to supply) type of adjustments.

Let's now turn on what the literature identifies as transition risks, namely the risks associated with the introduction of more stringent policies or the sponsorship of more climate-friendly technologies. The macroeconomic impacts from transition risks arise from fundamental shifts in energy and land use which can cause output loss. For these risks it is also reasonable to expect a mix of demand and supply downward adjustments (Batten (2018)), although the downward impact on supply could be more pronounced than the one on demand, leading to increasing prices and depressing production. The upward pressures on prices come from the transition to a low-carbon economy through the pricing of the externalities associated with carbon emissions. These upward pressures could partially be offset by technological changes that improve productivity or to the adjustment of consumers' preferences towards carbon-neutral goods and services. Results reported in Figure 4 are consistent with the view that the combination of shocks reflect downward supply pressures more than demand movements, especially for the technology shock which gives rise to a significant and persistent downward impact on production and significant positive impacts on all prices. The effects of policy stringency instead is more ambiguous and less negative on production than a shock to technology over the business cycle. We will explore further these results and the transmission channels in Section 5.

4.1 Robustness

As a robustness check we explored if and how the baseline results discussed above vary according to: (1) the variable ordering; (2) the change of proxy for real activity, (3) the addition of a measure of cross-country interdependencies, and (4) a possible time variation of the coefficients. Moreover, to have a somewhat more detailed measure of the magnitude of the climate shocks on the macroeconomic variables we compared them to the standard macroeconomic shocks (namely demand, supply, and monetary policy). This is also going to suggest how variables capturing various aspects of climate change can vary over the business cycle and, in turn, what is the "climate change value" of stabilization policies.

To check (1) we compute generalised impulse response functions as in Pesaran and Shin (1998) which allow all variables to react contemporaneously to a shock to one of them regardless of their position in the VAR. As a way of illustration, the appendix (see Figure A.3) reports the response of industrial production to a shock to the environmental degradation, both with a Choleski orthogonalization where industrial production is placed before the welfare costs and with a GIRF. The response looks quite different if we do not allow industrial production to react contemporaneously to a welfare shock (independently of its position in the VAR), which clearly shows the limitations of a given Choleski ordering but also confirms that our particular "identification scheme" (where climate comes before economic activity) is a sensible and robust one.[15]

[15] The full set of results with based on GIRFs is available from the authors upon request.

To check (2) and (3), we modified the baseline VAR specifications to include GDP (in levels or per capita) replacing Industrial Production and a measure of the cross-countries correlations (e.g. Chudik and Pesaran (2016)), that is captured by adding in a country VAR the cross country average of national GDP growth rates (calculated over the other countries). Baseline results are robust with GDP as an alternative measure of output and to taking into account spillover effects (see Appendix, Figure A.8).

To take into account the possibility of changing parameters over time we performed a simple exercise which compared the results of the model estimated over the full sample (1990-2019) with those of the same model estimated over the sample (1990-2008), i.e. before the great recession and the financial crisis. Results (see Appendix, Figure A.9) show that a shock to stringency, even if it has a less powerful effect on technology (that is also reflected in a less strong effect on output and energy prices), does not differ much from the full sample results. A similar result also appears for a shock to technology: the reason could be attributed to the fact that environmental policies and technologies had a faster development in the second half of the sample. The responses to a shock to GHG emissions does not vary in sign but does vary in magnitude, as the negative effect on prices seems to be stronger. However the responses to a one standard deviation increase to the Welfare cost of premature deaths has a positive effect on output. The forecast error variance decomposition (see Table 5) shows, however, that for the first half of the sample (before crisis) the importance of the Welfare Cost shock is relatively lower than for the full sample results. Overall this exercise hints to the fact that the importance and the effects of climate shocks on the macroeconomy might be more intense in recent years, as climate change and environmental degradation have become worse and the efforts to mitigate them have gained momentum.

As a final robustness check of the baseline results we compared them to a more standard identification of macro shocks, namely demand supply and monetary policy. We specified the VAR with the four climate variables (environmental policy, environmental technology, GHG emissions and welfare cost) and three macro variables (industrial production, total prices and long-term interest rates). We identify the standard macroeconomic shocks following the literature with a sign identification strategy (see Section 3.2.2). Identification and results are displayed, respectively, in Table 6 and Figure A.10 in the Appendix. As expected, results confirm that climate shocks, compared to standard supply, demand and monetary policy shocks, are lower in size but still significant in their signs. Interestingly enough, the variation over the business cycle of climate-related variables can be different in size and significance depending on the type of shock hitting the economy. A monetary policy shock, for instance, seems to have a more significant and sizeable effect than a demand or a supply shock not only on the welfare but also on the incentives to introduce new climate policies or innovations which, after a monetary tightening, would considerably and persistently shrink, causing a further and persistent increase in emissions and in the damage costs. This outcome – which gives us a preliminary idea about the "climate change value" of a stabilization policy such as monetary policy – may pose further limits to the margins of manoeuvre of a central bank that is committed to taking the impact of climate change into consideration in the monetary policy framework (see e.g. European Central Bank (2021)). Clearly, such a preliminary evidence deserves further investigation which goes beyond the scope of this paper and is left for future research.

5 A closer look: Transmission channels, sectors, and country

In this section we aim at contextualizing the previous results and extend the baseline analysis in two dimensions: first, we enlarge the set of endogenous variables in the baseline VAR to include variables that proxy for some of the main transmission channels – Business Confidence Index, Investments (governments, households and corporate) and Employment – as well as variables that capture a more granular sectorality – Value Added of energy and agricultural sectors. This extension not only can allow us to test the potency of some of the possible channels through which a shock to a climate-related variable reaches productions and prices (e.g. expectations and investment), but can also account for the possible diverse impact of climate-related shocks on different sectors. Second, we perform the analysis by groups of countries and check if results are sensitive to country-specific characteristics, related to country economic features – such as income – or climate traits – such as their exposure to and risk of natural disasters and adoption and use of a carbon tax.

5.1 Exploring the transmission channels

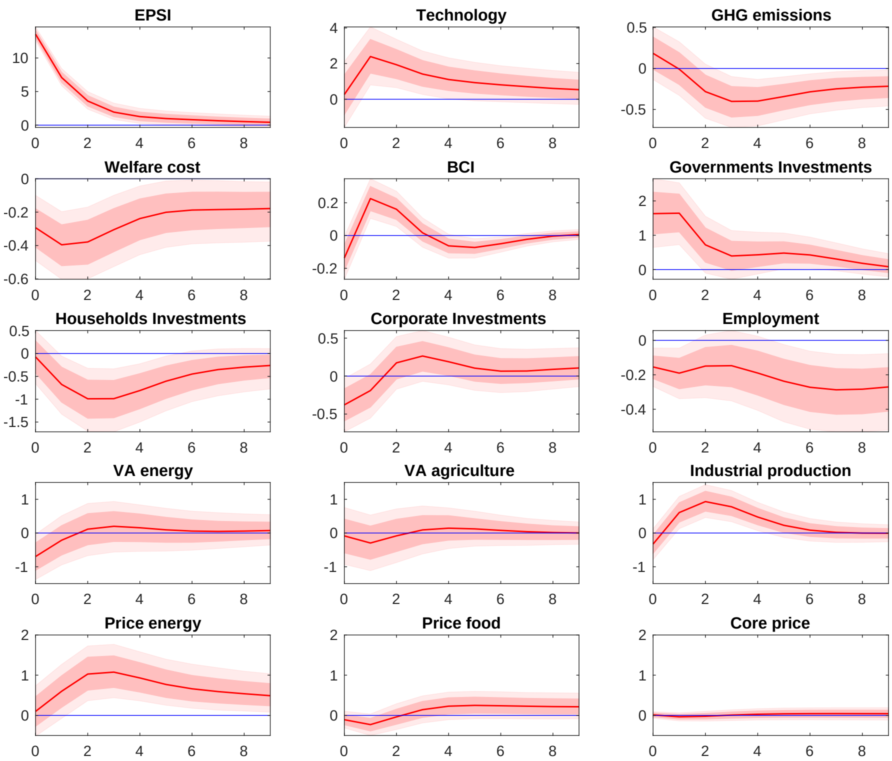
The enlarged VAR contains now 15 variables. All additional variables (BCI, Investments, Employment and Value added) are downloaded from the OEDC.stat database.[16] The IRFs to the four climate shocks are reported in Figures 5 - 8. The results found with the baseline specification are broadly confirmed with the extended VAR. In addition we can now have a better qualification of the transmission mechanism. For instance, Figure (5) reports the responses to a one-standard deviation shock to the environmental policy stringency index. The effects on the climate variables are as before, with an increase of policy-induced technology and a reduction of

[16]The business confidence indicator provides information on future developments, based upon opinion surveys on developments in production, orders and stock of finished goods in the industry sector. Numbers above 100 suggest an increased confidence in near future business performance, and numbers below 100 indicate pessimism towards future performance. To proxy for investments we use the gross fixed capital formation (GFCF). Investment by sector (measured as % of total GFCF) includes household, corporate and general government. For government this typically means investment in R&D, military weapons systems, transport infrastructure and public buildings such as schools and hospitals. Employment rates are defined as a measure of the extent to which available labour resources (people available to work) are being used. They are calculated as the ratio of the employed to the working age population. The value added by activity (volumes, energy and agriculture) reflects the value generated by producing goods and services, and is measured as the value of output minus the value of intermediate consumption. The data, expressed in US$ (2015), are downloaded from the STAN STructural ANalysis Database of the OECD.

both emissions and damage costs. The increase in technology is presumably linked to: first, the mix of demand-pull and technology-push policies comprehended by the EPSI and secondly, as a consequence, the immediate rise of government investment in research and development (R&D). This result is shown by the response of government investments that increase after the shock. However, its response is not persistent and dies out after 2 to 4 years, while private investments, after being initially crowded out, pick up in a consistent manner exactly after 2 years.

