Energy Economics 129 (2024) 107163

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

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

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ARTICLE INFO

JEL classification:
C11
C33
E32
E58
Q5

Keywords:
Environmental policy
Environment-related technologies
Physical risks
Business cycle
SVAR

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 green innovation. Overall, we find evidence of significant macroeconomic effects over the business cycle: physical risks act as negative demand shocks while transition risks act as downward supply movements. The disruptive effects on the economy typical of a disorderly transition are exacerbated for low income, high emission countries with no history of environmental policy or with a high exposure to natural disasters. In general, one size does not fit all and results support the need for a (possibly country-specific) policy mix to counteract climate change with a balance between demand-pull and technology-push policies.

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 if we don't take action to limit emissions (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 of maintaining monetary and financial stability. From a central bank perspective, this implies that researchers need to investigate two fundamental aspects: first, we need to provide evidence that these effects materialize over a horizon that is relevant for monetary policy. Once researchers support this, 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?

☆ This research was supported by the ClimateWorks Foundation. We would like to thank Christiane Baumeister and two anonymous referees for valuable guidance, and Marek Jarocinski, Michele Lenza, Haroon Mumtaz, Sam Fankhauser, Emilien Ravign 'e, Miles Parker, ECB's seminar participants, and NBER Summer Institute 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.

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https://doi.org/10.1016/j.eneco.2023.107163
Received 13 May 2022; Received in revised form 23 October 2023; Accepted 29 October 2023
Available online 10 November 2023
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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 change 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 can differ significantly across countries according to institutional and economic characteristics. For instance, countries that have introduced a carbon tax suffer less negative consequences in the transition to a low-carbon economy 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 and perform selected robustness checks. In Section 5 we discuss country heterogeneity. Section 6 provides a discussion on the implications of our findings for policy makers and economic modellers. Section 7 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. These estimates are subject to considerable uncertainty, because 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 been based on standard macroeconomic considerations (e.g. Andersson et al., 2020; Batten et al., 2020), on model-based simulations (e.g. NGFS, 2020a; IMF, 2020) or both (Breckenfelder et al., 2023).

Our work relates closely to the growing empirical literature that aims to test these channels and their macroeconomic consequences. However, because of the uncertainty surrounding the frequency and damages caused by these events, as well as the challenges in directly attributing them to climate change, there is still limited evidence on how the economy will be affected. Researchers have found that the impact of physical risks on prices and inflation varies substantially depending on the 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 et al., 2020; Canova and Pappa, 2021). With respect to the consequences of global warming, 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' behaviour, 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.

Mitigating and adapting to climate change requires substantial changes to the economy, which imply 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). Känzig (2021) identifies the specific effect of tightening of European carbon market. He finds that a higher pricing regime leads to an increase in energy prices, a persistent fall in emissions and an uptick in green innovation at the expense of a temporary fall in economic activity. Most of the empirical literature instead seems 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 et al., 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. Environmental policy intervention becomes necessary when facing two types of market failures: (1) environmental externalities where the market does not price pollution and firms and consumers lack incentive to reduce emissions without policy interventions, and (2) knowledge failures regarding 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 balances the use of demand-pull and technology-push instruments to address these two types of externalities, it tends to have greater effects on environmental innovation. This helps mitigate the occurrence of market failures that negatively impact 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 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 to provide some additional evidence

[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.

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). 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 analysis, the (available) data to proxy for both physical and transition risks requires a careful selection. In what follows, therefore, we first illustrate the climate data set – that covers 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, business confidence – and prices – consumer price index (CPI) split in energy and food and core.

3.1. Measuring physical and transition risks

The database used for the analysis combines several variables coming from different sources. We downloaded climate related variables from the OECD.stat Environment database.[3] 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. To proxy for climate change and environmental risks, we use two main variables: (1) The welfare costs of premature deaths because of exposures to environmental-related risks (that we call environmental degradation); and (2) Total greenhouse gases (GHG) emissions per unit of GDP (emission intensity). Data charts and additional details are in the Online Appendix A.

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. The index ranges from 0 (not stringent) to 6 (highest stringency) and is based on the degree of stringency of 14 environmental policy instruments divided in three equally weighted subindices, which respectively group market-based (such as carbon taxes, or trading schemes), non-market-based (e.g.emission limit values), and technology support policies (mainly public R&D). See Figures A.1–A.3 in the Online Appendix for more details on the composition of the index. The synthetic indicator, therefore, is inclusive of demand-pull and technology-push policies, primarily related to curbing greenhouse gas emissions and local air pollution, but not necessarily regulations across all sectors of the economy. In our analysis, we use the overall index – as proxy for a combination of measures – and each of the sub-indices related to market-based, non-market-based, and technology support policies. For further details on the construction of the index and its properties, see Botta and Kozluk (2014) and, more recently, Kruse et al. (2022).

Green innovation The proxy for green innovation counts the number of patents related to developments in environmental related technologies. See Figure A.4 and Table 1 in the Online Appendix A for more details on the type of technologies included and the time series of patents. They construct the statistics 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 mitigation technologies". The number of inventions developed by country's inventors is 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. First, patents themselves are a direct measure of countries' and firms' innovative performance that is eventually commercialized; Second, since patents applications are usually filled early in the research process, they are also a reasonable indicator of the level of R&D activity itself.

Environmental degradation The main 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 and soil; the destruction of habitat and ecosystems; and pollution).[4] OECD built this measure using epidemiological data taken from Global Burden of Disease Study 2019 (GBD, 2019), while they calculate the welfare costs using a method 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). It represents the individuals' willingness to pay (WTP) to secure a marginal reduction in the risk of premature deaths. See subsection A.3 and Figure A.5 in the Online Appendix A for more details of the construction of the welfare cost and its evolution. 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 do not 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 (see Figures A.32–A.34) by including temperature anomalies in the specification, and we use the data on exposure to natural disasters in Section 5, where we test country heterogeneity in their responses to certain shocks.

[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.

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

GHG emission intensities The data on emissions refers to man-made emissions of major greenhouse gases and emissions by gas.[5] 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 regarding energy and industrial emissions, are influenced primarily by shifts in energy intensity, economic structure, and fuel mix. Therefore, changes in activity levels (such as Industrial Production or GDP) do not directly correlate with emission intensities. Even in the event of major GDP changes, changes in intensity levels may be modest. Absolute emission levels are strongly pro-cyclical and influenced by GDP shifts (Doda, 2014; 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: 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 maintain their initial position regarding the average.

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, we can write the model as:

$$A_{i0} Y_{it_i} = \mu_i + A_i(L) Y_{it_i-1} + \nu_{it_i} \tag{1}$$

where the As are coefficient matrices, μ_i is a vector of country-specific constants, and ν_{it_i} is a zero-mean vector of orthogonal structural shocks with diagonal variance–covariance matrix D_i; and the notation X_{t_i} shows that the panel is potentially unbalanced and that the number of time series observations is country specific. The vector Y_{it_i} comprises two sets of variables, the climate-related variables and the macroeconomic ones. The climate block contains the four variables illustrated in the previous section: the Environmental Policy Stringency index, mitigation technologies, the welfare cost of premature deaths due to exposure to environmental risks and GHG emission intensity. The macroeconomic set of variables of interest include: industrial production, energy prices, food prices and core prices (i.e. total prices excluding energy and food). To account for and check the role of channels through which a shock to a climate-related variable reaches productions and prices, the VAR includes also variables that proxy for some of the main transmission variables: the Business Confidence Index, Investments (governments, households and corporate), and Employment. More details on these variable are in subsection A.4 in the Online Appendix. In the empirical analysis, all variables are in log levels multiplied by 100. The estimation period spans from 1990 to 2019 and the panel is homogeneous but unbalanced, as for some countries data are not always available over the full sample.[6]

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 $A_i(L) = A(L)$, 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 ($\epsilon_{it_i} = A_0^{-1} \nu_{it_i}$) are assumed to be serially and cross-sectionally uncorrelated.
3. A linear trend is used in the estimation to deal with part of the non-stationarity of most variables, complemented with a general Minnesota prior and a sum of coefficients prior.

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). We now discuss these assumptions.

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 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 GHG emissions, their adoption and use of a carbon tax, or their exposure to natural disasters or other risks) and pool the data for estimation separately by groups.

Assuming absence of serial and sectional correlation is 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. Therefore, we also add a global variable to the single country specifications – the global commodity price index – to capture a factor that is common among macro and climate measurements and can account for correlations and spillovers across country. This is similar in spirit to the usual Global VAR approach (e.g. Chudik and Pesaran, 2016). Notice, however, that by construction, the panel VAR uses a pooled approach whereby a common set of parameters is estimated across countries and used to derive IRFs that are by construction the same for all countries. In this sense, the shocks are not national, but also not global as in the GVAR literature. Therefore, analysing specific regional or global initiatives (e.g. Kyoto or Paris Agreement) does not come as a direct application of the framework. However, in Section 5, when running the VAR by groups of countries, we will capture and discuss specific regional aspects.

Finally, the linear trend is a convenient empirical method for accounting for a portion of non-stationary data, for partially compensating for the low lag order of the VAR, and for conditioning the estimation on initial values of the endogenous variables, which are in levels. A standard Minnesota prior augmented with a prior on the sum-of-coefficient is also used to complement this assumption. Under this specification, the model is a priori assumed to be difference-stationary for all variables, with some residual (possibly linear) non-stationarity captured by a deterministic trend.

