UNIVERSITY OF MILAN AND UNIVERSITY OF PAVIA

Essays on Energy and Climate Change Economics

Ph.D. Thesis

Author:
Giacomo Novelli

Supervisors:
Professor Marzio Galeotti and Professor Alessandro Olper

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Ph.D. Coordinator:
Professor Eduardo Rossi

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Chapter 1

Introduction

Coping with climate change implies a dramatic reduction in carbon and energy intensity, which may cause turmoil in the energy production and energy-related economic sectors. Indeed, carbon dioxide (CO_2) emissions represent 75% of the greenhouse effect (Atasoy (2017), Sirag et al. (2018)) and the vast majority of greenhouse gases (GHG) are energy-related (Fuentes et al. (2020)).
Despite all the difficulties, this challenge cannot be postponed due to the high impact of GHG on global warming and, in turn, on climate change. “As argued by Weitzman (2011), the fattening of the tails — the increase in the probability of potentially irreversible and catastrophic damages — justifies aggressive policy actions to stabilize greenhouse gas (GHG) concentrations in the atmosphere ("climate change mitigation") and adjust to the changing climate ("adaptation").” Acevedo et al. (2020).
Moreover, the CO_2 accumulation in the atmosphere is an extremely inertial process and climate change is accelerating worldwide (Kahn et al. (2019)).
Therefore, decoupling economic growth and polluting emissions is crucial to afford a just and sustainable growth through international cooperation in mitigation and adaptation policies, pursued at global and local level. In fact, sustainable growth is the only affordable path to increasing socio-economic prosperity with a low impact on long-run environmental quality.
As a matter of fact, the last economic downturns, namely the 2008 financial crisis and the Covid-19 pandemic, have not significantly reduced CO_2 emissions' level and concentration (Figure 1.1), causing only a moderate and temporary drop (Peters et al. (2012), Liu et al. (2020)). Indeed, Figure 1.2 shows that the global fossil fuel consumption is still growing over time, having experienced only a slight downturn for the financial crisis. Moreover, Kahn and Kotchen (2010) suggests that recessions may affect the structure of economic preferences, re-ranking the environmental concern as a secondary concern and implying negative consequences, such as policies aimed at boosting a fast recovery, sacrificing the environment. Thus, we should keep that from happening, and rather try to take advantage of these crises to support policies for sustainable and innovative growth.
Actually, 127 countries[1], representing around 63% of GHG emissions, have announced they will be carbon-neutral in the next future. This will imply an extraordinary political and economic effort to design and implement drastic energy, adaptation, and mitigation policies and invest in R&D and international cooperation.

This thesis is an empirical investigation of the macroeconomic impacts of energy policies in the light of the relevant change in the energy policies of most countries that is needed in order to cope with climate change. It also studies the long-run macroeconomic effects of climate change

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[1] Among them: the UK, the EU, Japan, Canada, China, South Africa, South Korea and the US.

in Europe, verifying which are the most affected regions and sectors, and which are the main channels of transmission of temperature and precipitation changes through the economy.

The first chapter is a cross-country empirical analysis aimed at showing that relevant changes in energy policies have effects on the stability and long-run growth of countries. It studies the macroeconomic effects of changes in the energy dependency index, which is an aggregate indicator considering both the energy consumption and energy imports of countries. We show that the energy mix, the energy intensity, and the energy consumption and imports of countries vary significantly, suggesting that a clear divide of countries in clusters is needed to appreciate the effect of energy price changes on their macroeconomic performance.

Specifically, we investigate whether the business cycle of countries with a similar degree of energy dependency shares some basic features - i.e. frequency, duration, and amplitude of recessions and recoveries -, and we analyse their synchronization with the energy price cycle. Furthermore, we study whether the impact of energy price changes on economic growth differs depending on a country's degree of energy dependency.

Therefore, we cluster countries in five groups, based on their degree of energy dependency, finding that the main features of the business cycles of countries clustered in distinct groups are significantly different. However, their business cycles are similarly synchronized with the energy price cycle.

Moreover, using a cross-sectionally augmented panel autoregressive distributed lag (CS-ARDL) approach, we show that major energy importer countries have a negative and significant long-run energy price elasticity of GDP, while major energy exporter countries experience the opposite effect, and the other countries are less or not significantly affected. We contribute to the resource curse paradox showing that the energy price volatility negatively affects the long-run economic growth of major energy importers, but it does not hamper the long-run growth of other countries.

We argue that the impact of energy price changes differs across countries with a different degree of energy dependency and that a balanced degree of energy dependency is preferable. Indeed, countries with a balanced profile of energy dependency experience shorter and shallower recessions, and the economic growth of major energy exporter and importer countries is much more affected by energy price changes.

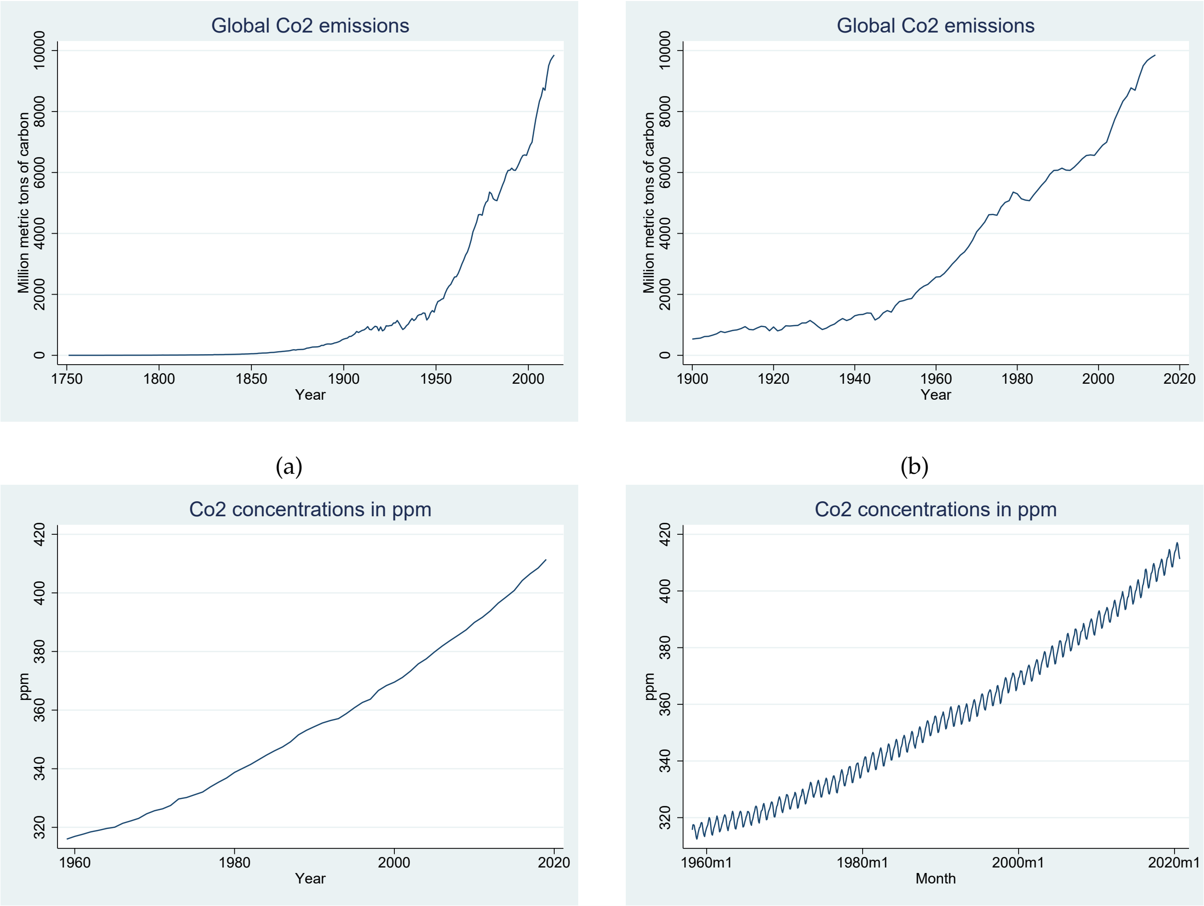
The second chapter studies the macroeconomic effects of climate change in Europe, verifying which are the most affected regions and sectors and which are its main channels of transmission through the economy.

We investigate the long-term macroeconomic effects of climate change on output and labour productivity of European industrial sectors, using a panel data set composed of the 281 European regions at NUTS 2 administration level from 1980 to 2017. Moreover, we analyse the main transmission channels through which climate change influences European economic activity, shedding some light on its impact on investments, employment and hours worked.

Overall, we do not find evidence of adverse or favourable effects of climate change on European economic growth at aggregate level, although all sectors and regions are diversely influenced by temperature and precipitation variations from their historical norms. Furthermore, we study the climate change effects in more and less developed regions, finding that the two sub-samples are differently affected and that the overall impact on economic growth in less developed regions is not higher than in more developed ones.

Finally, we notice that labour productivity is the main driver of climate change effects on growth and that agriculture, construction, and financial services sectors - the latter through the insurance industry - are the most affected sectors. We suggest that European policymakers should take into account all these features in the design of the optimal adaptation and mitigation policies.