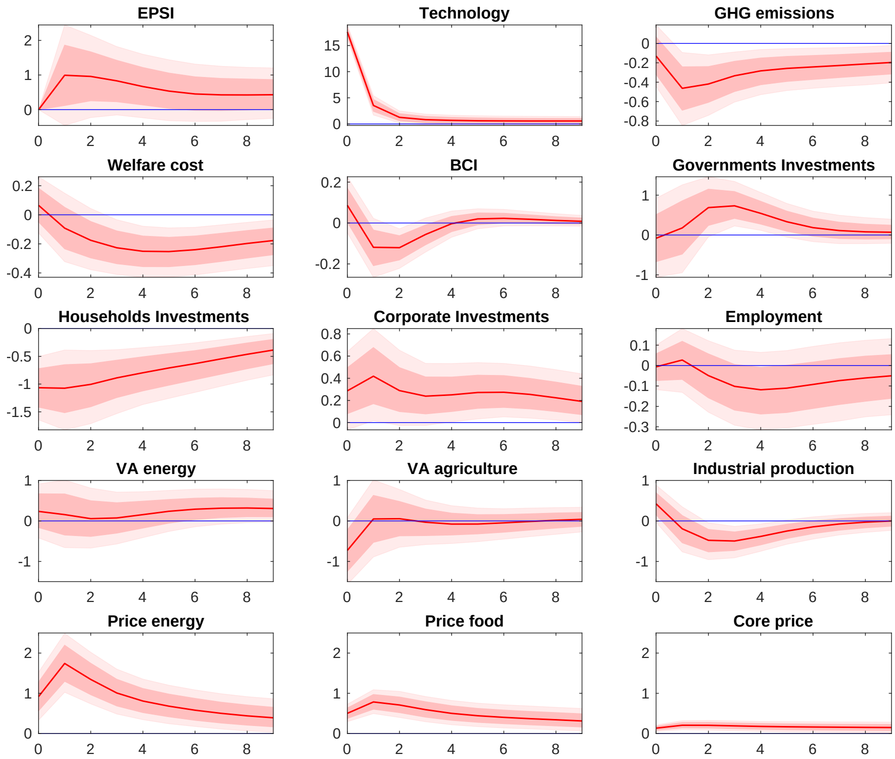
This finding squares consistently with the idea that environmental policies (and policy-induced innovation) create externalities that may require further policy action to provide sufficient incentives for private R&D directed at exploring new technologies as well as for the adoption of greener production methods (Popp (2019)). Therefore, while the goal of public direct investment (or incentives and tax policies) might not be enough to build the clean energy economy of the future, it can certainly create the conditions for the private sector to closing the adaptation gap. This seems to be confirmed by our results. Notice, however, that the tighter climate policy paired with higher government investment in green technologies crowds out entirely households investments, a typical demand-type shock induced by climate policies that promote investment in low-carbon technologies (Batten et al. (2020)).

Figure 5: Impulse response functions of a shock to EPSI



Sources: Authors' calculation; Sample: 1990-2019.

Figure 6: Impulse response functions of a shock to Technology



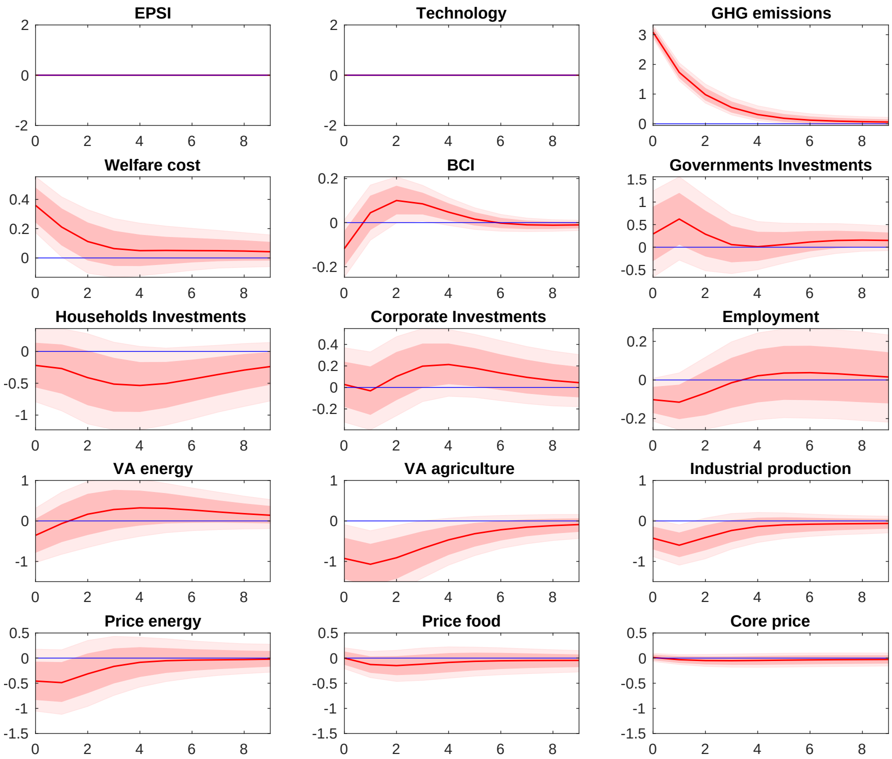
Sources: Authors' calculation; Sample: 1990-2019.

The effects of a policy shock on output and prices also broadly confirms the baseline results with a negative effect on the energy production – which, together with the positive response of the energy prices, gives rise to a typical cost-push type of response – and a significantly positive effect on industrial production after an initial negative sign. Somewhat surprisingly we also observe a negative effect on employment. In other words, results seem to indicate that the net effect between the job creation driven in a number of economic sectors with low emission intensities by a transitions to low-carbon, environmentally sustainable economy can be more than compensated by a significant job destruction in traditional emission-intensive sectors which likely causes a final negative effect on total employment.[17]

Notice, though, that the effects on employment and output as measured by industrial production, seem to point to a significant increase in overall productivity, a result that is consistent with the work of Brunel (2019) and Franco and Marin (2015).

[17] As a robustness check we analysed the effect of the policy shock on employment by sector. Results (not shown but available upon request) suggest that a shock to EPSI has a negative effect on employment in the service sector, while having a positive effect in the agriculture and industry sectors. Notice, though, that for the OECD countries of the analysis, the service sector is the one with the largest share of total employment. This would be enough to rationalise the negative effect we observe on the aggregate employment, most of which is driven by the service sector.

Figure 7: Impulse response functions of a shock to GHG emissions



Sources: Authors' calculation; Sample: 1990-2019.

To better understand the strength of some of these transmission channels, Panel (a) of Figure (9) describes the scenario where a shock to environmental policies is not followed by initial government investments and the resulting technological adaptation that can guarantee a transition to an effective low-carbon economy. We engineer this experiment by creating a sequence of shocks to technology and government investments that shut down their responses. As a result we find that the reduction of emissions and welfare costs is less intense, there is no 'crowding-out' effect on business investments, and there is a more muted reduction of employment as well as a lower inflationary pressure coming from energy prices.

While overall for environmental policy (and policy-induced innovation) we don't find substantial disruptive effects on the real economy with a combination of demand-side shocks resulting in investment crowding-out and negative supply-side shock in the energy sector, results are more clear-cut for a shock to environmental technology. This shock is interpreted as an exogenous increase in environmental technology that is not induced (or supported) by environmental policies or public investments.[18] Figure (6) shows that a sudden increase in the number of patents

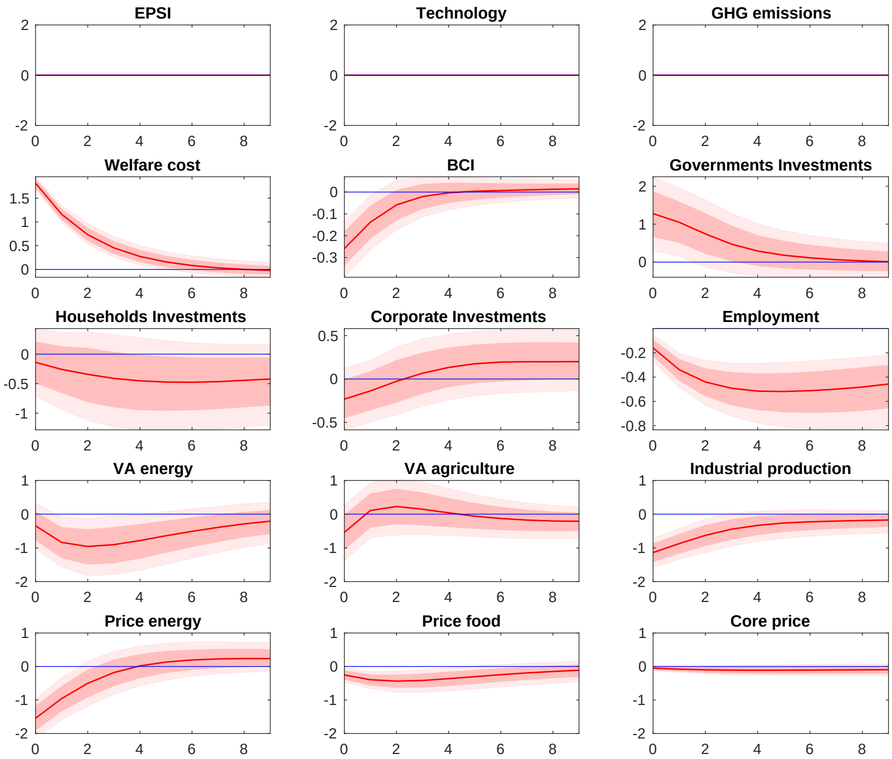
[18] In a counterfactual exercise we created the shock to environment-related technologies such that they would have no effect on the IRFs of EPSI. The effect on the macro block does not change drastically, suggesting that a the effect of technology on output and prices does not pass through the increase of policy or government investments.

for climate related technologies, while being very effective in curbing emissions and the damage costs, has a depressing effect on business expectations, somewhat on employment, and definitely on industrial production. At the same time, all prices are positively and significantly affected which suggest that the technological transition to low-carbon emission come at the cost of diverting resources from productive activities to mitigation investments. With a shock to technology, only households' investments are now crowded out, whereas new investment opportunities are taken up immediately by the private sector and subsequently also by the government (perhaps as a consequence of the endogenous increase in policy mitigation). The negative effect on business confidence (after an initial and short-lived positive response) is most likely related to the possible uncertainty about the rate of innovation and the adoption of clean energy technologies that follows the increase of the newly patented inventions (Batten et al. (2020), Batten (2018)). Overall these results provide preliminary evidence that a shock to policy (and policy-induced innovation), even though acts as a supply type of shock on the energy sector (increasing prices and reducing output), does mitigate the effect of climate change and has the potential to boost the economic activity. On the other end, however, the results of a shock to technology suggest that, if innovation is not supported from the supply- and demand-side by the right policy mix, then the weight of the transition to a low-carbon economy would be carried by businesses and private investments, resulting in market failures that have the potential to slow down the economy.