3.2.1. Reduced-form estimation

The reduced-form of model (1) is

$$Y_{it_i} = C_i + B(L) Y_{it_i-1} + \epsilon_{it_i} \tag{2}$$

where $C_i = A_0^{-1} \mu_i$, $B(L) = A_0^{-1} A(L)$, and $\epsilon_{it_i} = A_0^{-1} \nu_{it_i}$. We estimate this model using Bayesian techniques, which require specifying a prior

[5] It includes total emissions of CO2 (emissions from energy use and industrial processes, e.g. cement production), CH4 (methane emissions from solid waste, livestock, mining of hard coal and lignite, rice paddies, agriculture and leaks from natural gas pipelines), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6) and nitrogen trifluoride (NF3). Data exclude indirect CO2.

[6] In particular, the Business Confidence Indicator is not available for Canada and Hungary over 1990–1997, and for Czech Republic, Finland, Slovakia, and Sweden over 1990–1992, with a total NaN = 29. Investments are missing over 1990–1995 for all countries but US, Sweden, Norway, Korea, Finland, France, Australia with NaN = 79. Employment is missing for all countries in 1990, with NaN = 24.

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:

$$\boldsymbol{Y} = \boldsymbol{X}\boldsymbol{B} + \boldsymbol{E} \tag{3}$$

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:

$$p(\boldsymbol{B}, \Sigma) = p(\boldsymbol{B} \mid \Sigma)p(\Sigma) \tag{4}$$

with

$$p(\Sigma) = iW(S, \nu) \tag{5}$$

and

$$p(\boldsymbol{B} \mid \Sigma) = N\left(\boldsymbol{B}_0, \Sigma \otimes \Omega_0\right) \tag{6}$$

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 hyperparameters $\boldsymbol{B}_0$ and $\bar{\Omega}$, with the mean for the own lag equal to 1, the general tightness (λ) equal to 0.3 and the tightness for the constant is diffuse. For the covariance matrix of the residuals we assume a diagonal structure, and the estimation of its elements comes from a univariate AR(p) model. Finally, we use a sum-of-coefficient prior with shrinkage parameter $\tau = 3$. We implement the priors adding dummy observations. The posterior distribution is simulated 10 000 times and, we estimate the VAR with one lag.

3.3. Empirical strategy

Our paper aims to analyze the extent to which shocks to climate-related variables have meaningful effects on the macroeconomy over a business cycle horizon.[7] 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, consistent with similar empirical studies like Mumtaz and Alessandri (2021) and Kim et al. (2021), assumes that the shocks affecting the macroeconomic variables will not contemporaneously affect the climate variables. As a result, any potential impacts of macro shocks on climate or climate policy can only be observed after one year. Shocks hitting climate-related variables are more likely to have an 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 economic activity, while the economy gets hit by the damage that generates after emissions affect the climate system. However, we incorporate emission intensities into the model, as they are primarily influenced by energy intensity and the fuel mix, rather than 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 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, resulting from public interventions because of political shifts and, social and environmental pressures. While absolute technological development can respond quickly to economic activity (Dechezleprêtre et al., 2021), specific environmental technologies aimed at mitigating, and adapting 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 environmentally specific patenting activity will unfold relatively slowly.

In the climate block, we identify three shocks: an environmental policy shock (to the stringency index), a green innovation shock (to mitigation technologies) and an environmental degradation shock (to the welfare cost of premature deaths). We test the robustness of this identification strategy with multiple checks (see Section 4.3). When assessing the effect of environmental policies, the composition and structure of the stringency index as described in Section 3 allow for a granular analysis of the effects of environmental policies and can be used either in its general version – as a combination of all policies – or for all individual measures that have different policy targets. In fact, the market- and non market-based components target primarily the negative externalities of emissions, whereas the technology support component targets positive externalities from R&D that – absent public policy – may lead to sub-optimally low investment. Therefore, we can check the consequences of unexpected shocks to (i) a combination of all policies, (ii) market-based policies; (iii) non-market-based policies; and (iv) technology support.

When assessing the physical risks, we compute an unexpected shock to the welfare costs of environmental degradation while using the GHG intensities only as a control to proxy for future climate damages. We do not show the consequences of a shock to this variable, which could be more problematic to identify given that emissions may respond more rapidly to the state of the economy than other slow-moving climate variables, such as environmental degradation or temperatures. We use the latter as a robustness check in our analysis, and provides the same qualitative results as the proxy for environmental degradation.

The variable ordering in the VAR is such that an environmental policy shock (including technology support) increases the stringency index at time 0 while a technology shock increases the number of mitigation technologies without affecting at time 0 the policy index, which can react to it only after one year, and affects contemporaneously the emissions' intensities and the environmental degradation proxy but do not react contemporaneously to their movements. The assumption, therefore, is that, because of a shock to physical risks, governments are slow to put in place the policies and technologies needed for mitigating climate change consequences. On the other hand, the transition shocks, if suddenly implemented in the form of a new policy or to support innovation, can have visible effects on emissions and welfare costs in the same year. Finally, we leave the macroeconomic block unidentified in the baseline specification.[8] It is important to notice that the results we report in what follows, based on the Choleski orthogonalization, are qualitatively and quantitatively similar to those obtained using Generalised Impulse Response functions (Pesaran and Shin, 1998), which do not require orthogonalization of shocks and are invariant to the ordering of the variables in the VAR.[9]

[7] 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 the robustness Subsection of the Working paper version (Ciccarelli and Marotta, 2021).

[8] In further robustness checks in the Working Paper version (Ciccarelli and Marotta, 2021) 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.

[9] The results of this robustness check are reported in Ciccarelli and Marotta (2021).

3.3.1. Policy scenarios and selected channels

We complement the impulse response analysis and investigate also the effects of the physical and transition risks shocks under scenarios which test the effectiveness of the policy or the technology support, as well as the importance of selected channels. We conduct counterfactual experiments whereby, for instance, we leave unresponsive the policy support after a shock to technology, or we check the effects of a physical shock when leaving unchanged the policy and the technology support. Similarly, we check how important the expectation or the investment channels are in transmitting transition or physical shocks. Finally, when discussing the effects of a shock to environmental degradation, we also compare the baseline results with the ones obtained in a case where we restrict policy and innovation to react positively to such a shock (instead of being unresponsive either contemporaneously or over the whole horizon).

The counterfactuals are engineered as in Ciccarelli et al. (2015). To assess the relevance of the different channels, we conduct appropriately designed experiments that attempt to answer questions like: What happened in the data when a shock, such as environmental degradation, occurred alongside a combination of shocks that left policy and technology unchanged? The best approximation to these counterfactuals in a semi-structural setup can be obtained by checking the response of the system to a given shock (environmental degradation) when we combine such a shock with other shocks that neutralize the effect on specific variables (policy and technology) and set their IRFs to zero for the whole horizon. Mechanically, we do this by recursively constructing a sequence of shocks to the variables that we want to shut down (policy and technology) which offset to zero their responses to the given shock (environmental degradation).[10] Note that, in principle, this approach is not entirely immune to the Lucas' critique – which would totally apply if we constrained to zero the coefficients of the single equations as opposed to zero-out the IRFs – especially if the experiment does not imply a "modest" shock (or policy intervention in the words of Leeper and Zha, 2003).

A final word of caution. These counterfactual analyses depend on the ability to correctly identify and name the various shocks. One specific problem is that with the imperfection of our identification scheme, we might not be able to 'name' the specific shock that we construct to offset IRFs. But to the extent that we can interpret these shocks as shocks to the policy and technology variables, this "counterfactual-type" experiment is still a valid one to answers questions such as: What happened in the data in those occasions in which a shock to environmental degradation was accompanied by a combination of shocks that happened to leave policy and technology unchanged?

4. Baseline results

In this section we report the results as impulse response functions, to check if and how macro variables move after a one-standard deviation shock in two transition risks – policy and technology – and one physical risk – environmental degradation or welfare costs. Notice that our figures do not include the variables that we shock. In Section 4.3 we will subsequently complement the evidence with some robustness checks. Additionaly, in Section 5 we will analyze country groups to test how sensitive the results are to characteristics that are related to country economic features, such as income, climate traits, such as their exposure to risks of natural disasters, or institutional elements, such as the adoption and use of a carbon tax. Because the variables are transformed in log multiplied by 100, the unit scale of the IRFs is directly expressed in percentages.

[10] This should be equivalent to obtain out-of-sample forecasts of the other variables of the VAR conditional on a given path for the variables to be shut down over the forecast horizon and compare them with unconditional forecasts. See also Wong (2015), Bachmann and Sims (2012) or Baumeister and Benati (2013) for similar approaches and a discussion on the validity of these counterfactual experiments in a VAR setup.

4.1. Transition risks

4.1.1. The effects of environmental policies

Fig. 1 reports the effects of an unexpected shock on the aggregate measure of environmental policies as measured by the total stringency index. The red line represents the median responses, and the shaded areas are the 68 percent (dark) and 95 percent (light) Bayesian posterior probability intervals or credible sets. We will describe results as "significant" if at least the darker shaded area does not contain the zero line.