Figure 1.1: CO2 emission and concentration levels



(a)

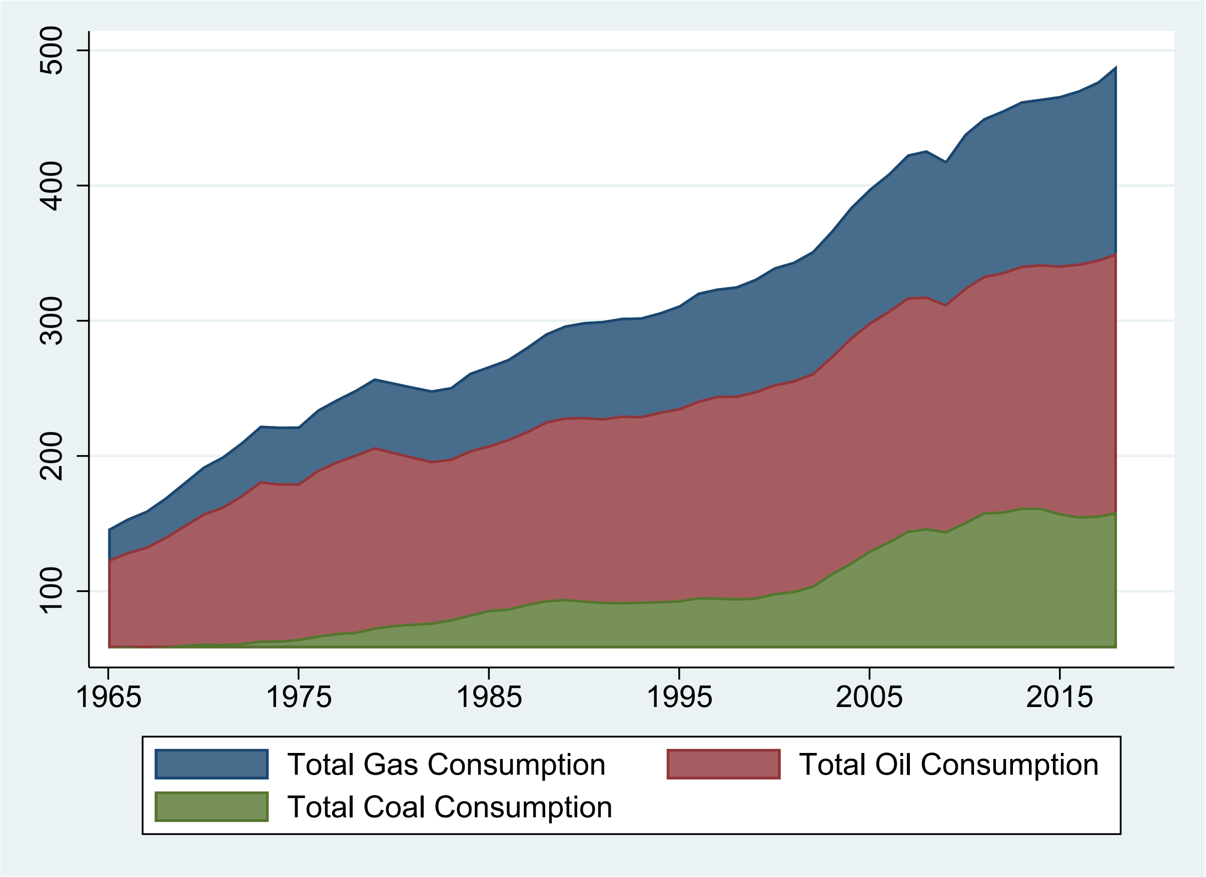
(b)

(c)

(d)

(a) Global Co2 emissions from 1751 to 2014; (b) Global Co2 emissions form 1900 to 2014; (c) Global Co2 concentrations in ppm from 1958 to 2020; (d) Global Co2 concentrations in ppm from March 1958 to September 2020.

Figure 1.2: Total Fossil Fuel Consumption



Total World Fossil Fuel Consumption in Exajoule from 1965 to 2018. Source: BP, Statistical Review of World Energy 1965-2019.

Chapter 2

The role of Energy Dependency on Macroeconomic Stability and Growth

The role of Energy Dependency on Macroeconomic Stability and Growth

Abstract

We investigate whether the degree of energy dependency of countries influences their macroeconomic performance in terms of stability and growth over time. Specifically, we verify if the business cycle of countries with a similar degree of energy dependency shares some basic features - i.e. frequency, duration, and amplitude of recessions and recoveries -, and we analyse their synchronization with the energy price cycle. Furthermore, we study whether the impact of energy price changes on economic growth differs depending on a country's degree of energy dependency.

There are two novel aspects in this paper. First, all energy commodities are considered, not only oil, and second, our work goes beyond the standard distinction between energy importing and exporting countries. We claim that energy importer and exporter countries are too heterogeneous in terms of net energy imports, energy consumption, and level of development to be clustered and analysed together. Therefore, we decide to cluster countries in five groups, based on their degree of energy dependency, finding that the main features of the business cycles of countries clustered in distinct groups are significantly different. However, their business cycles are similarly synchronized with the energy price cycle.

Moreover, using a cross-sectionally augmented panel autoregressive distributed lag (CS-ARDL) approach, we show that major energy importer countries have a negative and significant long-run energy price elasticity of GDP, while major energy exporter countries experience the opposite effect, and the other countries are less or not significantly affected. We contribute to the resource curse paradox showing that the energy price volatility negatively affects the long-run economic growth of major energy importers, but it does not hamper the long-run growth of other countries.

We argue that the impact of energy price changes differs across countries with a different degree of energy dependency and that a balanced degree of energy dependency is preferable. Indeed, countries with a balanced profile of energy dependency experience shorter and shallower recessions, and the economic growth of major energy exporter and importer countries is much more affected by energy price changes. We suggest major energy importing countries should reduce their degree of energy dependency, while major energy exporters may differentiate their energy production, avoiding to rely only on fossil sources.

Keywords: Energy price, Volatility, Energy security, Economic growth, Heterogeneous panel, Institutions.

JEL Codes: C23, C33, O43, Q43.

2.1 Introduction

Energy security is an issue of strategic importance for governments, firms, and households. It is a dynamic and polysemic concept (Chester (2010), Vivoda (2010)), which can be decomposed into seven main issues: energy availability, infrastructure, energy prices[1], societal effects, environment, governance, and energy efficiency (Ang et al. (2015)).
Due to its changing and multidisciplinary nature, energy security is studied by several academic branches, such as political science, sociology, engineering, economics. However, economists have mainly focused on the economic consequences of energy price and supply shocks, finding that such effects can vary across countries depending on several factors, including, most notably, energy dependency.
Indeed, energy dependency is a major concern of all geopolitical players because of the losses and damages caused by energy price fluctuations and supply shortages. Among them, European countries are some of the most exposed to energy dependency risks, being poor of fossil sources and relying on a few suppliers, while not having a common and strong international position. On the other hand, the energy efficiency and energy intensity of EU countries are noticeable, unlike the ones of other industrialized countries such as the US, Canada, and Australia. This is probably an effect due to their structural dependency problem. Indeed, a reduction of energy consumption is a straightforward strategy to decrease energy dependency, via the augmentation of energy efficiency and the reduction of energy intensity. Other relevant strategies consist in diversifying suppliers and energy mix, and limiting the reliance on major energy exporter countries to reduce their market power. A more recent strategy to curtail energy dependency is the augmentation of renewable energy production. Nonetheless, despite the number of potential strategies, only a few countries have committed to these policies.
Thus, energy dependency is still a hot topic, in particular in the US political debate where it has been present since the seventies, regardless of their limited degree of energy dependency with respect to other advanced and emerging countries. This paradigm does not apply to those countries which are major energy exporters, such as Middle-East countries, that are going through a different challenge, i.e. the energy-transition challenge, trying to maintain their competitive advantage when global economies will no longer be carbon-based.
As a matter of facts, the new challenges arising from the recent technological progress in fossil and renewable industries, from climate change and the Covid-19 pandemic have triggered and/or boosted dramatic changes in our societies, which will unsettle the energy global outlook and the inner structure of the energy market. Thus, our societies will have to rethink three deeply connected features, i.e. the economic, the energy, and the environmental features.

In this framework, we study the macroeconomic implications on stability and growth of energy price fluctuations in countries with a different degree of energy dependency. The results of the analysis may help policymakers in the design of optimal macroeconomic and energy policies, which will be needed in the light of a changing world. Indeed, the commitments of 127 countries[2], representing around 63% of GHG emissions, to be carbon-neutral in the next future will have some disruptive effects on global energy security and macroeconomics.
Our analysis is twofold intending to underline the implications of different energy profiles on the macroeconomic fluctuations and growth of countries. First, we study whether the main features of business cycles depend on the degree of energy dependency of countries, and second, we study whether the long-run impact of energy price fluctuations on economic growth is uniform in countries with a different degree of energy dependency.

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[1] The main features of energy price are: energy price level, energy price volatility and the degree of competition of energy markets (Ang et al. (2015)).

[2] Among them: GB, EU, Japan, Canada, China, South Africa South Korea, and the US, as in line with the first declarations of the new president Joe Biden.

There are two novel aspects with respect to existing macroeconomic literature. The first one is that all energy primary sources are considered in the analysis, not only oil. The main feature of this tentative is removing the asymmetries due to diverse energy commodity imports. For example, Australia is a net oil importer but a non-oil energy exporter, and the UK is a net oil exporter but a non-oil energy importer.

The second novelty is that this work goes beyond the standard distinction between energy importing and exporting countries, since we divide countries using quantiles of energy dependency. We have noted that countries composing the energy importer and energy exporter clusters are heterogeneous, in terms of net energy imports, energy consumption, and in terms of level of development. For example, both Italy and the US are net energy importers, but Italy imports 80% of its total primary energy consumption while the US imports just about 10%. A more granular classification should allow us to show whether the stability and growth of countries depend on the degree of energy dependency or not.

This work is composed of two parts studying the role of energy dependency in the relationship between energy price changes and the two main macroeconomic features, fluctuations and growth.

The first one investigates if countries with a similar degree of energy dependency share similar features in their business cycles and if their cycles are differently synchronized with the energy price cycle. The cycles are identified using the Harding and Pagan (2002) version of the Bry and Boschan (1971) algorithm, which finds the turning points of a series. We extrapolate the business cycle from the real GDP series, while the energy price cycle is obtained from the World Bank energy price index. Cashin and McDermott (2002) uses the same techniques and defines commodity price cycles as "movements in the level of commodity price between local peaks and troughs, [...] in line with business cycle dating literature".

The second one investigates whether energy price fluctuations impact differently economic growth depending on the energy dependency degree of a country. Using a cross-sectionally augmented panel autoregressive distributed lag (CS-ARDL) approach, we estimate the long-run effect of energy price changes on GDP growth, relying on a sample clusterization in groups of countries with a similar degree of energy dependency over time.

We produce our analysis using two similar datasets, where the first one is composed of 28 countries with quarterly data and the second one by 48 countries with annual frequency data. The countries composing the first dataset are a subset of the ones in the second dataset because we need long GDP series with quarterly frequency to perform the business cycle analysis, but many Middle-East and Northern-African countries (MENAs) and other African countries have started reporting quarterly GDP series from the late nineties, so we decide to drop them. On the other side, the second dataset is composed of a higher number of countries, such that we can cover the vast majority of global GDP in our analysis.