We now turn to the results of a one-standard-deviation shock to our climate-change variables (Figure 7 and 8). As discussed in the identification section, we are interested in understanding the effect of a somewhat "exogenous" shock to climate. As for the baseline model, we identify such a shock as an increase of GHG emissions or of the damage function (welfare cost of premature deaths due to the exposure to environment-related risks) that does not cause a response to policy or technology over the horizon. Put simply, we are identifying the climate shocks in the scenario in which climate condition and its physical risks worsen in an environment that is not protected by policy or technological efforts. Both types of shocks (pure emissions and increase in the damage due other causes than pure emissions) have very similar consequences on the economy. They both imply quite a negative effect on output and prices, including at impact, that can be explained by the negative effect on expectations, private investments and employment.

Notice that a sudden increase of GHG emissions in a given year has a positive effect at impact on the damage function as defined by the welfare costs of premature deaths. This "immediate" reaction of social costs, which has a negative effect on expectations at impact and therefore compresses the economy, is not surprising on a long time span but is perfectly plausible also in the short run. Among other things, GHG emissions contribute strongly not only to global warming through the accumulation of CO2 particles in the atmosphere, but also to local air pollution levels, which in turns have a direct effect on peoples' health, implying a non

Figure 8: Impulse response functions of a shock to Welfare cost of premature deaths



Sources: Authors' calculation; Sample: 1990-2019.

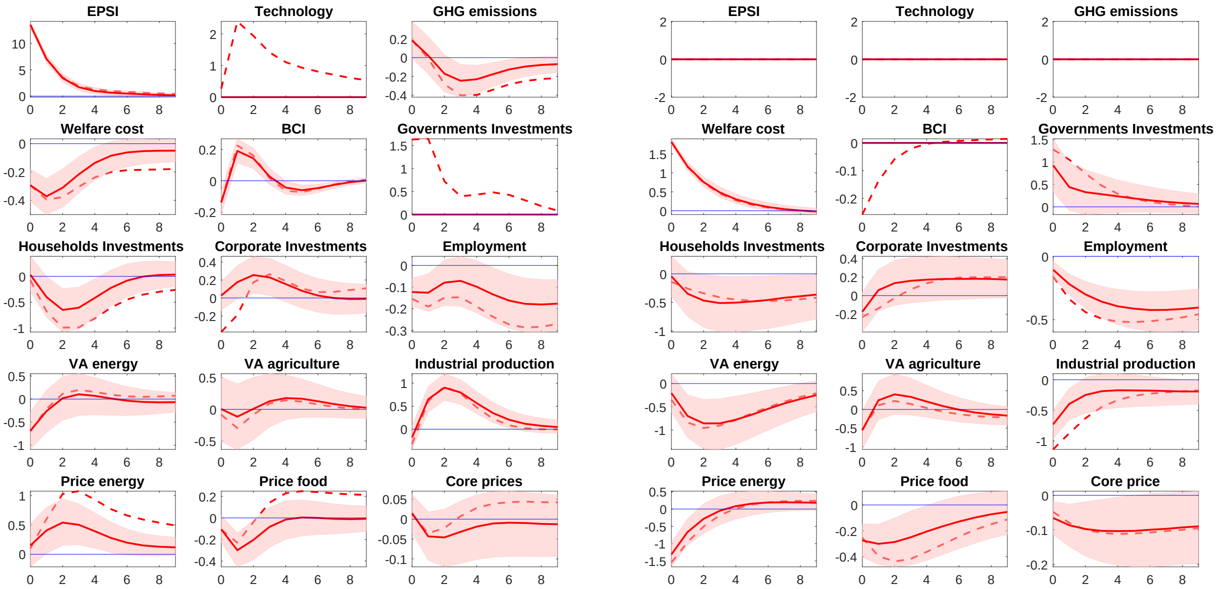
negligible economic cost (OECD (2016)). Hence, the variable welfare costs, being by construction a measure of the economic harm in a given year due to environmental degradation (including air pollution) reacts contemporaneously to a positive shock to GHG emissions. Moreover, the fact that this shock has a negative effect on production and prices ensures that it cannot be confused with a technology shock that causes emissions to increase.

To gauge how strong the expectation channel can be, panel (b) of Figure 9 shows the responses to a shock to the welfare cost of premature deaths built such that it does not have a (negative) effect on business confidence, i.e. shutting down the response of the variable BCI. Unsurprisingly, the effect of shutting down this channel confirms the idea that if firms become more pessimistic about the future due to the impact of climate change they would reduce investments (which would be taken up by government), leading to a more disruptive effect onto output and employment.

5.2 Country-specific characteristics

So far we have documented that, in general, shocks to transition risks put an upward pressure on prices while shocks to physical risks put a downward pressure on prices and output. The

Figure 9: Counterfactual exercises, the red dashed line represents baseline IRFs



(a) Scenario 1

(b) Scenario 2

Sources: Authors' calculation; Sample: 1990-2019.

aim of this section is to examine whether: (1) countries with different characteristics in terms of adaptation, mitigation, vulnerability, and exposure to both transition and physical risks are on average affected differently from a specific climate shock; and (2) there is a relationship between the magnitude of the effects found in the previous sections and some country specific characteristics. With the results in this section we aim to provide stylized facts relevant for policy makers that could potentially improve our understanding of climate shocks transmission to the global economy.

The enlarged VAR model is estimated by groups of countries homogeneously chosen based on a priori common specific features. The composition of the groups depends on a selection of country characteristics over the entire sample 1990-2019 related to climate, institutional, and geographical key features. Table 2 illustrates the different groups. The model is estimated by pooling the data for each selected subset of countries and the responses are normalized such that each IRF is divided by the standard deviation of the variable that we shock, for the sake of comparability across groups.

5.2.1 Carbon Pricing

Carbon taxes are widely considered as a potential cost-effective approach to reducing GHG emissions and an economically efficient policy instrument for de-carbonizing the energy supply and limit global warming. Its limited adoption (see Table 2) is explained by the several concerns over its negative effects on the economy (growth, income distribution, competitiveness) unless an

Table 2: Groups

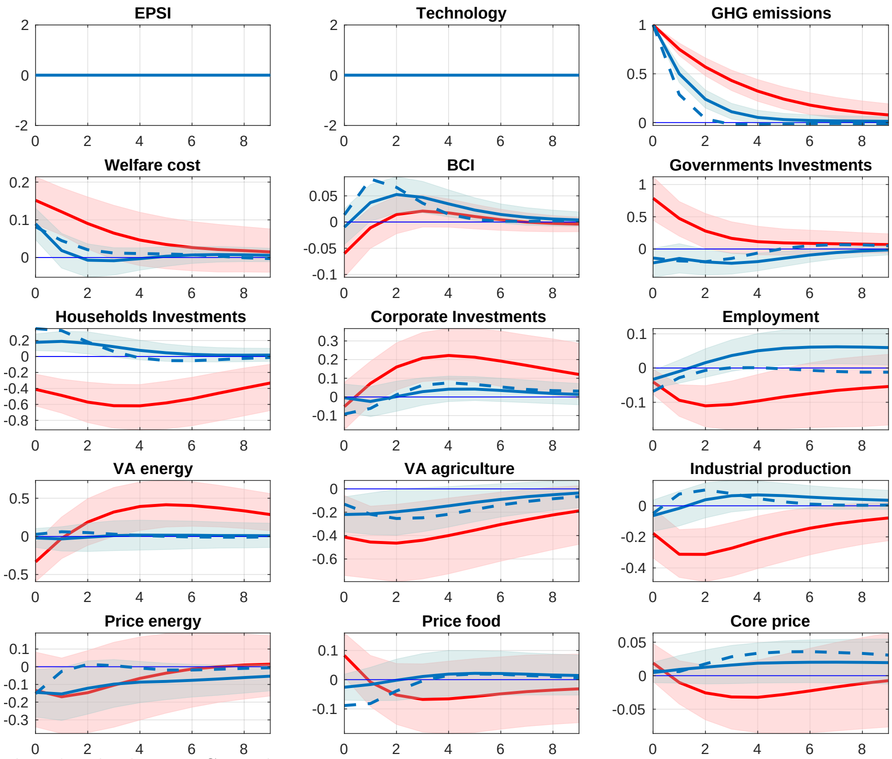
Variable	Groups	Countries
Carbon pricing	no carbon tax implemented or ETS	Australia, Austria, Belgium, Czech Republic, Germany, Greece, Hungary, Republic of Korea, Netherlands, Slovakia, United States
The World Bank - Carbon Pricing Dashboard	carbon tax implemented	Canada (2019), Denmark (1992), Finland (1990), France (2014), Ireland (2010), Japan (2012), Norway (1991), Portugal (2015), Spain (2014), Switzerland (2008), United Kingdom (2013)
	revenue recycling	Denmark, Finland, Ireland, Norway, Sweden, Switzerland
World Risk Index	high: >=3.30	Netherlands, Greece, Hungary, Italy, Ireland, Portugal, Spain, Japan, United Kingdom, Slovakia, United States, Australia
UNU-EHS, IFHV Ruhr-University Bochum	low: $<$ 3.30	Austria, Czech Republic, Denmark, Belgium, Germany, Norway, France, Sweden, Switzerland, Finland, Korea, Canada
Natural disasters, % population affected	high	Australia, Czech Republic, France, Greece, Hungary, Italy, Japan, Korea, Netherlands, Portugal, Slovakia, Spain, United Kingdom, United States
EM-DAT database	low	Sweden, Denmark, Finland, Belgium, Switzerland, Ireland, Norway, Germany, Canada, Austria
Gross National Income, US dollars/capita, 2019	high: $>$ 57K	Norway, Switzerland, Ireland, United States, Denmark, Netherlands, Austria, Germany
	medium	Sweden, Belgium, Australia, Finland, Canada, France, United Kingdom
OECD.stat	low: $<$ 47K	Italy, Japan, Korea, Spain, Czech Republic, Portugal, Slovakia, Greece, Hungary
Political Economy	nordic	Finland, Sweden, Denmark, Norway
	continental	Austria, Belgium, Germany, Czech Republic, France, Netherlands, Slovakia, Switzerland, Hungary, Korea, Japan
	mediterrean	Spain, Portugal, Greece, Italy
	liberal	United States, United Kingdom, Canada, Australia, Ireland

efficient revenue recycling is adopted (Braennlund and Gren (1999)). As argued in Section 3 and illustrated in Figure 3, the 24 countries in the analysis had a different evolution of climate policies during the 30 years of our sample, with some countries preferring technological innovation to putting a tax on carbon emissions. The questions we ask, therefore, are: how does the adoption of a carbon tax change the macroeconomic effects of climate-related shocks? and, what if revenues from carbon taxation are earmarked for spending that benefits citizens?