The shock to the aggregate environmental policy variable generates some expected dynamics in the "climate block", as it stimulates the number of patents in environmental technology destined to mitigation, and is followed by visible mitigation effects as represented by a significant reduction in environmental degradation and a medium term reduction in GHG emission intensity (after a small and insignificant initial increase). The increase in mitigation technology is linked to the mix of demand-pull and technology-push policies included in the total EPSI, and to the rise of investments in environmental research and development (R&D). This intuition is compatible with the positive response of government and corporate investments. The latter, after being immediately crowded, pick up in a positive and sustained manner over the entire horizon.

This finding is consistent 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 and 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 private and 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).

Regarding the other effects on the macroeconomic block, a striking general result is that climate-related shocks can have a significant impact on macroeconomic variables over a horizon comprised between 2 and 8 years, i.e. the "typical" range for a business cycle periodicity. The impact is quite strong on energy prices and can translate into significant variation in business (and consumers) sentiments or investments. 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.

More in detail, Fig. 1 shows that an initial muted effect on industrial production is followed by a more negative and persistent response over the medium term. Energy prices increase as expected in a significant and sustained manner together with food prices – possibly contributing positively to some pressure on headline inflation – while core prices decrease somewhat persistently. An unexpected shock to a combination of environmental policies generates a relative price adjustments with an overall reduction of the output and therefore a dominance of supply-type effects, driven by the energy sector, similar to a typical cost-push shock (in line with e.g., Känzig, 2021).

We also observe a negative effect on employment. This result suggests that transitioning to a low-carbon, environmentally sustainable economy may lead to job creation in certain economic sectors with low emission intensities, but it could also result in significant job destruction in traditional emission-intensive sectors, ultimately causing a negative effect on total employment. Notice, though, that the effects on employment and output as measured by industrial production seem to point to an immediate increase in overall productivity, a result that is consistent with the work of Brunel (2019) and Franco and Marin (2015).

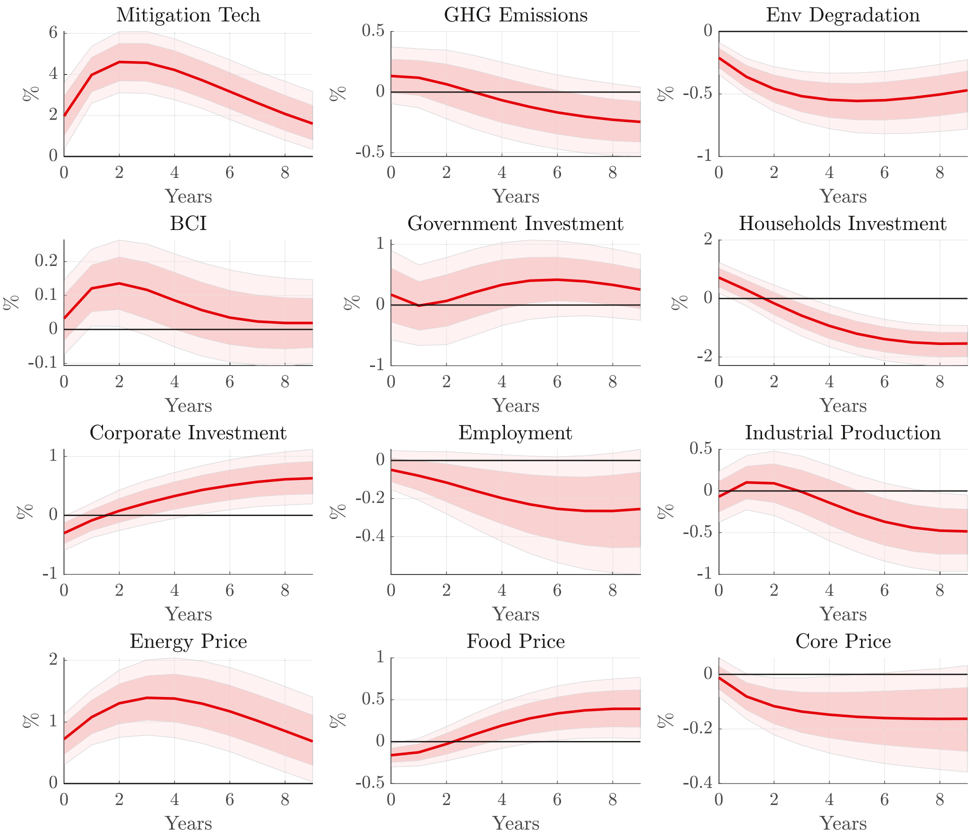

Fig. 1. Impulse response functions of a shock to Environmental Policy.

To better understand the strength of the transmission channels after an environmental policy shock, we perform two additional exercises. In the first exercise, we produce a scenario where a shock to environmental policies is not followed by a response to the government investments and by mitigation technologies that can guarantee a transition to an effective low-carbon economy. As explained above, we engineer this experiment by creating a sequence of shocks to government investment and mitigation technology that shut down their responses over the entire horizon. The results of the first exercise are reported in Figure A.7 in the Online Appendix. By shutting down the technology channel, we find that the reduction in environmental degradation is less intense, and there is a more muted reduction of employment as well as a lower inflationary pressure coming from energy prices.

In the second exercise, we investigate the results of a shock to each individual components of the EPSI (which we use one by one in the VAR in place of the aggregate measure), and we try to assess if the different policies, namely market-based, non market-based, and technological support, have different effects both on the climate and on the macro block. See Figure A.3 for more details on the different components of EPSI.

The results of the second exercise are reported in Fig. 2, while the full set of results is in the Online Appendix (Figures A.14–A.16). Several considerations are in order.

First notice that a shock to all market-based instruments, although more effective than other instruments to curb emission intensities (non market-based and technology support in fact have positive effects on intensities) does not appear to have a significant effect on output and prices, contrary to expectations. Let us qualify this articulated statement. First, we can explain that the fact that non-market-based and technology support policies increase emission intensities instead of reducing them. This is because the non-market-based policy component includes various policy measures that do not directly target GHG emissions. Instead, they focus on addressing other environmental concerns such as Nitrogen Oxides (NOx), Sulfur Oxides (SOx), Particulate Matter (PM), and Sulphur. These elements are distinct from GHG emissions, and therefore, a positive effect on GHG intensity is expected, as these policies primarily relate to environmental degradation variables. On the other hand, the tech support policies component encompasses policies aimed at promoting technological advancements and innovation in mitigating emissions. In our analysis, we found that the direct impact of these policies on emissions is statistically non-significant. The effect of mitigation technology on emissions is often complex and can involve a lagged response. This is because implementing patents and innovations in mitigation technologies may not respond immediately to government incentives and, therefore, policy might not have an immediate impact on emission reduction. It is important to note that emission intensity is the ratio of emissions to activity. Given that these non-market-based measures do not create financial incentives to curb emissions and, they have a negative (supply-type) effect on activity, the result of an increase in intensity is not unexpected. In fact, we can rationalize the increase by the fact that these policies may affect the economic activity side of the equation more strongly than they affect emissions themselves.

The second result, that market-based policies do not affect output and energy prices, is also not necessarily controversial, as also found e.g. by Konradt and Weder-Di Mauro (2021) for carbon taxes only. We believe it is because of the little adoption of carbon taxes across countries in our panel sample, and to the specific definition of market-based instruments which contain several instruments.[11] If we focus in particular on the composition of the market-based instruments used in the analysis, we can isolate the specific effects of the CO2 Emission

[11] Note that marked-based policies (as opposed to non market-based and tech support policies) are the only ones to include instruments such as the Emission Trading Schemes and CO2 Taxes that directly target GHG emissions, but also many others that are not necessarily directly related to energy costs.

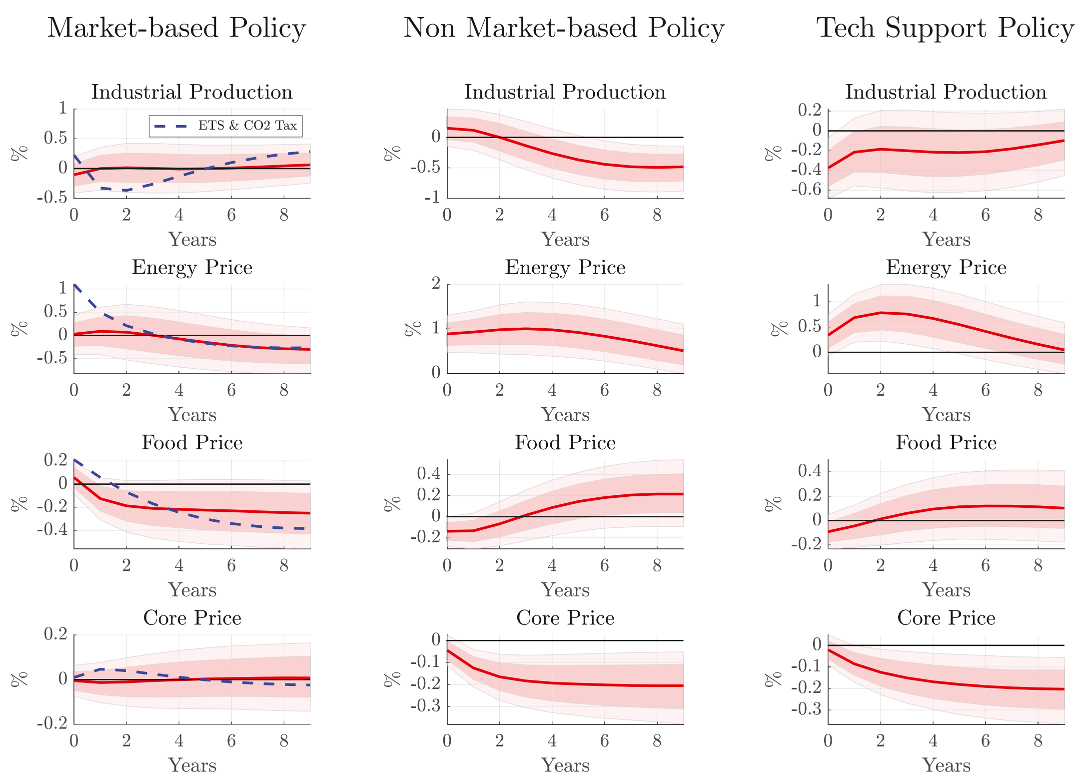

Fig. 2. Impulse response functions of a shock to Components of EPSI.