The rest of this work is organized as follows. In Section 2, we define the related literature this work is based on. In Section 3, we introduce the datasets and the division of countries in clusters, using the degree of energy dependency. In Section 4, we show the main features of the business and energy price cycle of the considered countries and their degree of synchronization. In Section 5, we present the main model. In Section 6, we offer some concluding remarks. In the Appendix, we show some robustness checks.

2.2 Related Literature

This work is based on four streams of literature. The first one investigates the concept of energy security, which is a polysemic and elusive concept, and its main literature references are

Kruyt et al. (2009), Chester (2010), Vivoda (2010) and Ang et al. (2015). In these papers, scholars define and analyse the concept of energy security, using various indexes and approaches. Due to its dynamic and complex nature, there is no broad consensus on its precise definition, therefore, a multitude of indicators is used to study it. IEA defines energy security as "the uninterrupted availability of energy sources at an affordable price. Energy security has many aspects: long-term energy security mainly deals with timely investments to supply energy in line with economic developments and environmental needs. On the other hand, short-term energy security focuses on the ability of the energy system to react promptly to sudden changes in the supply-demand balance. Lack of energy security is thus linked to the negative economic and social impacts of either physical unavailability of energy, or prices that are not competitive or are overly volatile." (IEA (2014)). Moreover, IEA evaluates energy security in terms of oil, gas, and electricity security and in terms of weather, climate, and digital resilience.
The index of energy dependency is one of the most used to investigate energy security, as in Pode (2010), Bortolamedi (2015), Bompard et al. (2017), Radovanović et al. (2018), Matsumoto et al. (2018), Trotta (2019). Besides, Radovanović et al. (2017), Filipović et al. (2018), Bluszcz (2017) focus on the energy dependency situation of European countries, which are among the most energy dependent ones.
We use the World Bank energy dependency index to cluster countries in homogeneous groups and evaluate whether the macroeconomic consequences of energy price fluctuations on stability and growth differ across the clusters.

This work is based on two other streams of literature concerning the methodologies used in our analysis, and it contributes to a fourth stream of literature investigating the resource curse paradox. The first part of our analysis is based on the stream of literature that studies the relationship between business cycles and the financial cycles, and it has had a renewed interest in the aftermath of the 2008 crisis (Claessens et al. (2012) and Jordà et al. (2017)). This stream of literature is based on Harding and Pagan (2002) and Harding and Pagan (2006), where the authors define the basic features of cycles and how to identify them using a new version of the Bry and Boschan (1971) algorithm, that replicates the NBER Dating Committee procedure (Burns and Mitchell (1946)). We use the same methodology to analyse the relationship between the business cycles and the energy price cycle. The cyclical behavior of commodity price cycles has a relevant impact on commodity-exporting and importing countries, as explained in Cashin et al. (2002): “Cycles are a dominant feature of commodity prices, and dealing with them is one of the most challenging issues facing policy makers in commodity-exporting developing countries”. We argue that energy prices affect all countries, so we decide to study both developed and developing countries, and both energy exporter and importer countries.

The third stream of literature analyses the macroeconomic consequences of oil price shocks, focusing on cross-country differences over time. This stream is inserted in a much broader branch of literature which concerns the estimation of the macroeconomic effects of oil shocks in G7 countries or even only in the US. Typically, they estimate reduced-form models arising from economic theory. Kilian (2008) is a must-read literature review of economic consequences of energy shocks, covering micro and macro approaches, demand and supply side point of views, various sources of energy shocks. Moreover, it concerns several energy commodities, but it does not consider cross-country variations. Unfortunately, there are not many papers quantifying the economic effects of energy price and supply shocks across different countries. A nice example is Peersman and Van Robays (2012) which uses a Bayesian structural vector autoregressive model (SVAR) with sign restrictions to identify the different responses to oil price and supply shocks of some advanced countries with a diverse profile of energy dependency, i.e. G7 countries plus Switzerland, Norway, and Spain. They find that the consequences of a rise in oil price caused by rising aggregate demand or oil-specific demand are the same across the considered countries. Nevertheless, these consequences are distinct for energy importing and exporting countries when considering a positive oil supply shock. Moreover, they find that countries improving considerably their energy dependency profile are less damaged from oil supply shocks and oil-specific demand shocks.

Other examples are Cashin et al. (2014), Mohaddes and Pesaran (2016), Mohaddes and Pesaran (2017), Mohaddes and Raissi (2019) which exploit global vector autoregressive models (GVAR). These works estimate country-specific impulse response functions obtained by embedding an oil price equation in a dynamic multi-country model. Although being quite innovative, GVAR models do not fully capture the differences in the degree of energy dependency, diving countries in net oil importers and exporters, without considering any other energy commodities.

The fourth stream of literature investigates the resource curse paradox, assessing that the abundance of oil, or other non-renewable resources, have an unconditional negative long-run effect on GDP growth (Sachs and Warner (1995)). However, recent works, relying on more advanced techniques, show that the problem is not oil or resource abundance *per se*, but its price volatility (De V. Cavalcanti et al. (2011), De V. Cavalcanti et al. (2015), Mohaddes and Pesaran (2016), Jarrett et al. (2019) and Van Eyden et al. (2019)). All these works find empirical support for a negative effect of oil price volatility on growth while estimating a positive effect of a rising oil price. Among them, some analyse the role of institutions suggesting that increasing the quality of institutions, in particular financial institutions (such as sovereign funds), can offset the negative effect on economic growth.

2.3 Data and Empirical Approach

The first part of our analysis is based on quarterly series and investigates the relationship between the business cycle and the energy price cycle of various countries. The second part enriches the analysis studying how energy price changes influence long-run economic growth taking into account for several confounding variables, with annual frequency.

Table 2.1 shows the main variables used in this work, covering both advanced and emerging countries, and energy exporter and importer countries, while Table 2.2 shows the main characteristics of the variables.

Table 2.1: Dataset

Main Variables	Data Source	Frequency
Real GDP in PPP in 2011 US\$, $Y_{i,t}$	Penn World Tables 9.0	Annual
Population in millions, $Pop_{i,t}$	Penn World Tables 9.0	Annual
Real GDP in PPP in 2010 US\$, $GDP_{i,t}$	Mohaddes and Raissi (2020)	Quarterly
Degree of Energy Dependency, $ED_{i,t}$	World Bank	Annual
Energy Price Index, Pe_t	World Bank	Monthly
Energy Price Index Volatility, Vol_t	Author's Calculation	Annual
Institutional Quality, $Inst_{i,t}$	Fraser Institute	Annual
Political Quality, $Pol_{i,t}$	Polity IV Project	Annual

Table 2.2: Overall, Between and Within Variation of the Main Variables

Variable	Mean	Overall Variation	Betweeen Variation	Within Variation
$Y_{i,t}$	12.68242	1.535682	1.480016	0.4609654
$\Delta y_{i,t}$	0.0331254	0.0480651	0.0147091	0.4609654
$ED_{i,t}$	-125.7954	832.8376	438.9374	710.5469
Pe_t	3.672099	0.6123876	0	0.6123876
ΔPe_t	0.0531927	0.2570177	0	0.2570177
Vol_t	0.1705926	0.1630029	0	0.1630029
$Inst_{i,t}$	5.826688	2.227157	1.750744	1.399128
$\Delta Inst_{i,t}$	0.0761624	0.2772663	0.0521334	0.2724225
$Pol_{i,t}$	4.039246	7.85197	6.971444	3.746498
$\Delta Pol_{i,t}$	0.1319742	1.316222	0.1761946	1.304565

The degree of energy dependency is the main variable of the dataset, it is proxied by the World Bank energy dependency index, $ED_{i,t}$, and it is used to divide countries into five groups.

$$ED_{i,t} = \left(\frac{\text{Net Energy Imports}_{i,t}}{\text{Total Primary Energy Consumption}_{i,t}} \right) \%$$

where i represents the country and t is time. The index varies from 100% to $-\infty$, where positive values refer to net energy importer countries, and negative values refer to net energy exporter countries. Net energy imports are estimated as energy use less production, both measured in oil equivalents, and energy use refers to use of primary energy before transformation, which is equal to indigenous production plus imports and stock changes[3]. The Im-Pesaran-Shin unit root test rejects the null hypothesis of homogeneous non-stationarity of this variable (Table 2.3), and Figure 2.1 graphically confirms the substantial stability of its mean and median over time. Moreover, the cross-section dependence (CD) test (Pesaran et al. (2004), Pesaran (2015)) does not reject the null hypothesis of cross-section independence (Table 2.5).

Table 2.3: Panel Unit Root Tests, Energy Dependency Index, 1971-2014

Method	Form	Statistic value	p-value
IPS	lag(AIC)	-1.7700	0.0384
IPS	lag(BIC)	-1.2960	0.0975
IPS	lag(HQIC)	-1.5196	0.0643
F-PP	no lags	4.0603	0.0000
F-PP	1 lag	4.6969	0.0000
F-DF	no lags	4.0603	0.0000
F-DF	1 lag	11.0939	0.0000
IPS	demeaned, lag(AIC)	-38.0806	0.0000
IPS	demeaned, lag(BIC)	-38.0806	0.0000
IPS	demeaned, lag(HQIC)	-38.0806	0.0000
F-PP	demeaned, no lags	63.0860	0.0000
F-PP	demeaned, 1 lag	51.8892	0.0000
F-DF	demeaned, no lags	63.0860	0.0000
F-DF	demeaned, 1 lag	124.1416	0.0000

Notes: IPS is the Im-Pesaran-Shin panel unit root test, F-PP is the Fisher-Phillips-Perron unit root test, and F-DF is the Fisher-ADF unit root test. The null hypothesis of the IPS test is that all panels contain unit roots, while the alternative is that some panels are stationary. The null hypothesis of the F-PP and F-DF tests is that all panels contain unit roots, while the alternative is that at least one panel is stationary.