Figure 10 shows the IRFs to a climate shock that increases emissions computed by running the extended VAR for three sets of of countries: (i) countries that did not adopt a carbon tax in the time span of our analysis (red line); (ii) countries that implemented a carbon tax (blue line); and (iii) countries that adopt a recycling of tax revenues or appropriate compensation measures (blue dotted line).

Accounting for country heterogeneity given by the application and use of a carbon tax qualifies substantially the baseline results along four clear dimensions. First, after the same initial shock, the response of GHG emissions is much lower and less persistent in countries that have a carbon tax and (even more) in countries that recycle its revenue. This implies a significantly lower damage cost in terms of welfare loss. Second, countries with a carbon

Figure 10: Impulse response functions of a shock to GHG emissions



Sources: Authors' calculation; Sample: 1990-2019.
Note: The red line indicates countries that didn't adopt a carbon tax; the blue line is for countries with a carbon tax implemented (1990-2019); the blue dashed line is for countries that do revenue recycling.

tax have a significantly higher confidence in near future business performance than countries without a carbon tax, which are actually pessimistic towards future performance. Third, with a carbon tax there seems to be no need for government to increase its investment in order to counteract the climate shock. As a consequence, the household's investment is not crowded-out any longer. Instead, households investments seem to be encouraged in countries with a carbon tax and even more so in those who recycle the revenues. Fourth, an increase in emissions is much less disruptive for the macroeconomy in countries with a carbon tax: (i) employment does not suffer and if anything it can even increase slightly; (ii) industrial and agricultural productions are also significantly less negative or slightly positive; and (iii) prices do not show a sustained and significant negative impact. Overall, this seems to indicate that if a carbon tax is in place, a climate shock does not correspond any longer to a negative demand-type shock that would otherwise be predominant as discussed in Section 4.

If we look at a shock to policy stringency and split the groups according to the same criterion (carbon tax-no carbon tax) we reach very similar conclusions (see Appendix, Figure A.4). In particular, (i) the response of confidence is highest in countries that do revenue recycling; (ii) public investments do not crowd out households' ones; (iii) we do not observe a persistent net job destruction; and (iv) the price of energy increases much more for countries with carbon tax because it implies that firms have to face an even tighter price on polluting. But if tax revenues are recycled this increase is not so high and long-lasting anymore while the impact on core prices is even negative. These results on employment and revenue recycling are consistent with Metcalf and Stock (2020) and Braennlund and Gren (1999).

5.2.2 Gross National Income

Climate change and level of income are certainly intertwined because climate change can affect low-income communities and developing countries more than advanced economies due not only to the increased exposure and vulnerability of the former but also to the better preparedness of the latter in terms of either mitigation policies or existing innovative solutions (Jay et al. (2018)).

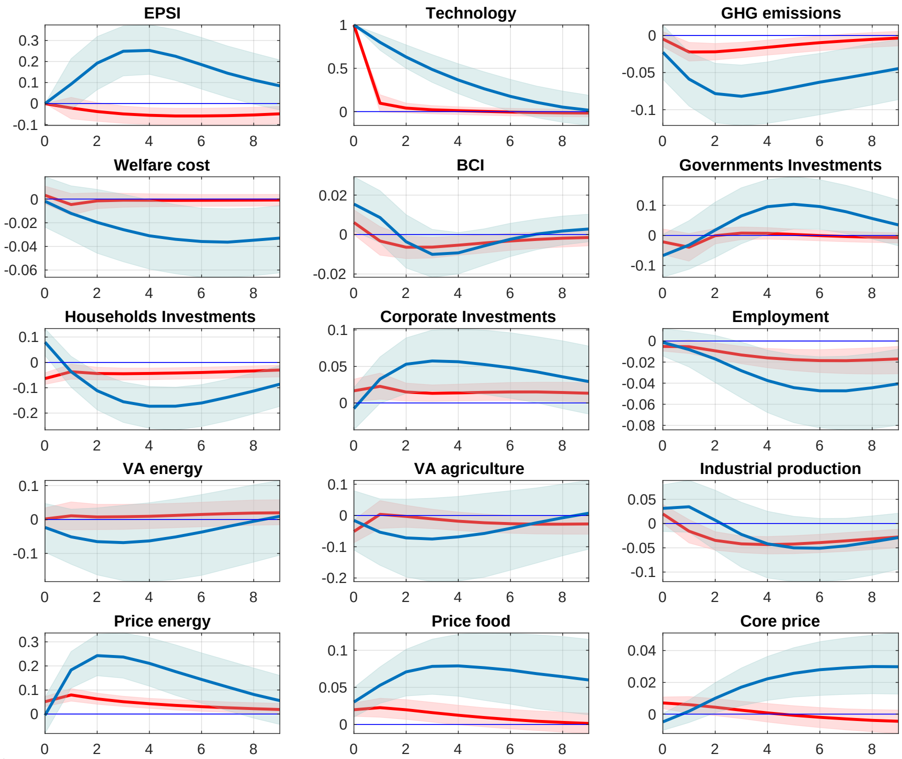
Given that in our sample we only have OECD countries and that the difference between low and high income countries is not huge, grouping the results according to income will give us an accurate idea on the different macroeconomic impacts of climate-related shocks between countries that have already in place good structures to mitigate climate or adapt their technology and countries that are not yet prepared.

For instance, Figure 11 reports the impulse responses to a shock to non policy-induced innovations for low (red) and high (blue) income countries. Several differences are noticeable. First, the same shock to technology is much more persistent in countries that are already prepared to receive additional technology. Second, this in turn implies that in better-prepared countries an increase in technology can be paired with a more stringent policy and with a much higher reductions of emissions and of the damage costs. Third, from a macroeconomic perspective, government and corporate investments are higher in high-income countries and these investments crowd-out households investment more than in low-income countries. Fourth, labor market adjustment to new climate technology and policies imply a more negative effect on employment in high-income countries. Finally, the negative effect on output in energy and agriculture sectors is more pronounced in high-income countries, while the industrial production is more or less unchanged over the medium-term (with an initial positive response). Note also that the positive effect on prices that we saw in the baseline results is much stronger for the high income countries, confirming a strong supply-side effect of an innovation shock in countries that are supposedly better prepared to receive it.

5.2.3 Exposure to natural disasters

Natural disasters (also those related to climate change) have a directly observable negative impact on the macroeconomy, especially in the short-run. As discussed in Section 3.1, we have

Figure 11: Impulse response functions of a shock to Technology



Sources: Authors' calculation; Sample: 1990-2019.
Note: The two groups of countries are low income (red line) and high income (blue line);

decided not to use a direct measure of climate-related natural disasters or extreme weather events in the VAR and rather preferred a more medium-run orientation in the choice of the variables. However, the relative exposure of countries and their vulnerability to natural disasters and extreme weather events is an important dimension of country heterogeneity to account for. Therefore in this section we check if certain shocks have different impacts on countries with different degree of vulnerability.

To define this exposure, we rely on two measures: 1) the intensity of natural disasters in the time span 1990-2019, and 2) the World Risk Index. The variable called "intensity of natural disasters" is built following Parker (2018)[19] using data coming from the *EM-DAT database* of natural disasters.[20] Alongside with the data and the type of disaster, the database reports information on the number of people killed and the number of people affected. We selected disasters that are most commonly attributed to climate change such as: meteorological, hydrological and climatological disasters (see table 3 for the classification of natural disasters). To form the groups we divided countries into high and low intensity of natural disaster, based on

[19]With the difference that for each country we aggregate all the types of disasters that happened each year.
[20]The data are collected by the Centre for Research on the Epidemiology of Disasters at the Université Catholique de Louvain.

Table 3: Classification of natural disasters

Disaster group	Disaster sub-group (type)
Meterological	Storm (ropical storm, extra-tropical storm, convective storm), Extreme temperatures (cold wave, heat wave, severe winter conditions), Fog
Hidrological	Flood (coastal flood, riverine flood, flash flood,Ice jam flood), Landslide (snow, debris, mudflow, rock fall), Wave action (rogue wave, seiche)
Climatological	Drought, Glacial Lake outburst, Wildfire (forest fires, land fire)

their average population affected from 1990 to 2019.