Trading Scheme (ETS) and the carbon tax only. This result is reported in the first column of Fig. 2, where the blue line represents the responses of output and prices to a shock to market-based policies constructed only with CO2 ETS and carbon taxes. The chart shows that (i) energy prices increase immediately by over 1%; (ii) this increase is not reflected in core prices; (iii) production reduces over the medium term. These findings are in line with those empirical analyses that focus only on these types of measures (e.g. Känzig, 2021).

Turning to the other sets of policy measures, non market-based (which include mostly emission limits) and technology support instruments, we observe a positive effect on energy prices and a negative effect on output (especially over the long term for non-market-based policies). The strong negative supply-side effect observed in the baseline results, therefore, appears to be associated with these two sets of policies and in particular with the technology support policies that encompass R&D subsidies, specifically aiming at support for renewable energy, including wind and solar. Although from a theoretical perspective, the response of energy prices to a technology shock could be ambiguous, as renewable sources have lower marginal cost in production which makes them less expansive and more competitive, our results can be rationalized at least in two dimensions, by reflecting on (1) the impact of tech support policies on oil prices, and (2) the energy price composition.

Technology support policies, specifically geared towards promoting renewable energy sources such as wind and solar power, have a direct effect on the energy landscape. The premise here is that these policies incentivize the adoption and expansion of renewable energy sources, reducing their costs and increasing their availability. As a result, this leads to a substantial positive supply effect on the share of electricity generated from renewables, causing an increase in the quantity supplied at lower prices. This not only encourages a shift in consumer preferences (e.g. higher demand towards cleaner energy sources) but can also induce shortages of traditional inputs which drive down their supply in energy generation. The decrease in demand for oil, downward pressures oil prices. However, it is important to consider that that various factors influence oil markets, including the behaviour of organizations such as OPEC. OPEC, acting as a profit-maximizing monopoly, may adjust its supply in response to changes in demand. This may result in an oil price that remains higher than before, affecting further the quantity of oil produced and demanded. For example, by Gornemann et al. (2022) support this view in a standard New Keynesian open-economy model, emphasizing the role of the feedback loop between ownership of the constrained input (e.g. oil), marginal propensity to consume, and the extent to which the input is used in consumption and production. This feedback loop plays a crucial role in deepening the sensitivity of prices to local demand conditions.

Energy prices are determined by a combination of factors, including the price and quantity of electricity, oil, and the total energy consumption. In our sample, the increase in the price of oil still exerts a dominant influence on overall energy prices. This dominance arises because the quantity of oil in the energy bundle is significantly greater than the quantity of solar and wind electricity. As a result, changes in oil prices have a more pronounced impact on the overall energy price equation. To provide empirical support for these explanations, we expand our baseline VAR to include oil and solar prices and quantities as well.[12] Fig. 3 illustrates the responses to the tech support policy shock of these variables. The results show that a shock to technology support policies generates a substitution in the energy mix as expected. However, given that fossil fuels still represent a predominant portion of the energy price composition in our data sample, the observed net result of an increase in total energy prices of Fig. 2 is not surprising.

Finally, notice that the above analysis does not make justice to the multifaceted nature of the relationship between technology support policies and energy costs. As also discussed elsewhere (Panetta, 2022), there are several other channels that can explain the implications

[12] Energy quantities (oil and solar) are measured as primary energy consumption by source, the units are expressed terawatt-hours (TWh). Data on energy prices and consumption is downloaded from *OurWorldInData.org*.

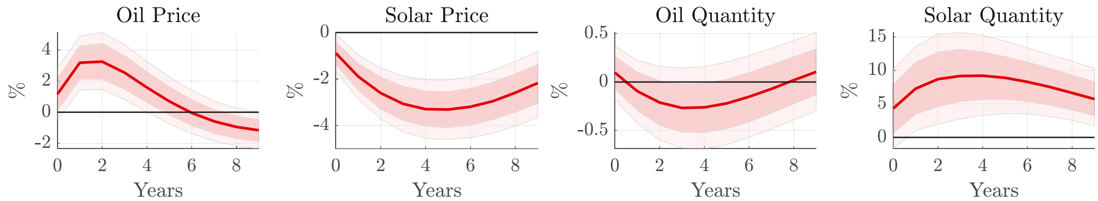

Fig. 3. Impulse response functions of a shock to Technology Support Policy: the energy mix.

of technology support policies on energy prices. These channels include factors like policy uncertainty, market adoption, and investment costs. Policy uncertainty lowers expected demand, which makes future payoffs highly uncertain and compresses investment in fossil fuels, leading to higher prices. Market adoption of renewable technologies may initially raise energy costs due to implementation expenses but could lead to long-term price reductions. The transition period from fossil to renewable sources can cause coexisting higher energy prices. Other factors, such as resource competition, labor costs, subsidies, intermittency, and grid integration, regulatory complexity, and market power, can further influence energy prices.

In conclusion, for some environmental policy instruments (notably carbon prices more than technology support measures) we do not find substantial disruptive effects on the real economy, with an almost perfect offsetting between (negative) demand-side and supply-side effects. Results are instead more clear-cut for shocks to policy instruments that induce a change in environmental technology. In the next subsection, we explore in more detail the implications of a shock to green innovation.

4.1.2. The effects of green innovation

We report the results of a shock that exogenously increases climate change mitigation technologies in Fig. 4. The impulse responses are very much consistent with the effects of a shock to the stringency index, in particular with those stemming from its non-market-based and technology-compatible policies, i.e. those types of policy instruments that stimulate green investment – either directly or indirectly via emission limits – more than putting a price on carbon emissions. Although the identification scheme implies that this shock is an exogenous increase in environmental technology that is not induced (or supported) by a contemporaneous increase in environmental policies or public green investments, the chart confirms that green innovation and environmental policy can reinforce each other – as indicated by a positive response of the policy index already one year after the shock.

Now, one could argue that a clear distinction between the effects of this shock and the ones due to the policy (especially the technology support) cannot be made, and, therefore, that the two shocks are in fact the same shock. In a counterfactual exercise, we shock the environment-related technologies while engineering a sequence of other shocks that offset the IRF of EPSI and set it to zero over the whole horizon. The effect on the macro block does not change drastically, suggesting that the effect of technology on output and prices does not pass through the increase of policy or government investments. The result of this counterfactual exercise is shown in Figure A.8 of the Online Appendix. In the robustness Section 4.3 we also propose a different identification approach that can better disentangle a shock to policy from a shock to green technology which confirms this result.

Fig. 4 also shows that a change in green innovation induces a reduction both in the level of emission intensities and in the cost of environmental degradation over the business cycle. While the immediate and persistent response of environmental degradation to a shock to Mitigation Technology may seem surprising, it can be explained with three sets of arguments. Firstly, the observed decrease in environmental degradation is relatively modest, approximately −0.3 percentage points from the baseline. In the variable's scale and the range of environmental factors it encompasses, this decrease may not be considered unusually large. Secondly, a shock to mitigation technology implies the immediate implementation of various measures aimed at reducing environmental impacts. It is important to recognize that these measures can have simultaneous implications not only for climate (air quality) but also for water quality, job safety, and waste management. Therefore, a contemporaneous (over a year) reaction of environmental degradation to mitigation measures is plausible, as these measures have multifaceted impacts on various environmental dimensions. Lastly, the observed response could also show a positive development, namely, the growing recognition of environmental costs within the community. As awareness of the environmental consequences of human activities increases, there may be a more proactive and immediate response to mitigate these impacts. In this sense, the contemporaneous (one year) reaction to mitigation measures suggests that society is becoming more conscious of the need to deploy new technologies effectively to reduce environmental burdens.

This combination of results from the climate system, although stimulating the business confidence, has a negative effect on employment and on output between 2 and 10 years (after an initial insignificant impact) and a significant effect on all price levels with different signs and dynamics: the price of energy increases faster and more forcefully with a peak between one and two years; food prices peak positively after three to four years and react in a more persistent manner; core prices react somewhat negatively and persistently over the entire horizon. All together, these effects suggest that the technological transition to low-carbon emission can come at the cost of diverting resources from current productive activities to mitigation investments, mostly impulsed by government and corporations. Governments pushe new investment opportunities (as a consequence of the endogenous increase in policy mitigation). After about four years, the private sector also takes them up, following a positive reaction of business confidence that takes some time to dissipate the 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). Households' investments continue to be crowded out after an initial positive reaction, perhaps because the more stable prospects of green innovations turn obsolete several available durable goods.