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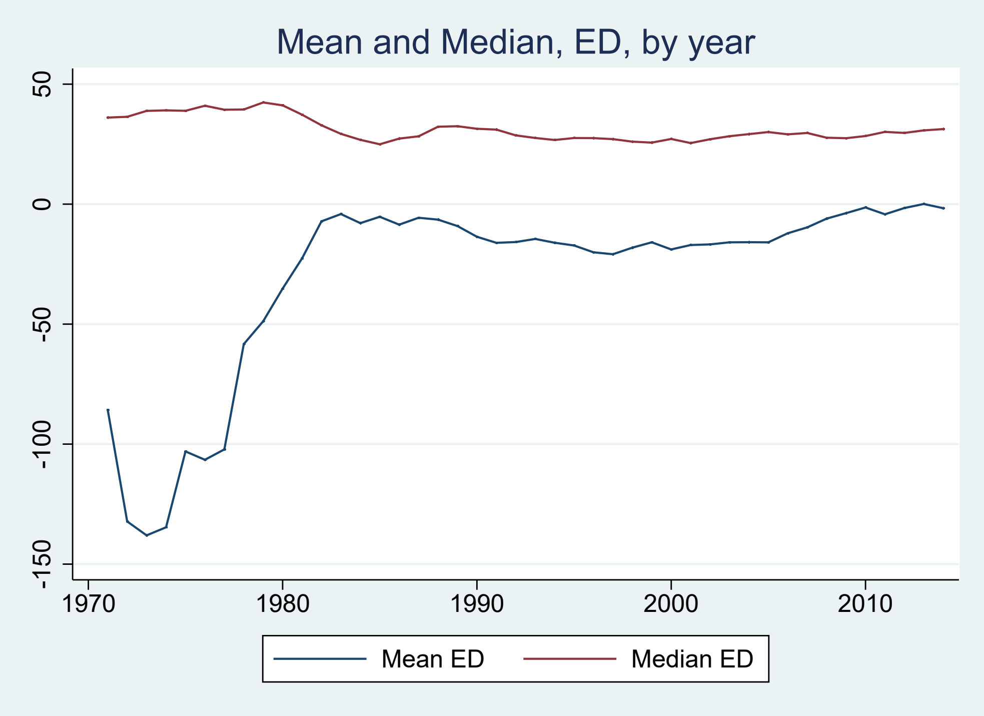
[3] World Bank definition of the Energy Dependency Index.

Figure 2.1: Mean and Median over time of the Energy Dependency Index.



We use the Energy Dependency Index to cluster countries in homogeneous groups because it is a synthetic indicator embedding information on two relevant energy-related features, such as the energy consumption and the net energy import of countries, while following their evolution over time.

As you can see from Table 2.2, this panel variable has a relevant between and within variation. That is the reason why we suggest countries should be clustered and investigated in accordance to their degree of energy dependency.

Moreover, it is suitable for the clusterization because, being a panel-stationary variable (Table 2.3), it is stable over time. Section 2.3.1 explains how we use this variable to cluster countries in five groups.

Table 2.4: Unit Root Tests, 1971-2014

Null hypothesis for ADF test: the variable has a unit root.
Alternative hypothesis for ADF test: the variable has not a unit root.
Null hypothesis for KPSS test: variable is stationary.
Alternative hypothesis for KPSS test: variable is not stationary.

Variable	ADF	KPSS	Lag selection criteria
Pe_t	-2.065	0.201**	AIC / Newey–West Bandwidth
ΔPe_t	-6.507***	0.136*	AIC / Newey–West Bandwidth
Vol_t	-5.112***	0.0699	AIC / Newey–West Bandwidth

Notes: The ADF is the Augmented Dickey-Fuller Test and its lag selection criteria is based on AIC. The KPSS is the Kwiatkowski-Phillips-Schmidt-Shin Test and its lag selection criteria is the Newey–West Bandwidth.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

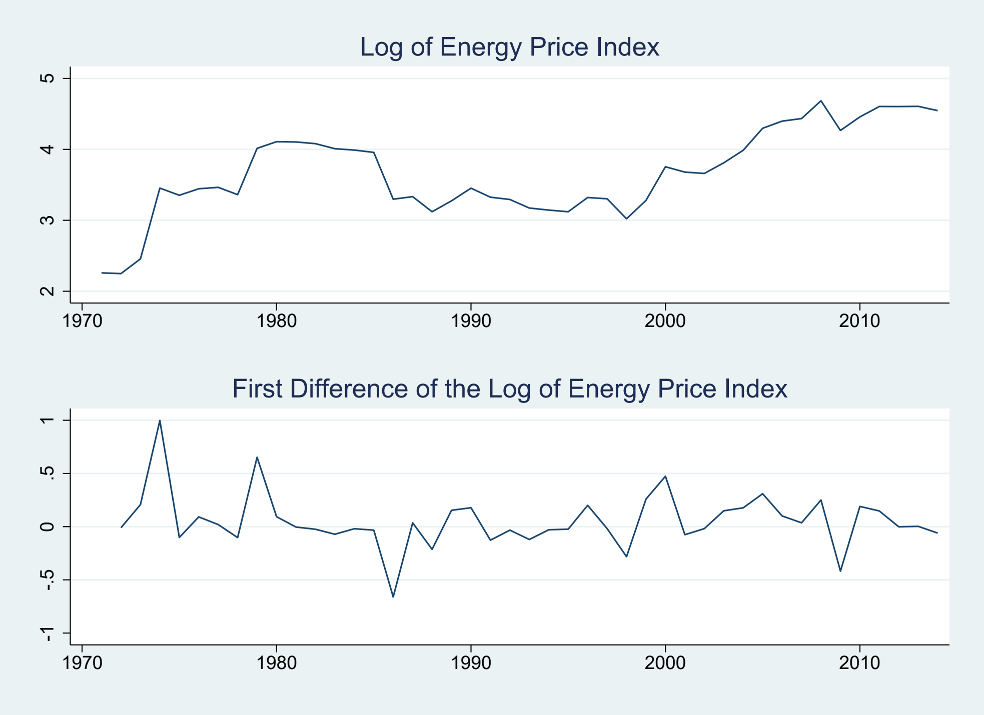
Table 2.5: Cross-Sectional Dependence Test, 1971-2014

Variable	Statistic value	p-value
$\Delta y_{i,t}$	41.37	0.0000
$ED_{i,t}$	1.87	0.0000
$\Delta Inst_{i,t}$	178.36	0.0000
$\Delta Pol_{i,t}$	31.71	0.0000

Notes: The null hypothesis for the Cross-Sectional Dependence Test (Pesaran et al. (2004), Pesaran (2015)) is the cross-section independence, while the alternative hypothesis is cross-section dependence.

The energy price index is obtained from the Pink Sheet of World Bank Commodity Price Data[4]. It is calculated as a weighted average of coal (4.7), natural gas (10.8), and crude oil (84.6) real prices, which, in turn, are weighted averages of several coal, natural gas, and crude oil prices. For example, the crude oil price used to calculate the energy price index is based on WTI, Brent, and Dubai oil prices. The energy price index varies only through the time dimension since it is a global index for energy commodity prices (Figure 2.2). The Augmented Dickey-Fuller test does not reject the null hypothesis of presence of unit root in the natural logarithm of the energy price index, namely Pe_t, while it rejects the null hypothesis for the first difference of its natural logarithm, namely ΔPe_t (Table 2.4).

Figure 2.2: The natural logarithm of the Energy Price Index.



We have calculated the energy price realized volatility index following the procedure in Jarrett et al. (2019) (Figure 2.3). This index of realized volatility is not event-based, but it is the

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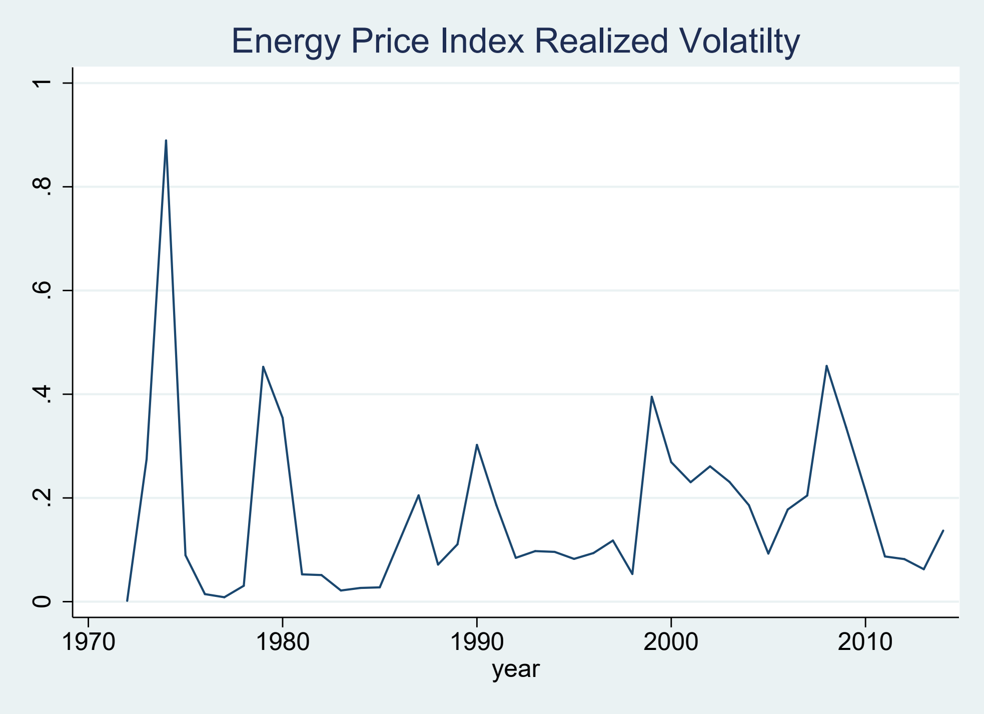
[4] The quarterly version of this series is an author's calculation based on the monthly version of the energy price index.

standard deviation of the year-on-year growth rate of monthly energy price, from 1971m1 to 2014m12.

Figure 2.3: The Energy Price Index Realized Volatility.