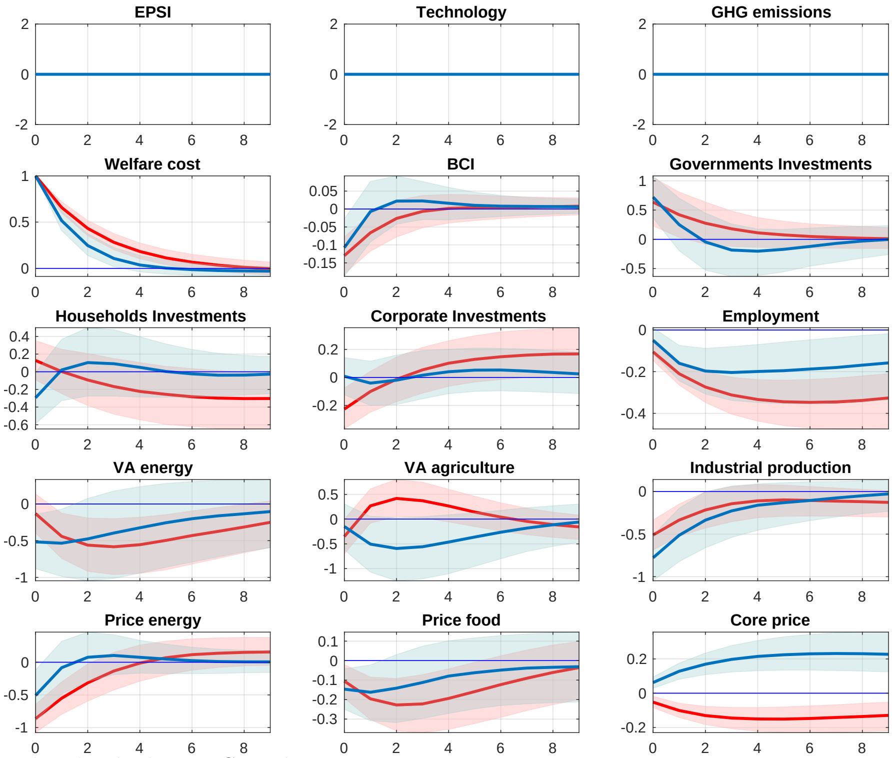
Regarding the World Risk Index (WRI), the variable developed by UNU-EHS describes the disaster risk for various countries and regions and is part of a bigger publication, the World Risk Report (Day et al. (2019)).[21] The report focuses on the threats from and the exposure to key natural hazards and the rise in sea level caused by climate change, as well as social vulnerability in the form of the population's and societies' susceptibility and their capacity for coping and adapting to climate change.[22] For the sake of brevity we report here only the results for intensity of natural disasters (see Figure A.5 and A.6 in the Appendix, for results with WRI).

Results to a shock to the welfare cost are reported in Figure 12 where we plot the impulse responses of highly (red) and lowly (blue) exposed countries (IRFs to the same shock using the WRI are in the Appendix, Figure A.5). Note that the response of the welfare variables itself is less persistent for countries that are less exposed to natural disasters or have a lower value of the world risk index. Moreover, the business confidence indicator and employment are less negative and persistent for less vulnerable countries. Finally, the demand-side effect of the climate shock (with a strong negative effect on core prices) is mostly for countries with a high exposure to natural disasters and a higher vulnerability to them. Interesting to notice here is that even though the two groupings – high exposure to disasters and high WRI – have different sets of countries this result is the same for the two groups. Countries with a high exposure to natural disasters are intended in terms of both their historical exposure in the last 30 years and in terms of their vulnerability, susceptibility as well as their adaptive capacity. Hence, these results suggest that for countries at high risk (which, interestingly enough, are also for the majority low-income countries), an additional positive shock to the cost that society has to pay due to environmental degradation has a more disruptive effect on the macroeconomy than for countries with lower risks, reinforcing the negative demand-type shock showed in the baseline

[21]Sources: United Nations University's Institute for Environment and Human Security (UNU-EHS), Institute for International Law of Peace and Armed Conflict (IFHV) of Ruhr-University Bochum.

[22]The WorldRiskIndex shows the level of risk of disaster due to extreme natural events for 181 of the world's countries. It is calculated on a country-by-country basis through the product of exposure and vulnerability. Exposure covers threats of the population due to natural disasters. Vulnerability entails the societal sphere and is comprised of three components: susceptibility, coping and adaptation. The composition of the index is described in greater details in the methodological notes available at www.WorldRiskReport. org/#data.

Figure 12: Impulse response functions of a shock to Welfare cost of premature deaths



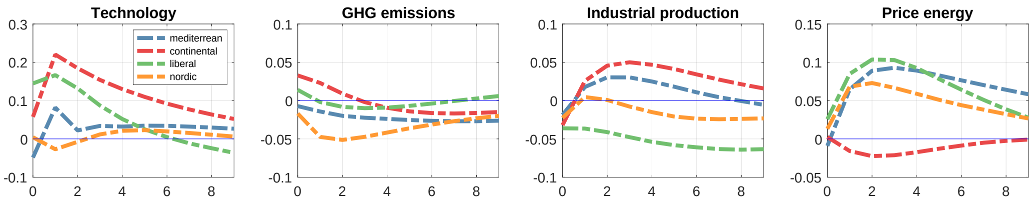
Sources: Authors' calculation; Sample: 1990-2019.
Note: The two groups are countries with a high average percentage of population affected by natural disasters (red line) and countries with a low percentage of population affected by natural disasters (blue line).

results. Similar negative results for output and employment are found by Kim et al. (2021) when analysing the macroeconomic effects of extreme weather shocks. Furthermore, these results are also consistent with recent work by Canova and Pappa (2021) who find that lower-income US states may be more severely hit by the catastrophic events. A possible explanation could be that in lower income states (or in our case countries) physical risks affect a bigger portion of their economic activity or alternatively because they lack the needed infrastructures or suitable private and public insurance schemes.

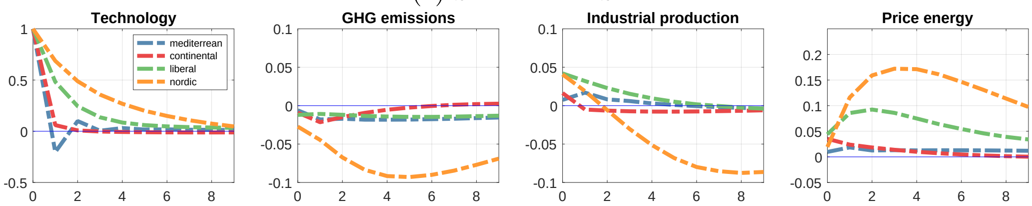
5.2.4 Political Economy and institutions: Liberal, Continental, Mediterranean and Nordic countries

For a final country grouping we consider the same geopolitical characteristics used in Section 3 to illustrate some data differences across countries. In this section we ask whether the macroeconomic impacts of climate-related shocks differ across countries with different geopolitical characteristics or institutional approaches to climate change (Driscoll (2020)) see Table 2 for details on the classification.

Figure 13: IRF of industrial production and prices to EPSI and Technology, geopolitical classification



(a) Shock to EPSI



(b) Shock to technology

Sources: Authors' calculation; Sample: 1990-2019.

Results are reported in Figure 13, which plots the IRFs of technology, GHG emissions, industrial production and energy price levels to shocks to the policy stringency index and the technological innovation. Results can be summarised as follows. A shock to stringency is interpreted as a shock to environmental policies and policy-induced innovation. Looking at the responses to a shock of technology it is possible to have a hint on what type of policy mix the different countries have adopted. Looking at panel (a) of Figure 13 it stands out the difference in the responses of continental and nordic countries. For the first group of countries a shock to EPSI is a boost to environmental technologies, while for the latter technology almost does not react. Furthermore, a shock to policy that is translated in more innovative green technologies also represents a boost to production and has almost a negligible effect on energy prices in continental countries. For these countries – which have historically invested more in environmental technologies – results seems to suggest that in the policy mix between demand-pull policies (that tend to increase prices) and technology-push policies (that give support to technological development and diffusion), the latter are predominant. This would also justify the slower decrease in carbon emissions observed for this group of countries.

On the other end, as shown by panel (b) of Figure (13), a shock to non-policy-induced technology accentuates its negative supply effects for nordic countries that have a history of climate policies and high taxation but didn't invest much in technology. Overall these results provide evidence of an unbalanced and not uniform policy mix adopted by different countries, which invest either in demand-pull policies of technology-push ones. On the other hand, green technological development that is not supported by the right policy mix, may result in market failures that have different sizes for different countries.

An alternative explanation to these results (that certainly needs more exploration) is that

that continental countries (in general with more technology and medium income) absorb better a policy shock, but the opposite is not true for countries that have a history of significant environmental policy where a shock to technology is more disruptive for their economy.

6 Concluding remarks

This paper provides an empirical exploration of the macroeconomic effects of climate-related events and climate policies. Its main contribution is twofold: First, we take a business cycle perspective and focus on the "gradual" impact of climate-related risks (both physical and transition), as opposed to considering either the very long run effects of climate change or the immediate impacts of natural disasters possibly caused by it. Second, to the best of our knowledge this is the first empirical attempt to include the interrelated effects of both physical and transition risks and test their economic consequences within a standard framework the combines exposure and vulnerability to climate change and environmental degradation, climate mitigation policies and adaptation technologies. In so doing we select carefully the variables that proxy for adaptation, mitigation and damage using a panel of 24 OECD countries over the period 1990-2019.

The paper shows that climate changes and policies to counteract them have a significant albeit not sizeable effect on the macroeconomy over a horizon between 2 and 8 years. In particular, the data of this analysis robustly support the view that the impact on output and prices of physical risks is overall negative whereas the final impact of policies and technology is positive on prices and negative on output. Therefore, physical risks are associated with demand-type of shocks while transition policies and technological improvement are more consistent with supply adjustments. Results also differ according to specific country institutional and economic characteristics as well as their different degrees of exposure to risks and vulnerabilities. Notably, in countries that have adopted a carbon tax and recycle its revenues, as well as in countries that have been adapting their institutions or are less vulnerable to climate or general risks, the disruptive effects of climate change and of the introduction of new policies or technologies to mitigate them are much more contained.

These results support the need for a uniform policy mix to counteract climate change with a balance between demand-pull and technology-push policies that help limit the disruptive effects on the economy in the short-to-medium run. Overall, green technological development that is not supported by the right policy mix may result in market failures that have different sizes for different countries with heterogeneous consequences on the phases and duration of their respective cycles. A coordinated approach on climate policies would therefore be essential for instance in a monetary union with common monetary and financial objectives. Climate change and the transition towards a more sustainable economy can affect price and financial stability through their impact on macroeconomic indicators, becoming a "threat" to business cycle synchronization among union members and, therefore, an additional constraint for the central bank's monetary policy strategy, as also recently acknowledged by e.g. the European Central Bank (2021).