Overall, these results provide preliminary evidence that a shock to environmental policy, even though it acts as a supply shock (especially on the energy sector) increasing prices and reducing output, mitigates the effect of climate change and, at least for non-market-based policy instruments, has the potential to boost economic activity. However, the results of a shock to green innovation (or to policies that support and induce green technologies) suggest that, if innovation is not supported from the supply- and demand-side by the right policy mix, 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 over the medium run.

4.2. Physical risks

We now turn to the results of a one-standard-deviation shock to our proxy for physical risks (Fig. 5), identified as a shock to the welfare cost of premature deaths due to environmental degradation (our damage function), in absence of a contemporaneous reaction of environmental policy, green innovation, and GHG emission intensity. The charts show

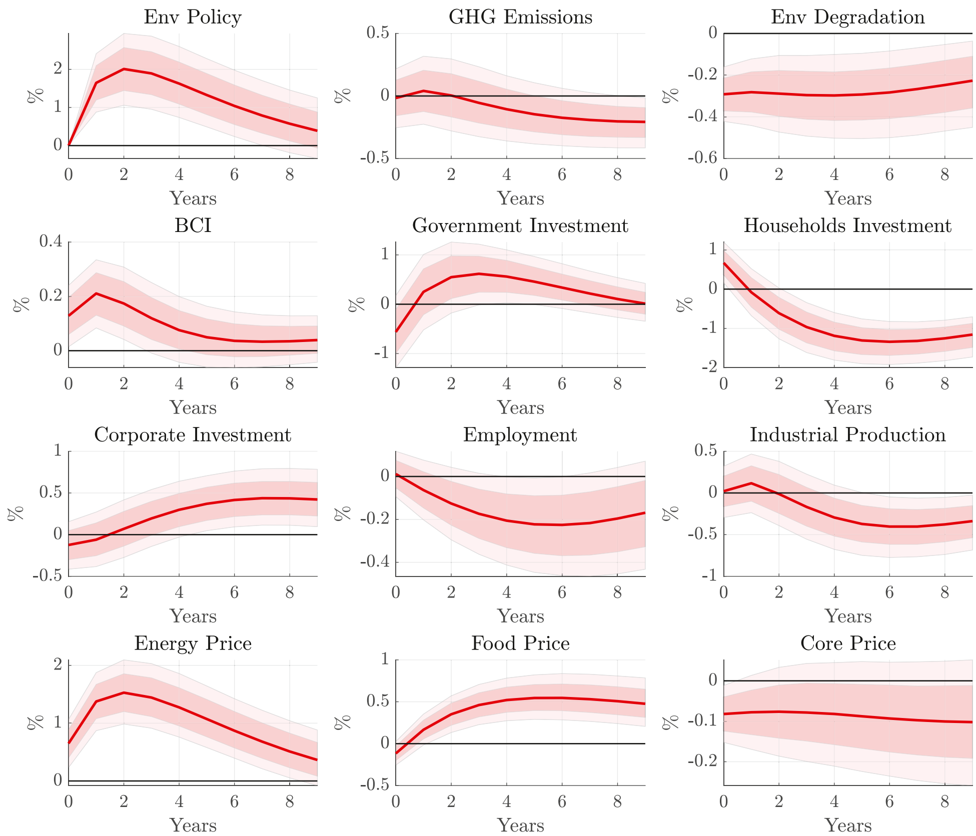

Fig. 4. Impulse response functions of a shock to Mitigation Technology.

that, in the climate block, such a shock generates a positive impact on emission intensity and a negative impact on policy and green innovation in the years after the initial shock. The responses of the other climate-related variables reinforce a (slow-moving) deterioration of climate conditions and physical risks in an environment that is not only not protected by green policy or innovation efforts, but that is also worsening because of the additional intensity of GHG emissions. This increase in emission intensities is of particular interest. The reinforcing link between emissions and welfare costs is not surprising over a long time span but is perfectly plausible also in the short-to-medium 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 negligible economic cost (OECD, 2016).

The shock to physical risks and the described effects on the climate block induce on the macroeconomic block a reaction that is equivalent to a strong negative demand shock: (1) It depresses expectations as embedded in business confidence; (2) It increases temporary corporate investment while crowding out government and household investments; (3) It has a negative and significant impact on employment, output, and prices. While the effect on production is fast – with a negative sign at impact – and relatively "short-lived", the responses of all prices typically peak between 5 and 10 years and are much more persistent. Also, notice that this shock's negative effect on production and prices ensures it cannot be confused with a technology shock or any other (positive) shock to economic activity that causes emissions to increase and the environment to deteriorate.

To further qualify the above results, we conduct two policy scenarios. In the first exercise we build a shock to environmental degradation such that the responses of environmental policy and green innovation are shut down over the entire horizon. In the second exercise, we identify with sign restrictions a physical risk shock that increases environmental degradation and imposes a positive reaction to the responses of environmental policy and green innovation. Fig. 6 reports the results. In the first scenario we want to simulate a world where there is no response at all from the policy side to the deterioration of environmental conditions, on the other side we want to see how the effects on the macroeconomy differ when mitigation efforts are in place. The first scenario (left panel of Fig. 6) confirms the baseline results with a negative demand-type effect on output and prices. More interestingly, the second scenario (right panel) shows that the negative effect on the macroeconomy due to the environmental degradation can be mitigated by policy interventions at least on relative prices, and that, if policy and innovation react to counteract a physical shock, energy and food prices increase similar to a standard supply-type of shock.

In order to gauge how strong the expectation channel can be, we performed an additional counterfactual exercise where we create a shock to environmental degradation such that it does not have a (negative) effect on business confidence, i.e. shutting down the response of the variable BCI over the whole horizon. 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. Figure A.9 in Online Appendix shows the responses of such a shock.

4.3. Robustness analysis

To check the robustness of our results, we perform five additional exercises about the model specification and the identification assumptions. Specifically, regarding model specification, we estimate the model by (1) removing the linear trend; (2) using two lags instead of one; (3) splitting the sample to check for possible structural breaks; and (4) experimenting with different proxies for real activity and for physical risks. With respect to the identification of the shocks of interest

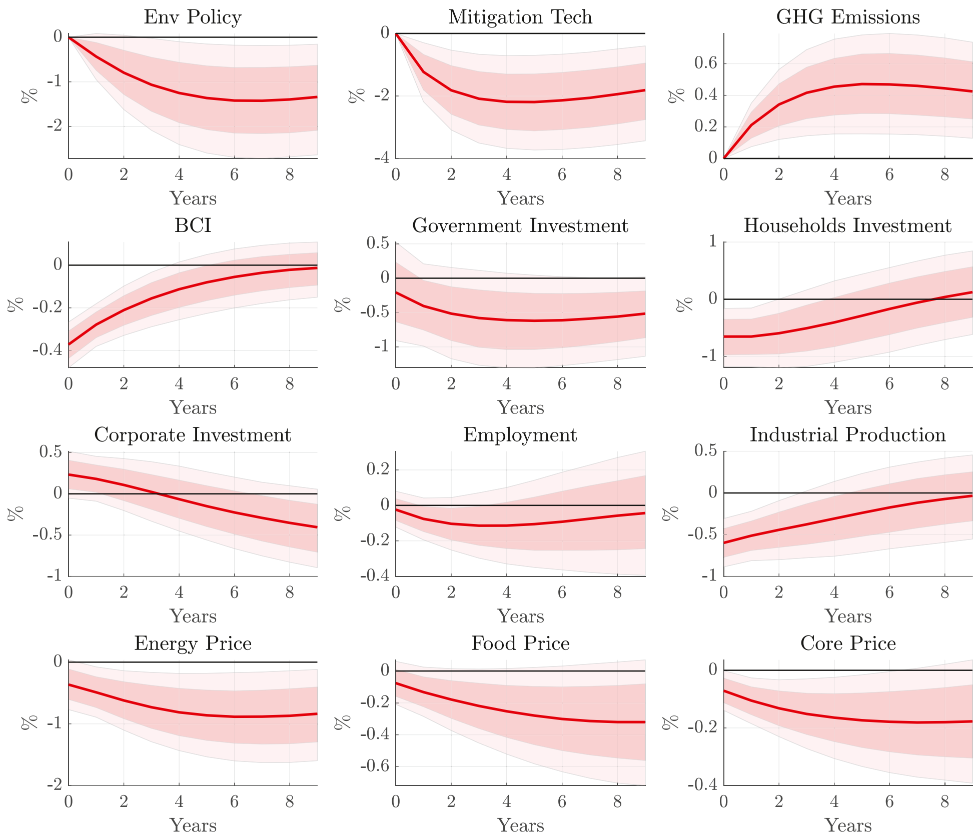

Fig. 5. Impulse response functions of a shock to Environmental Degradation.

we (5) change the variable ordering in the Cholesky identification scheme, we identify the shocks with two additional strategies: (6) the generalized *Max Share* from Carriero and Volpicella (2022) and (7) by using sign restrictions; All figures describing the robustness checks are reported in the Online Appendix A.