As regard to the real GDP series, in the first part of this work we rely on quarterly series, as it is common in the business cycle literature. The real GDP in PPP is obtained from Mohaddes and Raissi (2020), it has no missing observations and starts in 1979 because quarterly GDP series of emerging countries are less reliable before that date. This GDP data cover 28 countries over the period 1979q2-2016q4, while the quarterly energy price index is obtained from the Pink Sheet of World Bank Commodity Price Data[4] and it is a global index for energy commodity prices. The considered countries are clustered in quintiles based on their degree of energy dependency, as explained in Section 2.3.1, because we want to outline the features of business cycles and the energy price cycle and their synchronization, depending on the energy dependency degree of countries. However, the first quintile is composed of only Norway and Saudi Arabia, due to missing quarterly GDP series for MENA countries. This implies that the economic features of the first quintile which are shown in Section 2.4 are less reliable than the ones of the other quintiles.

On the other hand, in the second part of the analysis we rely on annual series. The real GDP series we use is in chained-PPP in 2011 US$, it covers 48 countries from 1971 to 2014 with no missing observations and it is obtained from the Penn World Tables 9.0 (Feenstra et al. (2015)). A per capita version of that series is calculated using the population variable, which is present in the same dataset. The Augmented Dickey-Fuller test rejects the null hypothesis of homogeneous non-stationarity of the real GDP series (Table 2.4).

This part of the analysis is extended using institutional quality and political stability as confounding variables. Both series cover the same countries and the same time span of the above-mentioned Penn World GDP series, with no missing observations.

The institutional quality variable is obtained as the average of three of the five sub-indicators composing the Fraser Economic Freedom Index and it varies from 0 to 10. The five sub-indicators are size of government, legal system & property rights, sound money, freedom to trade internationally, regulation. We decided to use only the following sub-indicators: legal system & property rights, freedom to trade internationally, and regulation. It is used to capture the huge heterogeneity in the dataset, due to the differences in the level of development. The Im-Pesaran-Shin unit root test does not reject the null hypothesis of homogeneous non-stationarity for the Institutional Quality variable[5], and the CD test (Pesaran et al. (2004), Pesaran (2015)) rejects the null hypothesis of cross-section independence (Table 2.5).

The political quality variable captures the regime political authority of countries and it spans from -10 to $+10$, where the two boundaries correspond respectively to complete autocracy and full democracy. This variable is obtained from Polity IV Project (Marshall et al. (2016)) dataset. The Im-Pesaran-Shin unit root test rejects the null hypothesis of homogeneous non-stationarity of the variable[5], and the CD test (Pesaran et al. (2004), Pesaran (2015)) does not reject the null hypothesis of cross-section independence (Table 2.5).

Table 2.6: Correlation

	$\Delta y_{i,t}$	$\Delta Pe_{i,t}$	$Vol_{i,t}$	$Inst_{i,t}$	$Pol_{i,t}$
$\Delta y_{i,t}$	1				
$\Delta Pe_{i,t}$	0.1140	1			
$Vol_{i,t}$	-0.0129	0.6451	1		
$Inst_{i,t}$	0.0186	-0.0623	-0.0057	1	
$Pol_{i,t}$	0.0509	-0.0040	0.0216	0.3803	1

2.3.1 Sample Clusterization

Most of the literature divides countries into oil exporter and importer countries, regardless of their advanced or emerging nature and of their net oil import and consumption over time. Moreover, we argue that these differences are even bigger when considering all energy commodities, not only crude oil. Indeed, Table 1 in Peersman and Van Robays (2012) underlines the huge differences in net energy imports and energy intensity in a set of advanced energy importer and exporter countries from 1986 to 2008, while Table 2.7 shows the differences in terms of energy consumption per capita of the countries we consider in our analysis.

For example, Italy and the US belong to the net energy importer countries but they experience very relevant differences in terms of energy consumption per capita (respectively 113 and 319 exajoule per capita) as in Table 2.7, energy intensity (respectively 93 and 172 tonnes of oil equivalent per US million dollars in weighted PPP) and net total energy imports (respectively 101 and 57 tonnes of oil equivalent per US million dollars in weighted PPP) as shown in Table 1 in Peersman and Van Robays (2012). The same pattern appears among net energy exporter countries since Canada, Australia, Norway and Middle-East countries have a diverse profile regarding the three above-mentioned energy features.

---

[5] The test has been performed four times: using Akaike information criterion and no trend, using Akaike information criterion and a linear trend, using Bayesian information criterion and no trend, using three lags.

Table 2.7: Energy Consumption per capita

Energy exporter countries	Energy consumption per capita, 1965-2019 average	Energy importer countries	Energy consumption per capita, 1965-2019 average
ARE	459	AUT	153
ARG	65	BEL	225
AUS	221	BGR	110
BHR		BRA	39
CAN	381	CHE	162
DZA	35	CHL	55
EGY	25	CHN	38
IDN	15	DEU	178
KWT	367	DNK	155
MEX	51	ESP	102
NGA		FIN	209
NOR	352	FRA	160
OMN	142	GBR	154
QAT	698	GRC	96
SAU	230	HUN	99
ZAF	92	IND	11
		IRL	127
		ISL	367
		ISR	102
		ITA	113
		JPN	144
		KOR	119
		LUX	369
		NLD	217
		POL	116
		PRT	72
		ROU	86
		SEN	
		SWE	249
		TUR	42
		USA	319

Notes: Author's calculation using annual BP data. The averages for the period 1965-2019 of energy consumption per capita are in exajoule.

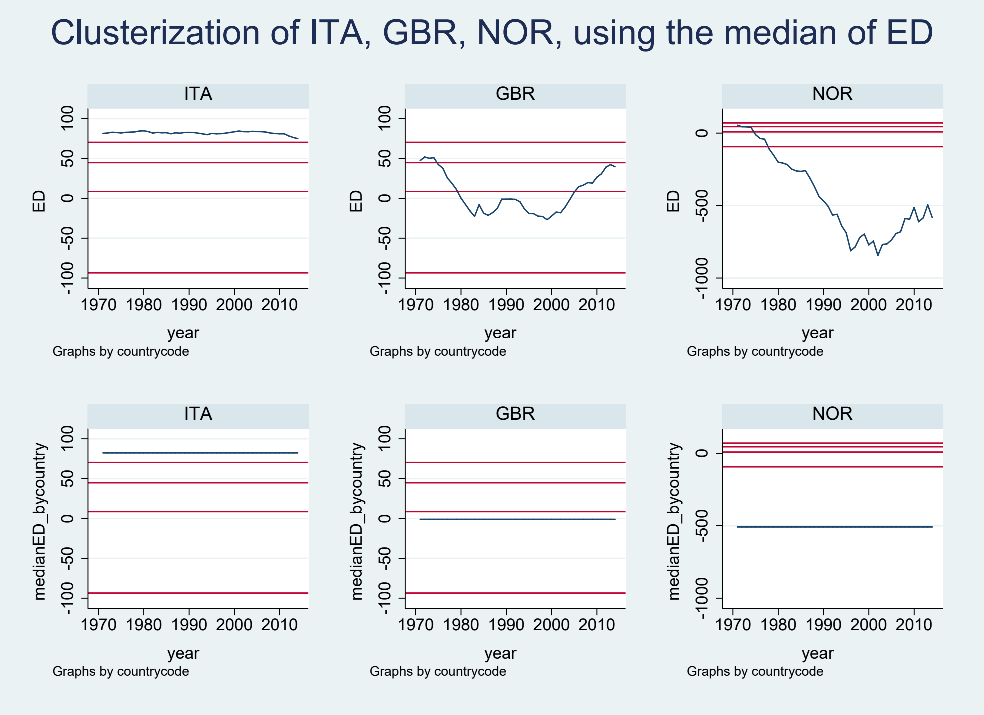
To deal with these sources of heterogeneity, we split the countries into more than two groups, using their energy dependency index, which concerns both net energy imports and energy consumption. Thus, we build five clusters, as in Table 2.8, to separate major energy exporting and importing countries from countries with a more balanced profile of energy dependency. This allows us to perform our analysis on homogeneous groups in order to disentangle the specific economic features of each cluster of countries and to check whether these features change among clusters.

Therefore, the sample is divided into five clusters based on the quintiles of energy dependency, and countries are sorted using the median over time of their energy dependency index.

1. Major energy exporting countries (i.e. ED1)
2. Energy exporting countries (i.e. ED2)
3. Energy balanced countries (i.e. ED3)
4. Energy importing countries (i.e. ED4)
5. Major energy importing countries (i.e. ED5)

An example of this methodology is represented in Figure 2.4.

Figure 2.4: Three examples of the clusterization methodology.



In the first row, the Energy Dependency Index of Italy, Great Britain, and Norway. In the second row, the median over time of the Energy Dependency Index of the three countries. The red lines define the thresholds of the five clusters of energy dependency.

Using this clusterization method, we build five groups that are balanced in terms of number of countries and observations. Moreover, this methodology does not allow countries to change quintile over time. We can rely on this clusterization method for the above mentioned reasons and because the energy dependency index is a panel stationary variable, as shown in Table 2.3, with only a few countries having a non-stationary energy dependency index (typically MENAs and BRIICs)[6]. Consequently, our analyses based on this clusterization method are reliable over time.

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[6] Besides, the non-stationarity of the energy dependency index of MENA countries is not a problem because they are concentrated in the first quintile and far from reaching the threshold values of the ED2 cluster

Table 2.8: Clusters of Countries

Clusters	ED1	ED2	ED3	ED4	ED5
	ARE	ARG	BRA	AUT	BEL
	BHR	AUS	DNK	BGR	ESP
	DZA	CAN	IND	CHE	IRL
	KWT	CHN	ISL	CHL	ISR
	NGA	EGY	NLD	DEU	ITA
	NOR	GBR	NZL	FIN	JPN
	OMN	IDN	ROU	FRA	KOR
	QAT	MEX	SEN	GRC	LUX
	SAU	POL	SWE	HUN	PRT
		ZAF	USA	TUR	
N	9	10	10	10	9
$N \times T$	396	440	440	440	396

Notes: countries do not change cluster over time.

Table 2.9: Descriptive Statistics of the Energy Dependency Index of each Cluster

	Observations $N \times T$	Mean	Median	Standard Deviation	Skewness	Kurtosis
ED1	396	-808.7732	-375.6448	1766.51	-6.472091	53.6529
ED2	440	-32.13322	-21.51809	43.42577	-.895235	3.434006
ED3	440	25.67975	23.95699	23.3107	.1595211	5.603342
ED4	440	57.21313	57.49670	11.17165	-.136215	2.411545
ED5	396	81.46474	81.73589	12.91109	-2.513427	17.80289
Total	2112	-125.7954	26.40433	832.8376	-13.71254	244.1463

Notes: Descriptive statistics are calculated across countries of the same cluster and over time.