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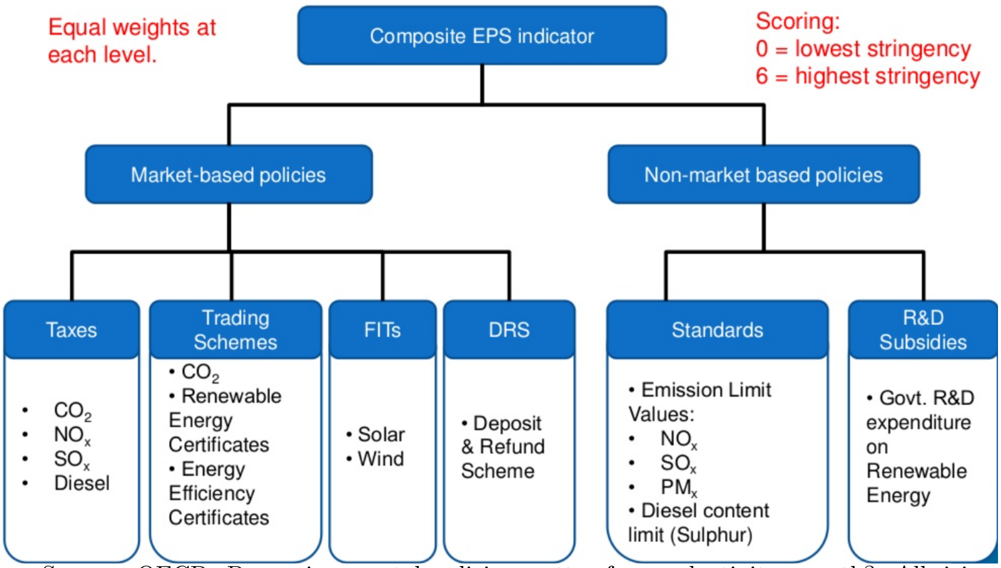
A Appendix

Figure A.1: EPS indicator structure:the policy-induced (implicit and explicit) cost of polluting faced by firms



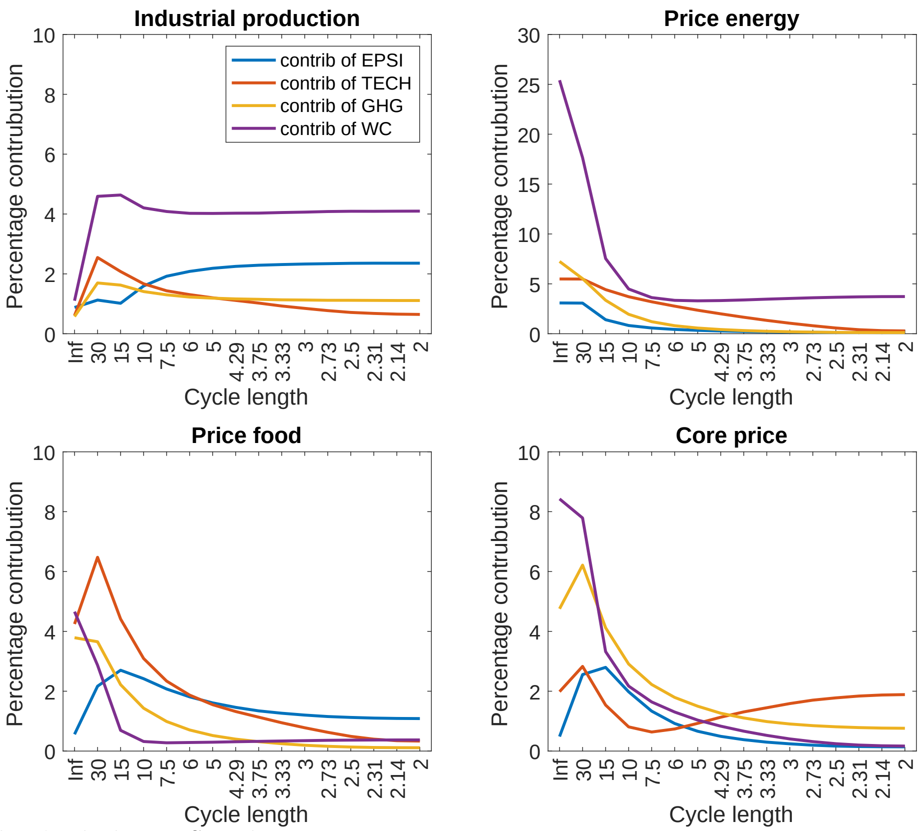
Sources: Source: OECD: Do environmental policies matter for productivity growth? Albrizio, S.,E. Botta, T. Kozluk and V. Zipperer (2014);

Table 4: Spectral decomposition

	Business cycle component (2-8 years)	Medium cycle component (8-30 years)
Panel A. Percentage contribution of EPSI		
IP	85.5	14.5
Pe	25.1	74.9
Pf	67.5	32.5
Cp	39.6	60.4
Panel B. Percentage contribution of TECH		
IP	62.1	37.9
Pe	46.7	53.3
Pf	40.0	60.0
Cp	70.2	29.8
Panel C. Percentage contribution of GHG		
IP	72.3	27.7
Pe	19.6	80.4
Pf	26.5	73.5
Cp	43.3	56.7
Panel D. Percentage contribution of WC		
IP	77.0	23.0
Pe	43.5	56.5
Pf	32.0	68.0
Cp	25.7	74.3

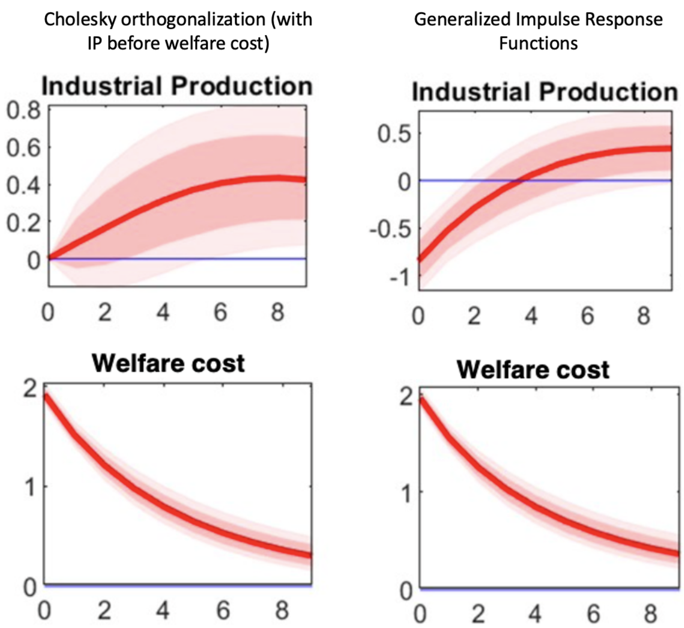
Sources: Authors' calculation; Sample: 1990-2019.
Note: The table shows the contribution of each climate shock to the total spectral density at the business and medium cycle frequencies.

Figure A.2: Spectral decomposition



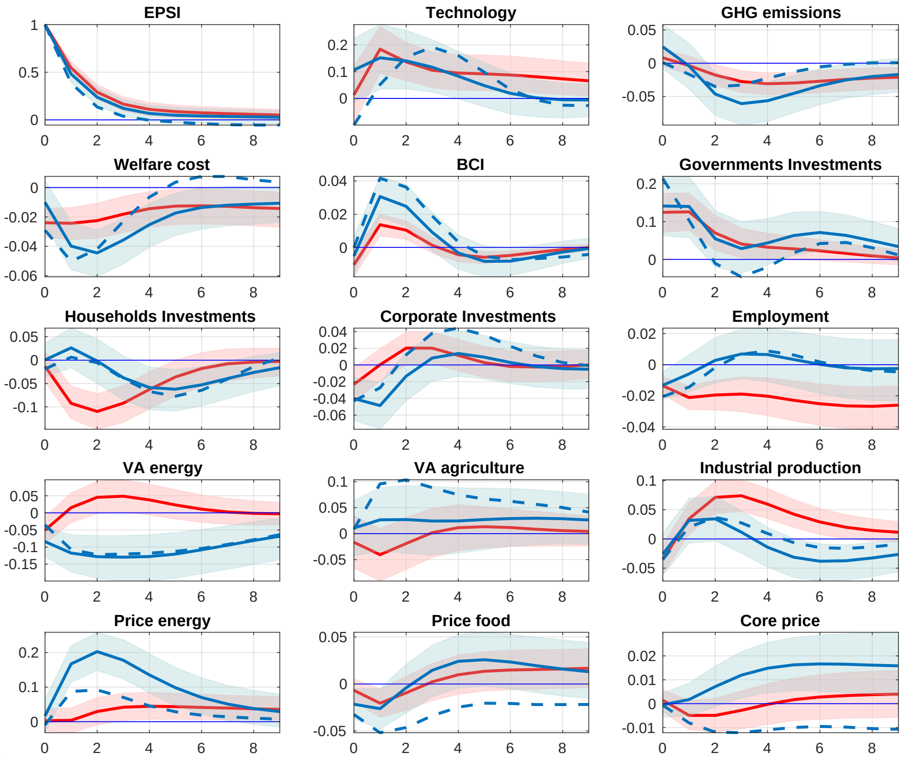
Sources: Authors' calculation; Sample: 1990-2019.
Note: The figure plots the fraction of spectral density of the four main macro variables due to each climate shock at different cycles.