Regarding (1)–(2) the results turn out to be very robust to alternative choices (see Figures A.17–A.22). Regarding (3), to check for 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 only over the sample (2008–2019), i.e. after the great recession and the financial crisis. Over this period, as we know, the data show some visible changes that could be key to understanding our findings. Results (see Online Appendix, Figures A.23–A.25) do show some interesting changes in that, after the great recession, a shock to policy stringency can reduce emissions more and earlier than before but at the mere cost of crowding out government investment and green innovation and at expenses of business confidence. After 2008, however, a shock to green policies stimulates private investment earlier than before, which affects positively industrial production in the very short run, and has a less persistent positive impact on energy prices. We find very similar results for a shock to Mitigation Technology, while a shock to environmental degradation overall behaves more like a negative supply shock and increase energy and food prices. Some of these changes with respect to the baseline, such as the reduction in green innovation and negative effect on confidence are consistent with the view that right after the great recession public's concern about climate change declined, and that the "crisis of confidence" in climate change can rebound only after business cycle conditions, and the labor market in particular, improve (see e.g., Scruggs and Benegal, 2012). Finally, baseline results are also robust if we use the GDP level as an alternative measure of output, and temperature anomalies as an alternative measure of Physical Risks (4). Results are reported in Figures A.32–A.37 of the Online Appendix. When using temperature anomalies the only notable difference with the baseline results after a physical shock is the immediate increase of household investments (with other results remaining qualitatively similar), which is consistent with the fact that households respond to an increase in temperature by an increase in electricity usage in response to temperature shocks (Ciccarelli et al., 2023).

With respect to the robustness check (5) on the identification assumption and the variable ordering, Table 4 in the Online Appendix reports the correlation matrix of the reduced-form residuals of the model. The table allows to identify for which variables the Choleski ordering still leaves some significant correlations. For instance, environmental degradation appears to still have some correlations with the climate block variables. For this reason, we perform the first order check using environmental degradation as the first variable in the model. The second check is to place the macro block before the climate block, in line with the circular scheme that typically starts with economic activity having an impact on emissions and, therefore, on climate. Results are again very robust to all ordering checks, as shown in Figures A.26–A.31 in the Online Appendix.

To better disentangle the two shocks to transition risks, e.g., Env Policy and Mitigation Technology, we have employed a novel approach inspired by Carriero and Volpicella (2022). Specifically, we have disentangled the effects of two key shocks: Environmental Policy and Mitigation Technology, using their Generalized Max Share identification method. This approach extends the conventional Max Share identification to simultaneously disentangle multiple shocks in Structural Vector Autoregressions (SVARs). The advantage of this approach lies in its ability to handle the potential endogeneity of Environmental Policy and Mitigation Technology while separating their effects.

The identifying assumption at the heart of the strategy is twofold. First, both shocks should maximize a function capturing the total variation of the three key variables in the Forecast Error Variance Decomposition (FEVD). This means that the shocks aim to explain as

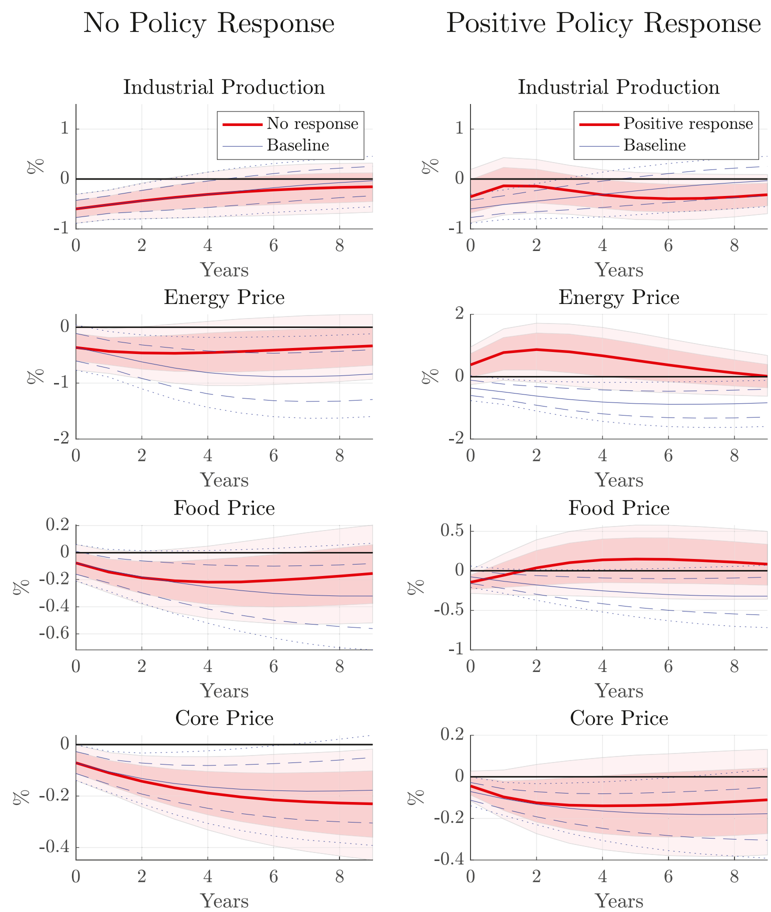

Fig. 6. Impulse response functions of a shock to Env Degradation: 2 policy scenarios.

much of the variation as possible in all three variables, acknowledging that the shocks may be interrelated. Second, each shock must explain more of the variation in its corresponding target variable than the other target variable. For example, the Environmental Policy shock must explain more of the variation in EPSI (Environmental Policy Stringency Index) related to market-based policies than in Mitigation Technology.

Our findings, as presented in the Online Appendix (Figures A.10–A.11), illustrate the IRFs of a shock to Environmental Policy (specifically, tech support policies) and a shock to Mitigation Technology, compared against the baseline results where the shocks are identified using the Cholesky decomposition. Notably, the IRFs in both cases exhibit substantial overlap, showing that a shock to Environmental Policy, identified to maximize the FEVD of both Environmental Policy and Mitigation Technology, explains 100% of the FEVD of Environmental Policy. This result lends powerful support for the validity of the Cholesky identification, despite the greater flexibility inherent in the Generalized Max Share identification.

For enhanced robustness, we extended our identification strategy to include also sign restrictions, as detailed in the Online Appendix (A.7). Results for a shock to physical risks has been discussed above (Fig. 6). The ones for a shock to transition risks are also in line with the baseline, with a less negative impact on production. To identify a shock to transition risk, we imposed four distinct sign restrictions, whereby a positive shock to transition risks is assumed to:

1. simultaneously increase Environmental Policy and Mitigation Technology at impact;
2. simultaneously reduces the values of Environmental Degradation and GHG emission intensity.

The purpose of these assumptions is to vaguely mimic a ‘holistic’ global scenario, which includes a comprehensive set of policies covering both the regulation and the technological impulse needed to achieve a transition. In turn, these impulses should have a visible prompt impact on the environment, which could be necessary to push the subsequent levels of deployment.

Because this analysis checks how robust the main results are to a recursive identification scheme, we are deliberately agnostic about the expected signs of the macro variables.[13] The results reported in the Online Appendix (A.7), however, are remarkably consistent with our baseline findings and with the robustness check based on other identification strategies, such as the Max share explained above, confirming the main narrative of the paper.

4.4. Summary of the findings and interpretation

To conclude this section, we can summarize and interpret our findings through the lens of the discussion on the channels we have entertained in Section 2.

First, to answer the very first question that we ask, our results robustly show that climate related shocks have a significant effect on the business cycle. Nevertheless, the forecast error variance decomposition (FEVD) (see Table 3 in the Online Appendix) shows that their magnitude is not so sizeable to imply that they are to be regarded as

[13] As rightly pointed out by one referee, it is important to acknowledge the potential pitfalls of such agnostic sign restrictions, e.g. Wolf (2022) – who shows that in sign-based identification linear combinations of other shocks may be misidentified as the shock of interest especially if only few restrictions are imposed in a large VAR – or Baumeister and Hamilton (2020) – who explain why sign restrictions alone might not even be enough to allow us to answer the question.

strong direct sources of business cycle movements. Even though the effect on the business cycle is small, the importance of the climate shocks can become more substantial over a longer cycle in line with the idea that climate change's economic implications are bound to become more and more significant in the long run if no mitigation and adaptation actions are taken.

Second, it is important to recall that in our simple set up we do not have extreme weather events or natural disaster associated with climate change. 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 with climate change act as (negative) supply-side shocks or as a combination of both negative supply and demand shocks through a number of different channels. The effect of these shocks on production or output is certainly negative at least in the near term. Our results are consistent with this simple fact. 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 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 us turn to what the literature identifies as transition risks, namely the risks associated with introducing 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. Our results are consistent with the view that the combination of green policy and investment shocks reflect downward supply pressures more than demand movements, especially for a shock to technology or to technology-inducing policies which give rise to a significant downward impact on production and significant positive impacts on sectoral prices. The effect of market-based policies instead seems to be much more ambiguous and certainly less negative on production than a shock to green technology over the business cycle.

Notice that this evidence is very much supported by and consistent with the expectations of large European firms. In a recent ECB survey, over 80% of responses show that the overall impact of the green transition in terms of climate change and related policies will be to increase investment, costs and prices, especially during the transition phase (Kuik et al., 2022). We will discuss the implications for policy makers and modellers in Section 6.

5. Country-specific characteristics

So far, we have documented that shocks to transition risks put an upward pressure on prices while shocks to physical risks put a downward pressure on prices and output. The aim of this section is to examine whether 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. The results of this section can help provide stylized facts relevant to policy makers that might improve our understanding of climate shocks transmission to the global economy. We estimate the baseline VAR model by groups of countries homogeneously chosen based on 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 in the Online Appendix illustrates the different groups. We pool 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. We discuss a selection of results below.