Figures 2.5, 2.6, 2.7, 2.8, 2.9 show the energy dependency index of the countries in the five groups, while Table 2.9 shows the descriptive statistics of the energy dependency index of the five groups of countries.

An alternative clusterization method could have been based on the use of the first year of the energy dependency index of each country as a reference to divide countries into clusters. However, we do not adopt this procedure because it would have biased the analysis, not taking into account for the huge transformation in the degree of energy dependency of some countries in the first years of our sample. Indeed, the recession in early seventies due to the oil crises have significantly affected the energy policies of some countries. For example, Norway was a net energy importer in 1971, but in a few years its energy dependency profile was completely changed, and nowadays it is one of the major global energy exporter countries.

Figure 2.5: The Degree of Energy Dependency of countries in ED1.

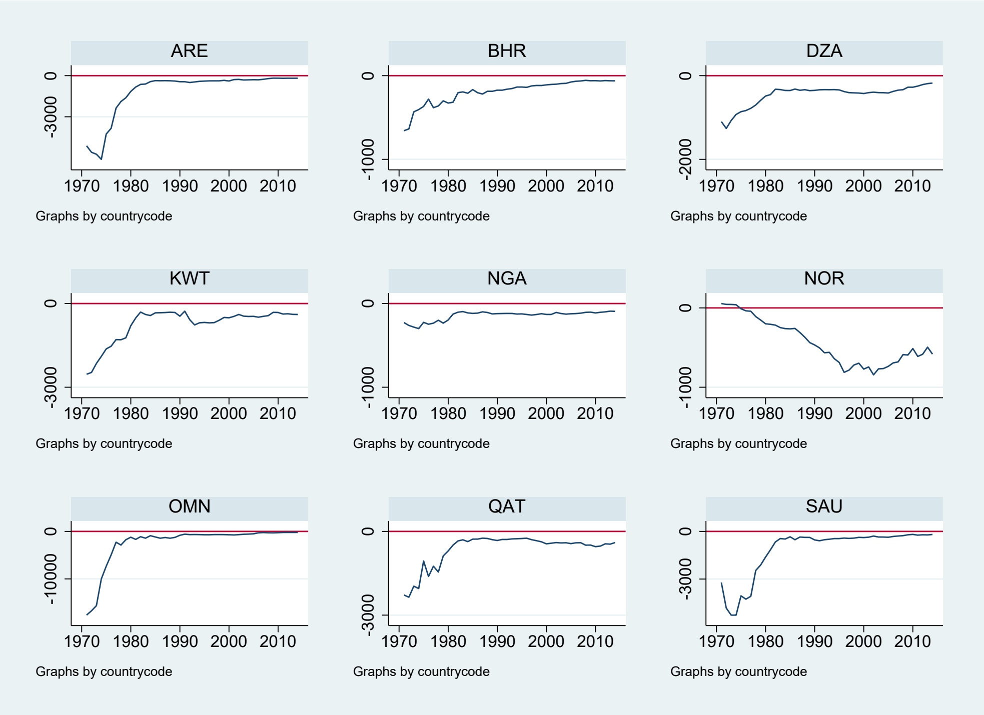


Figure 2.6: The Degree of Energy Dependency of countries in ED2.

Figure 2.7: The Degree of Energy Dependency of countries in ED3.

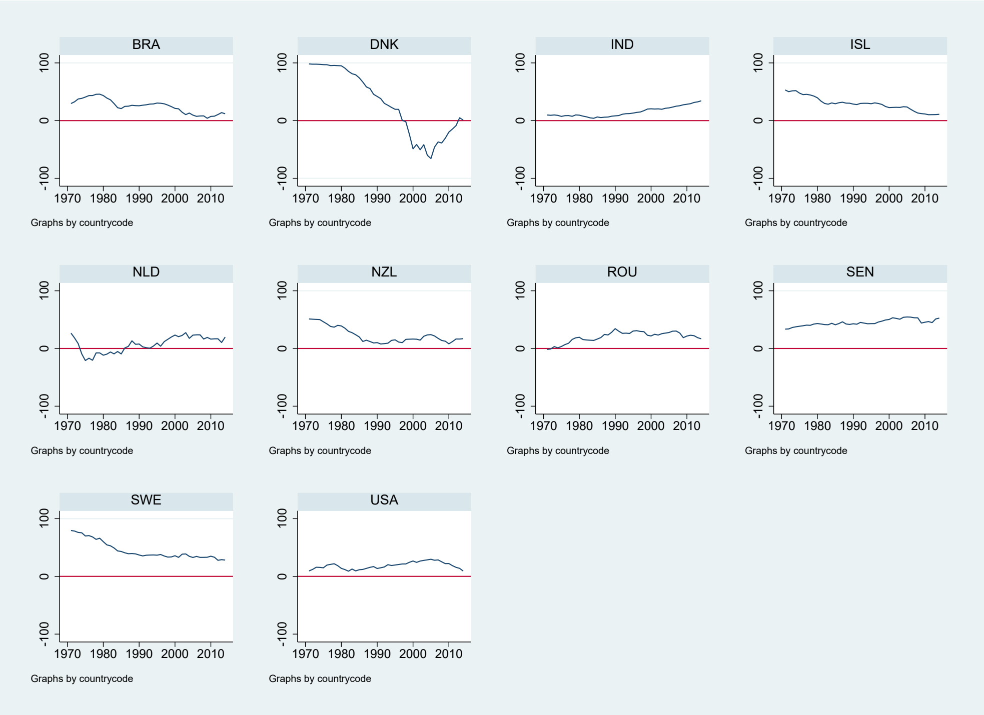


Figure 2.8: The Degree of Energy Dependency of countries in ED4.

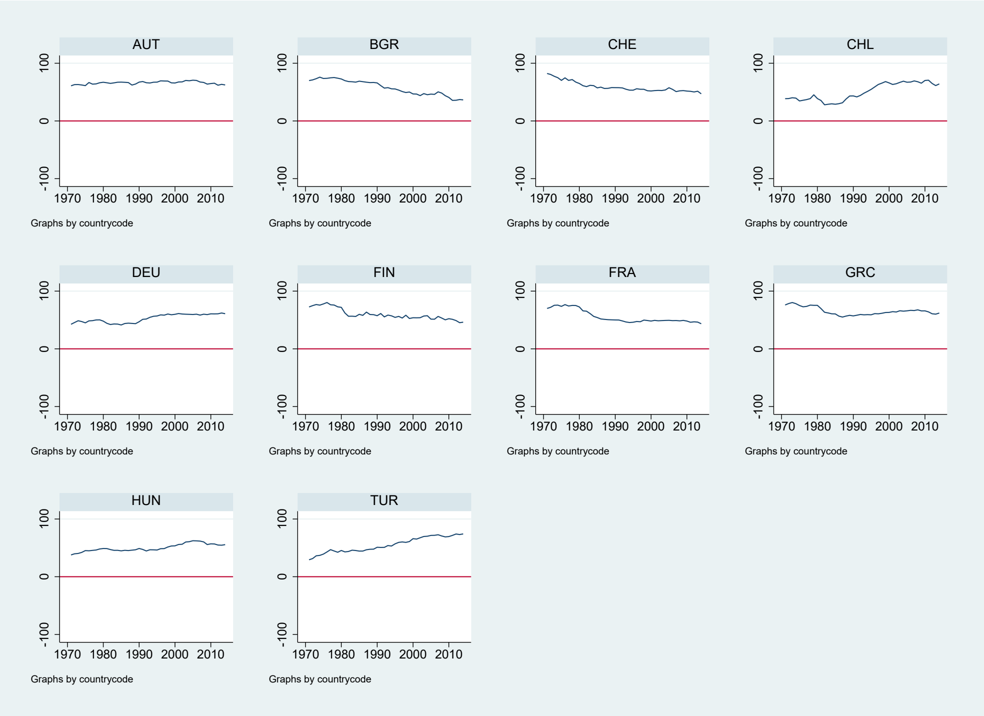
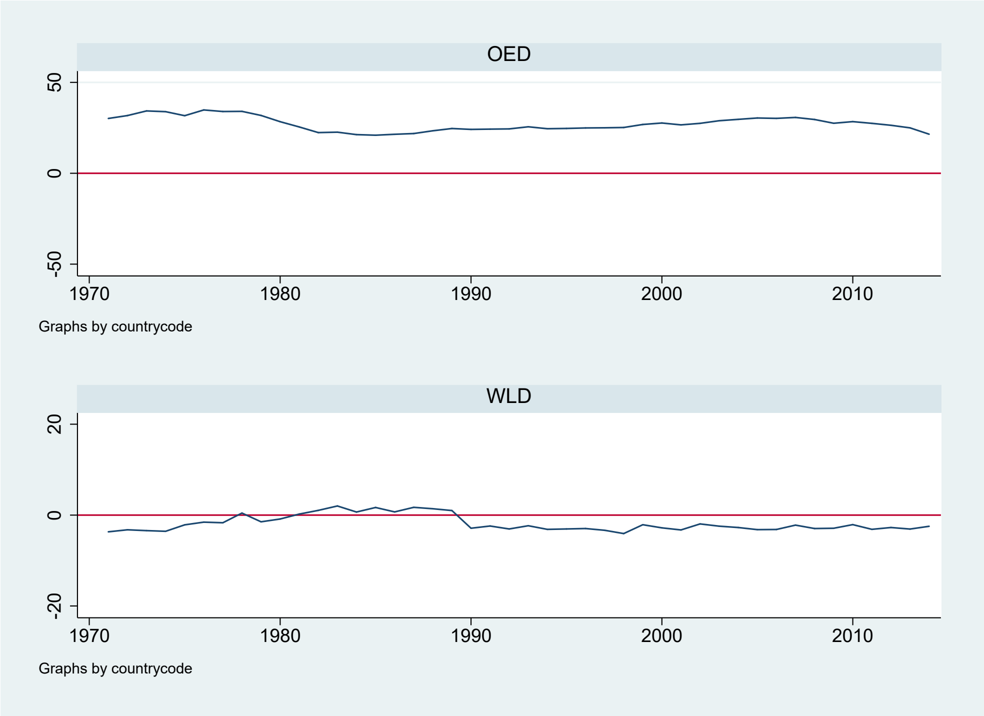


Figure 2.9: The Degree of Energy Dependency of countries in ED5.