Figure A.3: Robustness check: Generalized responses vs Choleski ordering



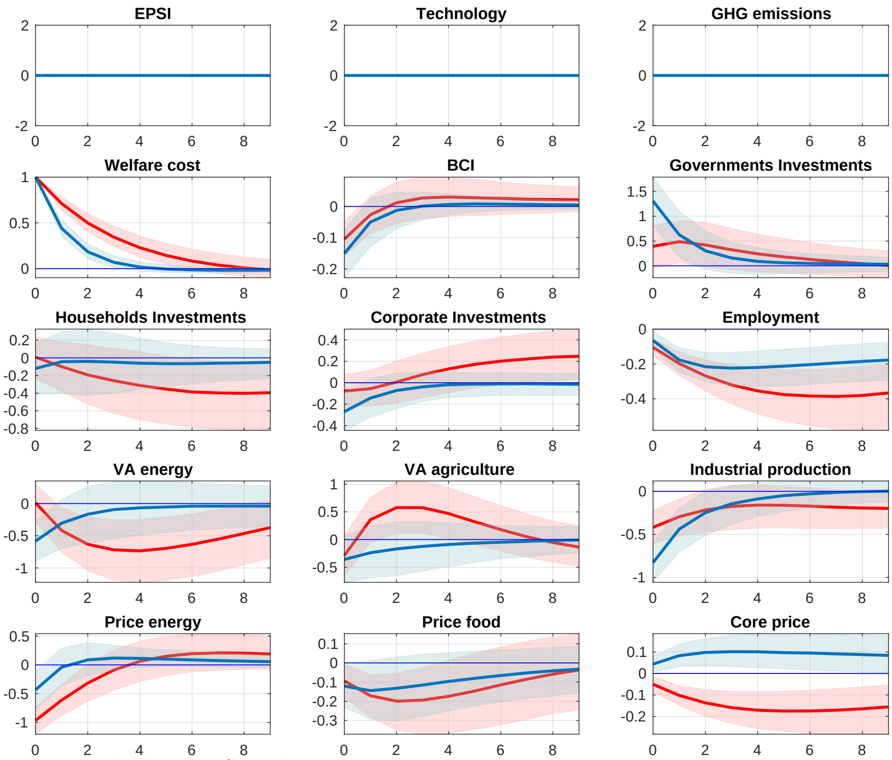
Sources: Authors' calculation; Sample: 1990-2019.
Note: The chart reports the response of Industrial Production to a shock to Welfare cost with a Choleski ordering where IP is placed before Welfare cost (on the left) and with a GIRF (on the right).

Figure A.4: Impulse response functions of a shock to EPSI



Sources: Authors' calculation; Sample: 1990-2019.
Note: The red line indicates countries that didn't adopt a carbon tax; the blue line is for countries with a carbon tax implemented (1990-2019); the blue dashed line is for countries that do revenue recycling.

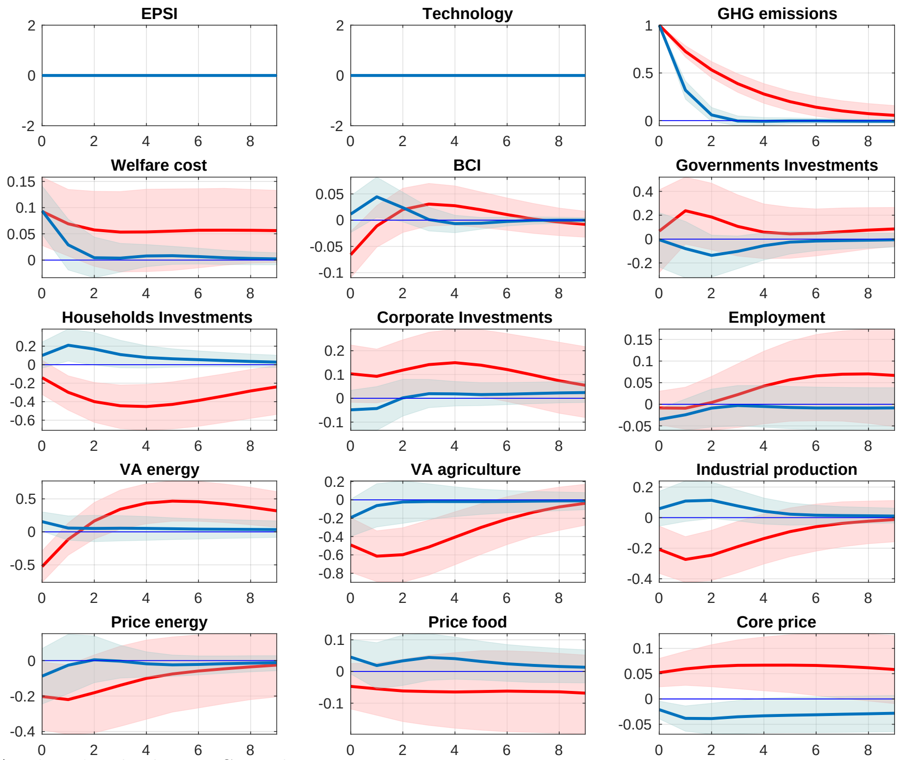
Figure A.5: Impulse response functions of a shock to Welfare cost of premature deaths



Sources: Authors' calculation; Sample: 1990-2019.

Note: The two groups are countries with a high (red line) and low (blue line) World Risk Index (2019)

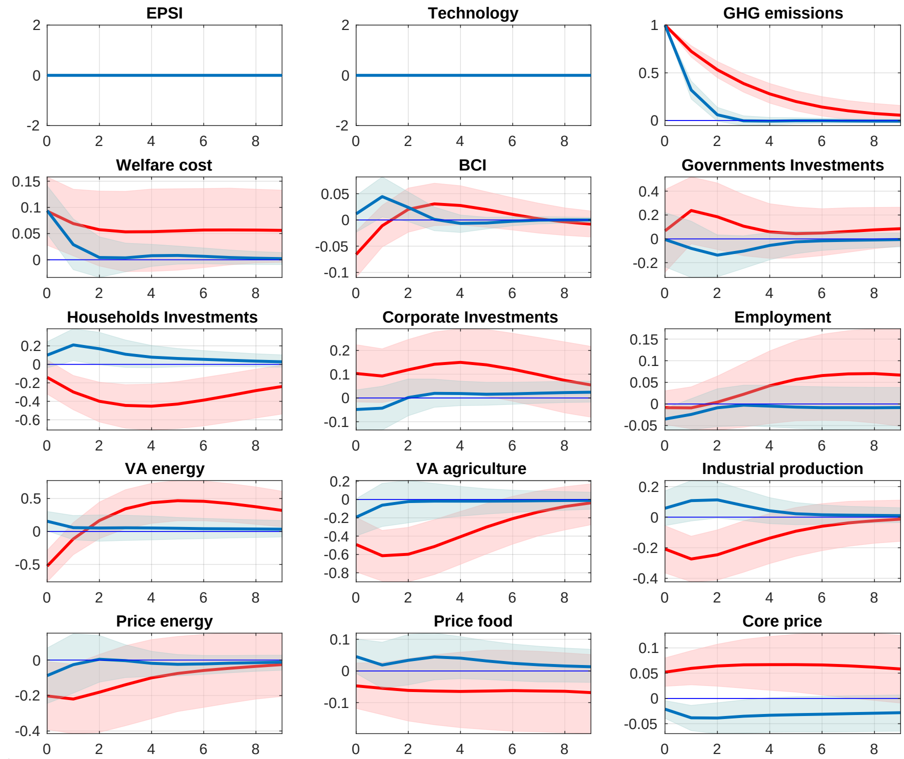
Figure A.6: Impulse response functions of a shock to GHG emissions



Sources: Authors' calculation Sample: 1990-2019

Note: The two groups are countries with a high (red line) and low (blue line) World Risk Index (2019)

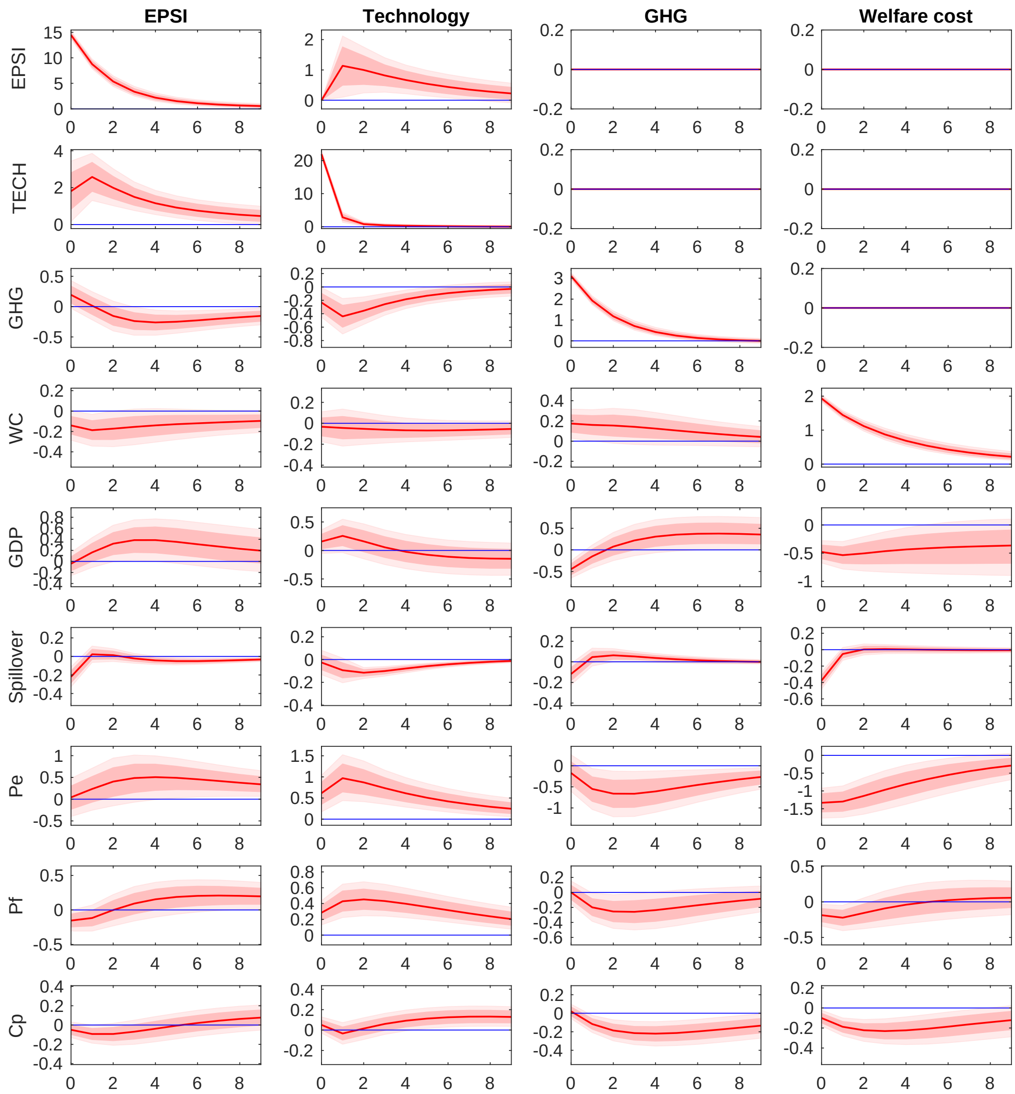
Figure A.7: Impulse response functions of a shock to GHG emissions



Sources: Authors' calculation; Sample: 1990-2019.