5.1. 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 efficient revenue recycling is adopted (Braennlund and Gren, 1999). As argued in Section 3 and illustrated in Figure A.1, 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 question we ask, therefore, is: how does the adoption of a carbon tax change the macroeconomic effects of environmental policy-related shocks?

Before answering the question, notice that, conditional to acknowledging that the countries included in this analysis are overall the largest emitters in the world, countries that have introduced a carbon tax are also the same who are categorized as low emitters in the sample. This is an important remark: when considering transition risks, such as sudden adoption of environmental policy or diffusion of a specific new green technology, we must also look at which countries are more at risk. The literature and the general debate consider that countries with the highest GHG emissions are the ones whose economies are most likely to be more exposed to a faster and disorderly transition in order to reach their climate targets.

Fig. 7 shows the macroeconomic responses to an environmental policy shock when we run the VAR for two sets of countries, according to whether they have implemented a carbon tax (low emitters, blue line) or did not adopt a carbon tax in the time span of our analysis (high emitters, red line). Five sets of differences seem to emerge. First of all, when countries have a carbon tax in place, the same sudden policy shock does not need to be as persistent as for the high emission countries with no carbon tax. However, this additional policy is enough to stimulate green innovation in virtuous countries much more than in countries with no carbon tax, and to induce a much stronger and persistent decrease in emission intensities. Second, countries with low emissions and a carbon tax have a significantly higher confidence in the near future business performance than countries without a carbon tax and high emissions. Third, when a carbon tax is in place, the possible recycling of its revenues would initially encourage households' investment, which will only later be crowded out by government and private investment. Instead, for high emitting countries with no history of carbon tax, an unforeseen shock in environmental policies implies only a response of corporate investments, with a quite negative

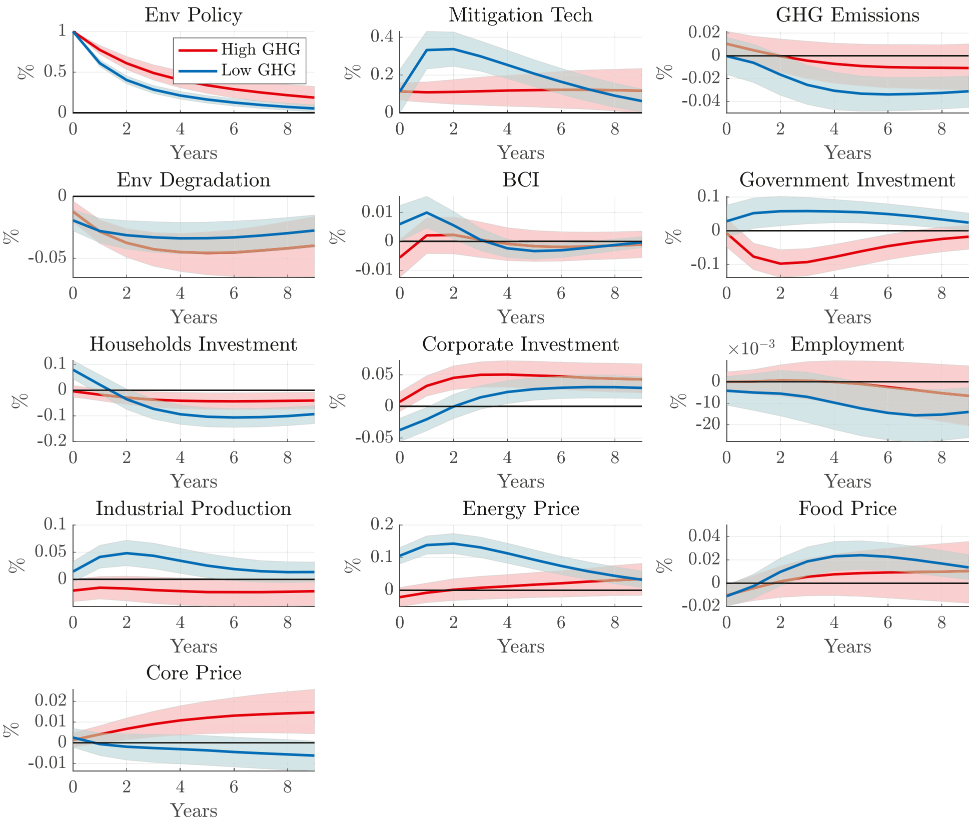

Fig. 7. Impulse response functions of a shock to Environmental Policy: Carbon Tax/Low Emissions vs. No-Carbon-Tax/High Emissions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

effect on government investments, signalling the lack of historical government intervention for those countries. Fourth, consistently with e.g. Metcalf and Stock (2020) and Braennlund and Gren (1999), in countries with a carbon tax and low level of emissions, the real effects on the economy are much less negative, and although with a more visible net job destruction, productivity increases due to a positive reaction of industrial production whereas in high emission countries production declines persistently. Finally, the price of energy increases more significantly for countries with a history of carbon tax whose firms have to face an even tighter price on polluting. However, this does not translate to a higher impact on core prices. In fact, core prices increase substantially and persistently in countries with no carbon tax and higher emissions. This evidence, together with a negative response of real activity, reinforces the view that a disorderly transition can act as a strong negative supply shock for high emitters.

5.2. Gross national income

Climate changes affects low-income communities and developing countries more than advanced economies because of 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, Fig. 8 reports the impulse responses to a shock to mitigation technologies for low- (red) and high- (blue) income countries. Several differences are noticeable. For high income countries, an increase in green innovation improves the business confidence more than in low-income countries. This is associated with higher corporate investments in high-income countries which crowd-out households investment much more than in low-income countries, possibly due to substitution effects and a sensible reduction of durable goods based on soon-to-be obsolete technology. Third, labor market adjustments to new green technologies seem to have a more negative effect on employment in the low-income group, although not statistically significant. Industrial production is also more or less unchanged over the medium-term. Finally, while in high-income countries a shock to green innovation translates into a relative price effect, for low-income countries total prices increase, confirming a strong supply-side effect of the green transition in countries that are supposedly less prepared to receive it.

5.3. Exposure and vulnerability to climate change

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 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 levels of vulnerability. To define which countries are most exposed and vulnerable, we rely on a measure called World Risk Index. 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).[14]

[14] 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.

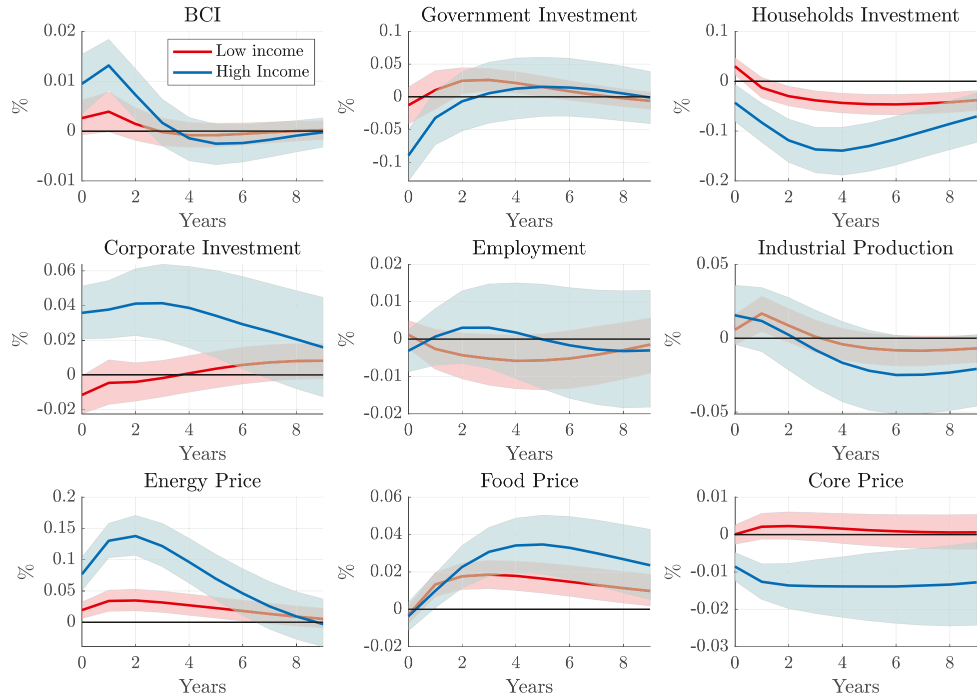

Fig. 8. Impulse response functions of a shock to Mitigation Technology: High Income vs. Low Income. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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.[15] We report results to a shock to environmental degradation in Fig. 9 where we plot the impulse responses of high-risk (red) and low-risk (blue) countries. One notable result is that the responses of prices in high-risk countries are all more persistent than in low-risk countries. The demand-side effect of the shock (with a strong negative effect on all prices, especially core prices) is strongest for countries with a high exposure to natural disasters and a higher vulnerability to them. By definition of the WRI, countries are categorized based on their historical exposure in the last 30 years as well as in terms of their vulnerability, susceptibility, and adaptive capacity. Hence, these results suggest that for countries at high risk (which are 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 results. Similar negative results for output and employment are found by Kim et al. (2021) when analysing the macroeconomic effects of extreme weather shocks. 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 because they lack the needed infrastructures or suitable private and public insurance schemes.

[15] 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 comprises three components: susceptibility, coping and adaptation, see Figure A.6 in Appendix. The composition of the index is described in greater details in the methodological notes available at www.WorldRiskReport.org/#data.