Figure 2.10: The Degree of Energy Dependency of OECD countries and the whole world.



2.4 Evidence based on Cycles

2.4.1 Methodology

In this work, we use the "classical" definition of business cycle, as in Burns and Mitchell (1946). Thus, we rely on the Harding and Pagan (2002) version of the Bry and Boschan (1971) algorithm to identify the phases in the business cycle of each country.
The algorithm defines local minima and local maxima, following some standard censoring rules, which are the turning points of the series, and defining the cycles and their phases. Specifically, a complete cycle is composed of a recession, which is the part of the series from a peak to a trough, and an expansion, which is the part of the series from the trough to the peak. The recovery phase is the first part of the expansion, the one spanning from the trough to the last peak level before the recession, while another definition is the growth achieved after four quarters from the trough (Sichel (1994)). Due to the algorithm, complete cycles must last at least 5 quarters and each of its phases must last at least 2 quarters.
Following Cashin and McDermott (2002), we identify the phases of the energy price cycle using the same methodology.

The main features of cycles are frequency, duration, and amplitude. The frequency is the number of phases identified. The duration of a recession is the number of quarters between a peak and the next trough. The duration of a recovery is the number of quarters needed to reach the previous peak level of the variable. The amplitude of a recession is the percentage change from peak to trough. The amplitude of a recovery is the percentage change from the trough to 4 quarters ahead.
Analogously, we define upturns and downturns of the energy price cycle as recoveries and recessions of business cycles. Finally, we calculate the synchronization between each country's business cycle and the energy price cycle, using the Concordance Indexes proposed by Harding and Pagan (2006). As robustness check, we perform our synchronization analysis between each country's business cycle and the lagging (leading) energy price cycle (Section 2.A.2). The construction of the Concordance Indexes can be seen in Subsection 2.4.4.

2.4.2 Business Cycle: Main Features

We identify 156 recessions and 156 recoveries in our sample. Energy exporter countries experience 45 recessions and 47 recoveries, while energy importer countries experience 111 recessions and 109 recoveries.
The typical recession lasts more than 4 quarters and causes a 2.74% fall in real GDP, while the typical recovery lasts 5 quarters and generates a 4.73% increase in real GDP.
Recessions (Recoveries) of energy-exporting countries are longer and associated with a greater percentage loss (gain) in GDP with respect to energy importing countries.
Looking at Table 2.10, we can affirm that the business cycle of energy exporter countries is statistically different from the one of importers, and that this finding remains valid even when dividing the countries in quintiles of energy dependency. Following our clusterization, we note that the duration and the amplitude of recessions and recoveries of countries in ED3, that are the ones with a balanced degree of energy dependency, are statistically different from the ones in the other clusters. Thus, we use this quintile as a reference.
Both recessions and recoveries of countries in ED3 last less than one year, showing short periods of economic loss and fast rebounds. This is quite remarkable if we think that only the recessions of major energy importers have a similar length, but they are characterized by a 1% more fall in real GDP. Moreover, their recoveries statistically last as the ones of major energy-

exporting countries, but the latter have the possibility to adapt their energy production to shorten recessions and speed up recoveries. These countries are noticeably able to regain the 6.42% of real GDP in less than one year. On the other side, their recessions last more than one year and report losses for more than 3% points of real GDP.

Focusing on the number of events, i.e. recessions or recoveries, we see that recessions monotonically decrease and recoveries monotonically increase when moving from countries with a low degree of energy dependency to countries with a higher one. This may argue in favour of policies aimed at increasing the energy dependency degree, however, we suggest having a balanced profile of energy dependency is preferable. Indeed, countries in ED3 experience shorter and shallower recessions than the other countries.

This is a relevant finding implying that maintaining a balanced degree of energy dependency is associated with less costly recessions on average. Furthermore, these countries have shorter and stronger recoveries with respect to countries in ED4 and ED5 clusters, but less pronounced with respect to countries in ED1 and ED2. In fact, countries in the first two quintiles are typically emerging countries, and these countries have very prominent business cycles (Claessens et al. (2012) and Aguiar and Gopinath (2007)).

In this light, having a balanced energy dependency degree shows significant benefits in recessions, which is *per se* an important finding and also a very good reason to support policies aimed at converging to moderate degrees of energy dependency.

As a robustness check, we provide the results using an alternative clusterization based on energy importer and exporter countries, which are in turn divided due to their level of development.

Finally, it is worth mentioning that, following the literature, we focus our analysis on recoveries, not expansions. The definitions of recoveries and expansions are proposed in Section 2.4.1.

Table 2.10: Business Cycle: Basic Features.

	N° of Events	Duration	Amplitude
Recessions			
Full sample	156	4.27	-2.74
Energy exporter countries	45	4.68	-4.00
Energy importer countries	111	4.10***	-2.23***
ED1	41	4.15***	-3.14***
ED2	36	4.57***	-3.89***
ED3	33	3.82	-1.23
ED4	29	4.55***	-2.97***
ED5	17	3.85***	-2.28***
Recoveries			
Full sample	156	4.42	4.73
Energy exporter countries	47	4.49	6.09
Energy importer countries	109	4.40	4.18***
ED1	18	3.41	6.42***
ED2	29	5.45**	6.04***
ED3	33	3.75	4.63
ED4	36	4.63*	3.82***
ED5	40	4.41*	3.33***

Notes: Duration is in quarters, while Amplitude is in percentage. Duration for recessions is the number of quarters between peak and trough. Duration for recoveries is the time it takes to attain the level of output at previous peak after the trough. Amplitude for recessions is based on the decline in output from peak to trough. Amplitude for recoveries is based on the one-year change in output after the trough.

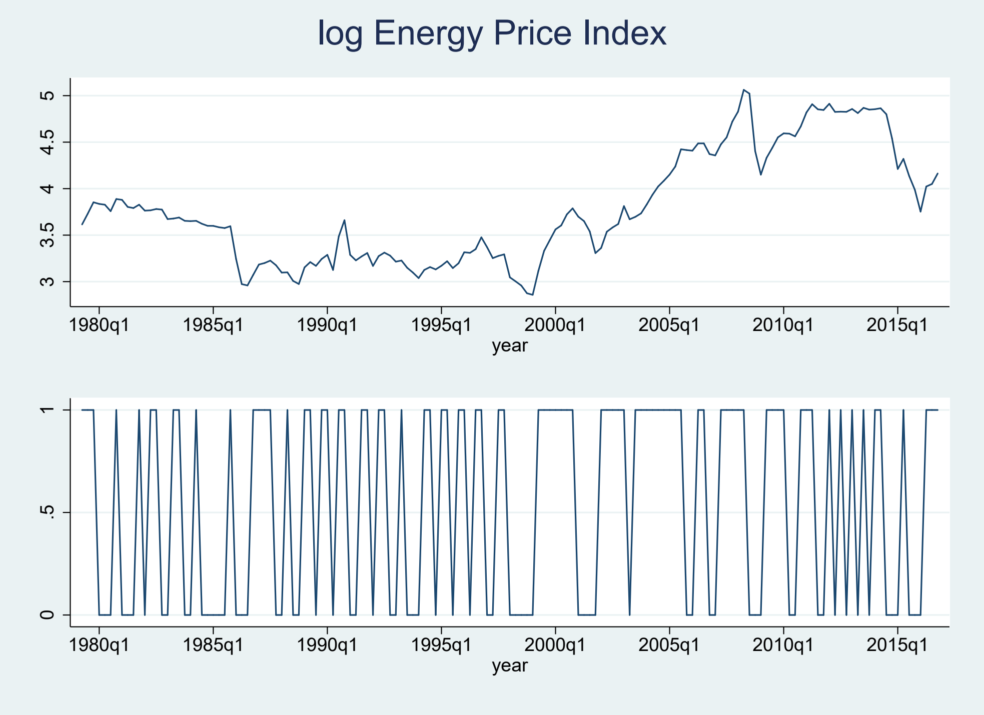
Significance refers to the difference between energy exporter countries and energy importer countries and to the difference between each quintile (i.e. ED1, ED2, ED4, ED5) and the third quintile (i.e. ED3).

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

2.4.3 Energy price cycle: Main Features

The energy price cycle can be seen in Figure 2.11. Its typical upturn lasts 4.9 quarters and it is associated with a 2.74% change in price, while the typical downturn lasts 5.6 quarters and is associated with a -5.69% change in price.
Comparing Tables 2.10 and 2.11, we see that the energy price cycle is characterized by much more frequent expansion and recession phases (i.e. upturns and downturns), with deeper recessions and smoother expansions. The synchronization between this cycle and the business cycles of the considered countries is shown in Section 2.4.4.

Figure 2.11: The Energy Price Index and its cycle.



In the top panel, the natural logarithm of the energy price index. In the bottom panel, the upturns and downturns of the energy price cycle, where the ones are the expansions and the zeros are the recessions.

Table 2.11: Energy Price Cycle: basic features.

	N^o of Events	Duration	Amplitude
Energy Price Downturns	151	5.6	-5.69
Energy Price Upturns	151	4.9	2.74

Notes: Duration is in quarters, while Amplitude is in percentage terms. Duration for downturns is the number of quarters between peak and trough. Duration for upturns is the time it takes to attain the level of output at previous peak after the trough. Amplitude for downturns is based on the decline in output from peak to trough. Amplitude for upturns is based on the one-year change in output after the trough.

2.4.4 Coincidence Indexes

We calculate the degree of synchronization between the business cycle of each country and the energy price cycle using the concordance index, CI, proposed by Harding and Pagan (2006). This index shows the amount of time that the two cycles spend in the same phase. It is equal to 1 if the two variables are perfectly pro-cyclical, i.e. simultaneously in expansion or recession, and 0 if they are perfectly counter-cyclical, i.e. simultaneously one in expansion and one in recession or vice versa. We want to underline that this index only describes a coincidence of events, without implying any sort of causation. Its construction can be seen in Subsection 2.4.4. In Table 2.12, we see that the probability that the business cycles and the energy price cycle are both in expansion or recession is close to 0.5 in the whole sample and in the sub-samples. This finding implies that it is not possible to guess the phase of a business cycle from the phase of the energy price cycle, or vice versa.