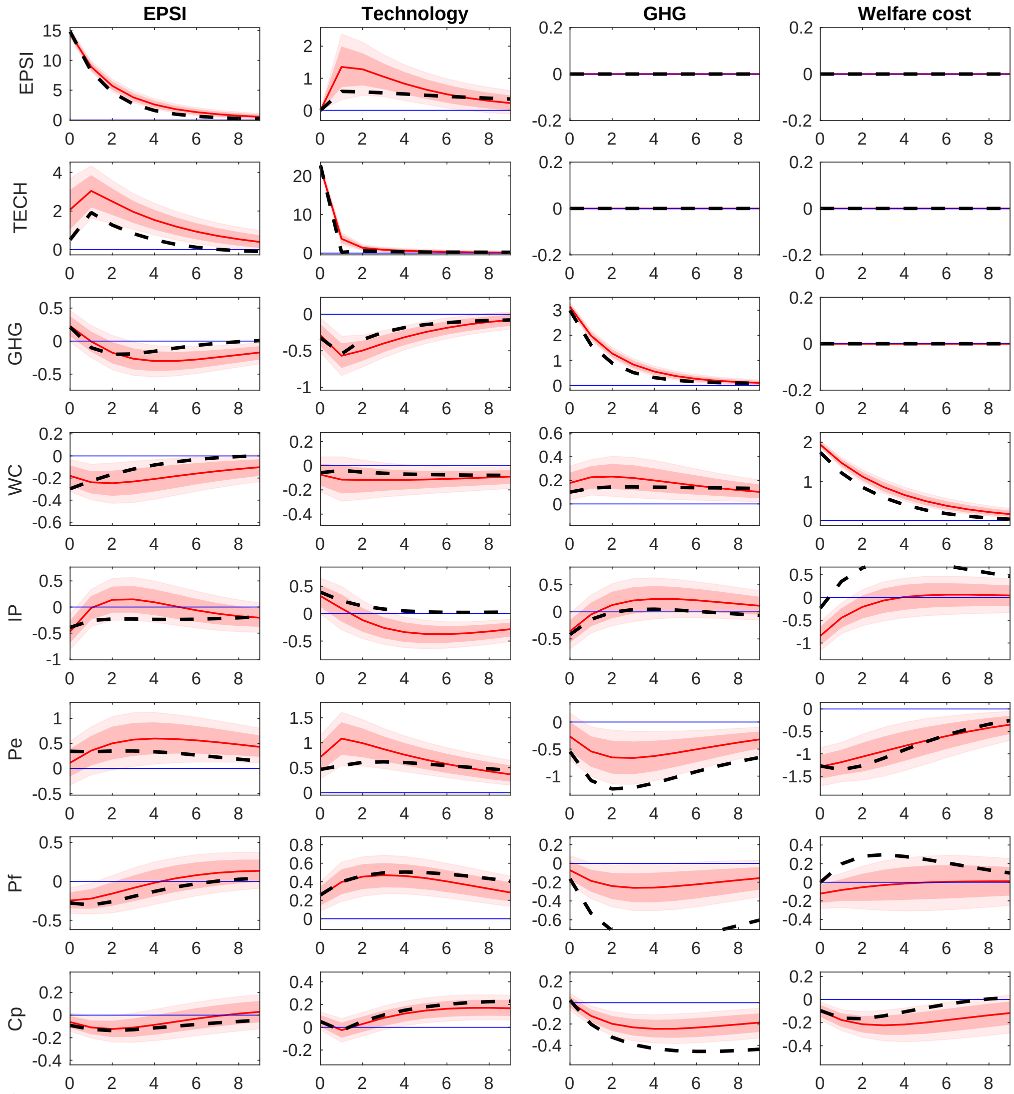
Note: The two groups are countries with a high average percentage of population affected by natural disasters (red line) and countries with a low percentage of population affected by natural disasters (blue line).

Figure A.8: Baseline results, cross-country correlation



Sources: Authors' calculation; Sample: 1990-2019.

Figure A.9: Baseline results, full sample vs sample 1990-2008 (before crisis)



Sources: Authors' calculation; Sample: 1990-2008.
Note: The black dashed line represent the median of the IRF of the model estimated in the first half of the sample (1990-2008)

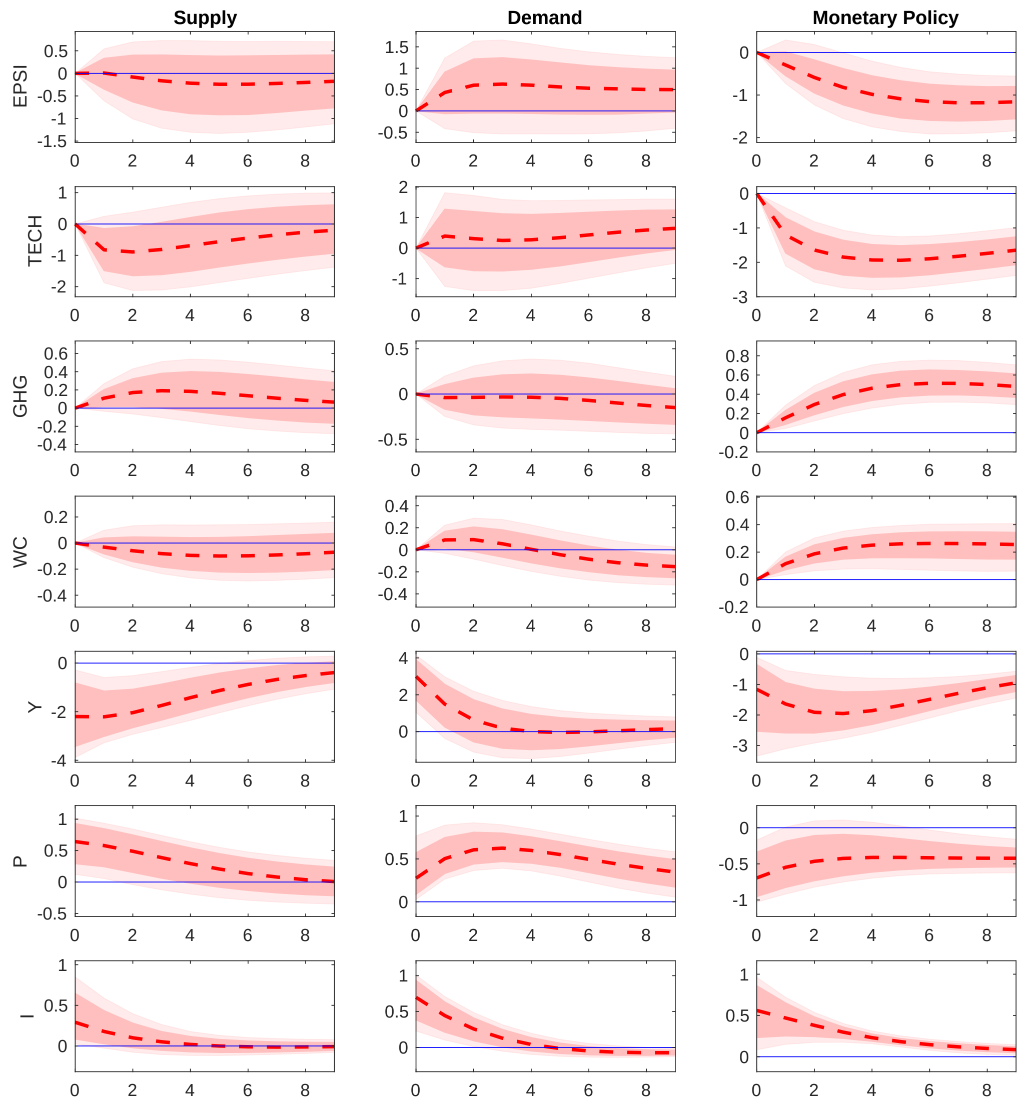
Table 5: Variance decomposition, baseline results (sample 1990-2008)

		EPSI	TECH	GHG	WC	IP	Pe	Pf	Cp
	1 y	100.00	0.15	0.52	2.75	1.39	0.48	1.78	0.69
$EPSI_t$	5 y	92.60	1.34	1.30	2.85	1.29	0.86	1.54	1.57
	10 y	87.15	1.36	1.34	2.61	1.65	1.01	1.26	1.25
	1 y	0.00	99.85	1.15	0.18	1.31	0.87	1.53	0.26
$TECH_t$	5 y	0.43	85.91	3.95	0.46	0.86	2.27	4.88	0.96
	10 y	0.71	83.22	3.87	0.86	0.84	3.00	5.87	2.89
	1 y	0.00	0.00	98.09	0.33	1.54	1.15	0.63	0.14
GHG_t	5 y	0.00	0.00	84.04	1.53	0.97	8.17	10.54	10.01
	10 y	0.00	0.00	76.01	2.77	1.03	10.00	13.56	16.04
	1 y	0.00	0.00	0.00	96.36	0.47	6.24	0.11	0.76
WC_t	5 y	0.00	0.00	0.00	90.03	5.57	9.90	1.47	1.91
	10 y	0.00	0.00	0.00	81.11	9.32	8.89	1.42	1.42

Table 6: Sign restrictions for identification of climate and aggregate macro shocks

	Climate Shocks				Supply	Demand	Monetary Policy
	EPSI	TECH	GHG	WC	Y	P	I
EPSI	1	0	0	0	0	0	0
TECH	0	1	0	0	0	0	0
GHG	0	0	1	0	0	0	0
WC	0	0	0	1	0	0	0
Y	?	?	?	?	-	+	-
P	?	?	?	?	+	+	-
I	?	?	?	?	+	+	+

Figure A.10: Sign identification, macro block



Sources: Authors' calculation; Sample: 1990-2019.