6. Discussion and policy implications

We have motivated our paper claiming the relevance of this type of research for policy makers and modellers. From a central banking perspective, the interesting question is to what extent climate change and policies can not only change the monetary policy strategy but also imply additional trade-offs to be managed, over the short and the medium run. For economists and modellers, evidence on the interaction between climate change and the economy establishes empirically validated assumptions for the models.

The results presented above seem consistent with facts about the relationship between climate and the macroeconomy which can indeed have important implications for modellers and policy makers. The first robust finding is that climate change and policies to counteract them have a significant, albeit not sizeable, effect on the macroeconomy over a business cycle horizon (i.e., between 2 and 8 years). This implies that climate change not only is a concern for government and fiscal authorities, but it can also imply the need for monetary authorities to modify their reaction functions accordingly. More concretely, the data of this analysis supports the view that physical risks are consistent with developments that push prices and activity in the same direction, whereas the final impact of policies and technology is positive on prices and negative on output. Therefore, while physical risks are more associated with demand-type shocks, transition policies and technological improvement might be more consistent with supply adjustments. In other words, the green transition creates an additional trade-off to central banks, as conventional (and unconventional) monetary instruments are designed to act on output and prices in the same direction. Depending on the persistence or entrenchment of the consequences of these shocks on inflation, the monetary authority may flexibly decide to intervene or to look through the shocks, and allow inflation to deviate from the target in the short term.

Our results also go a bit further. One of our findings is that, overall, a combination of climate policies has strong positive effects on energy and food and a moderate or even negative effects on core prices. Ultimately a combination of these policies seems to affect relative prices only. To the extent that these shocks are not dissimilar from

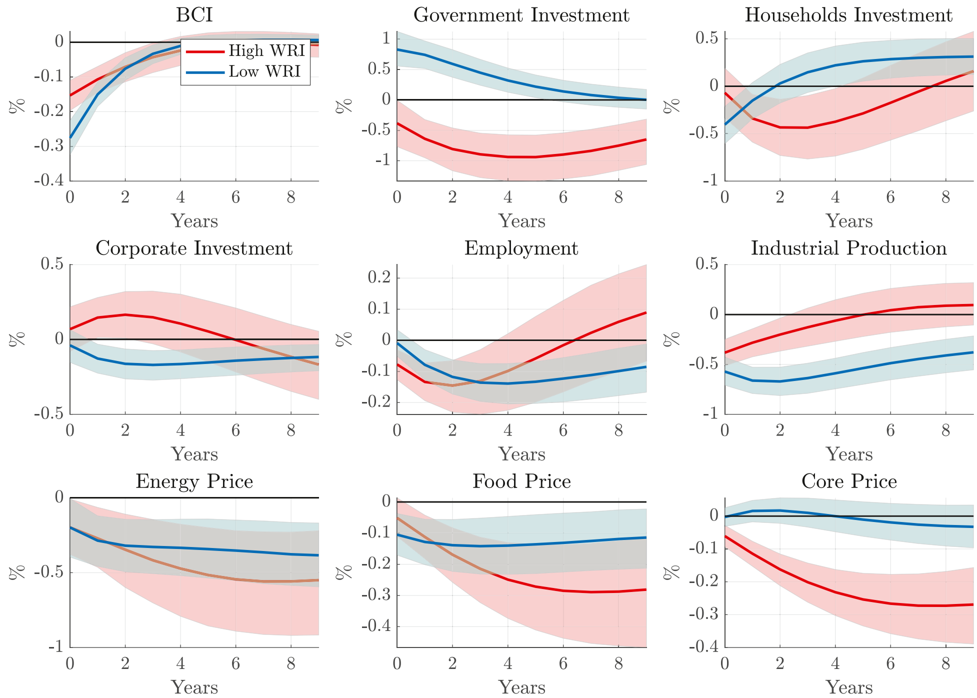

Fig. 9. Impulse response functions of a shock to Environmental Degradation: High risk vs. Low risk countries based on the World Risk Index. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the usual relative price shocks of the past, the monetary authorities will let the economy adjust without intervening. However, as also stressed by a recent report of the Bank of England, the relative price shocks associated with the transition to net zero may be different from the types of shocks that the central banks have faced in the past. Concretely, "the price of carbon (whether set via a tax, emissions trading scheme, or other means) rises steadily over time. Therefore, it is possible that the impact on inflation may become generalized and persistent" (Angeli et al., 2022).

When it comes to the green transition, an important qualification that we make in the paper has to do with the types of policies. When economists talk about climate policies one of the immediate associations is with carbon prices: If the emitted CO2 is costly, we typically produce less of it. Therefore, carbon pricing is one of the most effective ways to reduce emissions because it eliminates a market failure directly at the source by pricing the emission costs. However, carbon prices are only a limited fraction of the whole set of policies,[16] and our results show that different climate policies affect prices and quantities very differently, with technology support being the only 'pure' supply shocks, while non-market-based policies can generate a positive response of output and energy prices and can have a negative effect on core prices.

Another fundamental caveat – for both economists and policy makers – is that results differ according to country-specific (institutional and economic) characteristics as well as to their different degrees of exposure to risks and vulnerabilities. In countries with little or no history of environmental policy and where the level of emission intensities is relatively higher, a shock to aggregate climate policies (including a mix of market, non-market, and technology) behaves like a pure supply shock with a persistent increase of all prices. 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 introducing new policies or technologies to mitigate them are more contained. These findings reinforce the view that a disorderly transition can certainly have negative effects over the medium term.

These results give several important messages to both modellers and policy makers. Available models give somewhat plausible but ambiguous responses depending on key modelling assumptions about, e.g., expectations or policy rules (see e.g. Ferrari and Landi, 2022 for deflationary effects of the green transition). They have other limitations: (i) they only focus on one policy measure, namely carbon taxes; (ii) their conclusions are very uncertain and depend on different (but all plausible) assumptions on the relative importance of various channels that can generate either inflationary or deflationary dynamics; anyway (iii) their calibration is based on a history with little or no climate transition and very low carbon taxes. Our results also suggest that we need more sophisticated and complete models which include various forms of heterogeneity (across countries and sectors) as well as more realistic designs of the scenarios. Models should notably consider other features of the green transition that include not only carbon tax but also other types of policies, green technology, and climate shocks. Moreover, they also need empirically validated facts based on all ingredients and general equilibrium considerations as well as non-linearities in their response to physical and transition risks.

Our results definitely confirm that climate change and policies have macro implications that are relevant for central banks, the conduct of monetary policy, and financial stability. Climate risks may complicate the correct identification of shocks relevant for the medium-term inflation outlook, making it more difficult to assess the monetary policy's stance. Therefore, the strategy of some central banks (notably the ECB) includes now climate change considerations: climate change and policies imply additional constraints in the usual trade-offs for central banks and may affect the transmission mechanism of monetary policy by changing the demand side (e.g. consumption and investment decisions) via several channels (e.g. business confidence and the uncertainty around the nature and timing of the structural transformation implied by the green transition can reduce the sensitivity of demand to

[16] The OECD policy stringency index that we have used in the analysis – conveniently split according to the various sources of policy measures used by countries – shows very precisely market-based policies have been more than doubled in terms of stringency by non market-based and technological support policies over the last 30 years (see Figure A.3).

conventional policies). The optimal Central Bank response to climate risks at a given time will clearly depend on the projections of the state of the economy at medium term given initial conditions (e.g., the inflation rate at the time), using all available information (Breckenfelder et al., 2023).

From a more general policy perspective, our results support the idea that one size does not fit all, and suggest instead the need for a 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 cause 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, but with some heterogeneity due to GHG emissions, carbon tax recycling, or other institutional and economic factors.

The comprehensive analysis and discussion presented herein hinge on the currently available data and established concepts. Given the rapid evolution of our society, the very metrics that have conventionally gauged the prosperity and well-being of nations are poised for transformation. Our findings, while valuable, are inevitably susceptible to the integration of novel concepts such as resilience, biodiversity, and degradation into the assessment of our primary reference variables. Notably, emerging notions like "Economic Resilience" are pivotal for the trajectory ahead. Only through the incorporation of reliable metrics for these concepts can we gauge the adaptive capacity of our economies to navigate change, achieve environmental and social objectives, and surmount both conventional and contemporary challenges.

The introduction of new data concepts is firmly advocated by several think tanks who argue that GDP per capita is already an unreliable indicator of economies' capacity to recover from crisis. Using a newly developed economic resilience index, for instance, the ZOE Institute confirms some of our results. In particular, not only do they show that there are big differences in how well EU economies can absorb, recover from, and adapt to shocks depending on their resilience, but also they argue that "countries already hit hardest by crises are least prepared for future challenges".[17]

7. 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 that combines exposure and vulnerability to climate change and environmental degradation, climate mitigation policies and adaptation technologies. In so doing, we handpick 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 change 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 shocks, while transition policies and technological improvement are more consistent with supply adjustments. Results also differ according to country specific institutional and economic characteristics and 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 more contained.

These results support the idea that one size cannot fit all and would therefore suggest the need for a (possibly country-specific) 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 to climate policies would therefore also 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).

CRediT authorship contribution statement

Matteo Ciccarelli: Conceptualization, Methodology, Data analysis, Writing – original draft, Writing – reviewing & editing. **Fulvia Marotta:** Conceptualization, Methodology, Data analysis, Writing – original draft, Writing – reviewing & editing.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2023.107163.

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