Therefore, we decide to calculate the same index when both series are simultaneously in expansion, CI_{exp}, and when both series are simultaneously in recession, CI_{rec}, taking into account for a non-linearity in the energy-business cycle relationship. The construction of these two indexes is presented in Appendix, in Section 2.4.4. The results reported in Table 2.12 show that the indexes are still close to 0.5 when considering CI_{exp}, and that they drop to 0.1 when considering CI_{rec}. This evidence implies that it is not possible to guess whether a business cycle and the energy price cycle are simultaneously in expansion and that there is a low probability that a business cycle and the energy price cycle are simultaneously in recession. This result could suggest an asymmetry in the effects of energy price movements on business cycles. Across clusters, we can see statistically significant differences among the indexes, but these values do not detach largely from the index of the full sample.

It is worth noting that major energy-importing countries have the highest probability of business cycles and the energy price cycle being both in expansion, while major energy-exporting countries have the highest probability of business cycles and the energy price cycle being both in recession. Summing up, we can assess that the business cycle of countries in different clusters of energy dependency is similarly synchronized with the energy price cycle, while major energy exporter/importer countries have a higher probability of being simultaneously in recession/expansion with the energy price cycle. Once again, having a balanced degree of energy dependency can be beneficial for the business cycle since its phases result to be less associated with the phases of the energy price cycle, that are characterized by frequent and sharp upturns and downturns.

Table 2.12: Concordance Indexes

	CI	CI_{exp}	CI_{rec}
Full Sample	0.581	0.487	0.094
Energy exporter countries	0.585	0.480	0.104
Energy importer countries	0.580	0.491^{***}	0.089^{***}
ED1	0.566	0.440^{***}	0.125^{***}
ED2	0.577	0.496^{***}	0.081
ED3	0.566	0.482	0.083
ED4	0.592	0.486^{*}	0.105^{***}
ED5	0.598	0.501^{***}	0.096^{***}

Notes: Significance refers to the difference between energy exporter countries and energy importer countries and to the difference between each quintile (i.e. ED1, ED2, ED4, ED5) and the third quintile (i.e. ED3).
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

To ensure the robustness of our analysis, we perform the same concordance analysis using leading and lagging energy price cycle, obtaining broadly consistent results with the ones presented above (Tables 2.24 and 2.25 in the Appendix in Subsection 2.A.2).

Construction of the Concordance Indexes

Construction of the Concordance Indexes, as in Harding and Pagan (2006):

1. Harding and Pagan (2002) version of the Bry and Bosch's algorithm disentangles expansions and recessions of the natural logarithm of GDP and Energy Price series.
2. The business cycle series of each considered country, $logGDP_t$, is transformed in a dummy variable $S_{GDP,t}$, with $S_{GDP,t} = 1$ during expansions and $S_{GDP,t} = 0$ during contractions:

$$\begin{cases} S_{GDP,t} = 1 & if \quad \text{expansion} \\ S_{GDP,t} = 0 & if \quad \text{contraction} \end{cases}$$

3. The same procedure is done with the energy price cycle series, $logPe_t$.
4. Finally, the Concordance Index is:

$$CI = \frac{1}{T} \left[\sum I(S_{GDP,t} = 1; S_{Pe,t} = 1) + \sum I(S_{GDP,t} = 0; S_{Pe,t} = 0) \right]$$

Therefore,

$$CI_{exp} = \frac{1}{T} \left[\sum I(S_{GDP,t} = 1; S_{Pe,t} = 1) \right]$$

and

$$CI_{rec} = \frac{1}{T} \left[\sum I(S_{GDP,t} = 0; S_{Pe,t} = 0) \right]$$

2.5 Estimation of Long-Run Effects

2.5.1 Methodology

To estimate the long-run effect of energy price changes on economic growth, we exploit a cross-sectionally augmented panel autoregressive distributed lag (CS-ARDL) approach, relying on a sample clusterization in groups of countries with a similar degree of energy dependency over time.

This panel ARDL approach fits for long-run analysis and has some appealing properties, clearly presented by Pesaran in a series of papers (Pesaran and Smith (1995), Pesaran (1997) and Pesaran and Shin (1998)). These papers show that this approach is robust to the omitted variable bias, that it produces consistent estimates whether the I(0) or I(1) nature of the considered variables, and that it allows for feedback effects among variables.

Furthermore, this approach returns consistent estimates if a sufficient number of lags is used (Chudik et al. (2016)). After considering several lag orders, we decide to rely on 3 lags for all variables because we need to include enough dynamics, since we are focusing on long-run effects, and because we want to avoid any data mining critique due to the use of a diverse number of lags for the variables. This choice is endorsed by several applied econometrics papers, i.e. Chudik et al. (2016), Kahn et al. (2019), Jarrett et al. (2019) and Mohaddes and Williams (2020).

Moreover, we add a cross-sectional augmentation of the dependent variable and the regressors to account for the presence of cross-sectional dependence and endogeneity in our data[7].

Following the literature, we assume that the error has a multi-factor structure

$$u_{i,t} = \lambda_i f_t + \varepsilon_{i,t}$$

where f_t are the unobserved common factors, λ_i are their loadings, and $\varepsilon_{i,t}$ is the serially uncorrelated idiosyncratic error with zero mean. Unobserved common factors can be seen as common global factors such as financial and economic crisis, energy market structural changes, technological progress. As proposed in Pesaran et al. (2015), we proxy the unobserved common factors term, $\lambda_i f_t$, with the cross-sectional average of the dependent variable and we deal with the cross-sectional dependence of regressors including their cross-sectional augmentation.

Finally, as in Jarrett et al. (2019) and Mohaddes and Williams (2020), we rely on the Pooled Mean Group estimator (PMG) because we are interested in estimating the long-run effect of energy price changes on economic growth in a specific set of countries rather than the individual long-run response of each country.

We estimate the following panel CS-ARDL model for each cluster:

$$\Delta y_{i,t} = \alpha_i + \sum_{l=1}^{p} \gamma_{il} \Delta y_{i,t-l} + \sum_{l=0}^{p} \beta_l \Delta Pe_{t-l} + \sum_{l=0}^{p} \psi_l Vol_{t-l} + \sum_{l=0}^{p} \delta_{il} \Delta Inst_{i,t-l} + \sum_{l=0}^{p} \varphi_{il} \overline{x}_{i,t-l} + \varepsilon_{i,t} \tag{2.1}$$

where $\Delta y_{i,t}$ is growth rate of real GDP in country i at time t, α_i is the country-specific fixed effect, ΔPe_t is the growth rate of the energy price at time t, Vol_t is the energy price index volatility at time t, $\Delta Inst_{i,t}$ is the growth rate of the quality of institution index, $\overline{x}_{i,t-l}$ is the cross-sectional averages vector, i.e. $\overline{x}_{i,t} = \left(\overline{\Delta y}_{i,t}, \overline{\Delta Inst}_{i,t}\right)$, and $\varepsilon_{i,t}$ is the serially uncorrelated idiosyncratic error.

---

[7] Chudik et al. (2017) and Mohaddes and Raissi (2017) suggest a minimum of 25 continuous observations in time for each country are needed to estimate a panel CS-ARDL model without endogeneity problems.

We compute the long-run Mean Group (MG) effects from the short-run coefficients in Equation 2.1, as in the following example:

$$\theta_i = \phi_{il}^{-1} \sum_{l=0}^{p} \beta_l$$

where $\phi_{il} = 1 - \sum_{l=1}^{p} \gamma_{il}$, which is the speed of adjustment[8]. Then, the long-run Pooled Mean Group (PMG) effects are obtain from the individual MG coefficients, restricting them to be the same for all countries within a cluster[9]. Indeed, we are interested in the long-run PMG effect concerning all countries within a cluster. Thus, we estimate the pooled long-run coefficients across the cross-sections while allowing the country-fixed effects and the short-run coefficients to vary. Consequently, each country has its unique residual variance and speed of adjustment.

Having controlled for common global factors, such as energy market structural changes over time, we ensure the reliability of our results and we can compare the long-run coefficients of each cluster, avoiding the normalization problem[10].

Moreover, we have performed our analysis on homogeneous clusters in terms of energy dependency, concerning net energy imports and total primary energy consumption, and in terms of level of development, due to the presence of the institutional quality variable in Equation 2.1. Finally, we have produced several robustness checks, estimating the model using the growth rate of GDP per capita as dependent variable (Subsection 2.5.3), using a different set of regressors (Subsection 2.5.3), and using an alternative clusterization (Subsection 2.5.3).

2.5.2 Empirical Results

We estimate Equation 2.1 on the whole sample and on the five sub-samples in which we have divided the countries using their degree of energy dependency, i.e. ED1, ED2, ED3, ED4, and ED5[11]. We report in the tables only the pooled long-run effects and the average speed of adjustment[8], namely $\widehat{\phi}$, because we are interested in the long-run growth effects, not in the short-run dynamics. Moreover, we exclude the cross-sectional augmented variables from the tables for clearance reasons.

We start by estimating the effect of an energy price increase on the GDP growth rate of energy exporter and importer countries. As expected, we find a positive effect of an increase in the energy price on the GDP growth rate of energy exporter countries and a negative one for importers (Table 2.13). Since these are straightforward results, we advance in our analysis by performing the regressions on the five groups of countries.

Overall, we note that the long-run effect of a positive change in the energy price growth rate on GDP growth rate is significantly different among clusters of energy dependency, and monotonically decreasing across quintiles. Table 2.14 shows that this effect ranges from being positive

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[8] The speed of adjustment is the speed at which an economic system converges to its long-run equilibrium. Therefore, it depends on the persistence of the explanatory variable, relying on the fact that the impact of a change in the explanatory variable takes time to work (Kydland and Prescott (1982)). For instance, a rise in income at time 0 may result in higher investments at time 1 that, in turn, can increase income at time 2. If the estimated speed of adjustment, namely $\hat{\phi}$, is negative and significant, the long-run relationship among the variables exists, as well as the adjustment process to the long-run equilibrium. In particular, if $-1 < \hat{\phi} < 0$ the adjustment is stable, if $\hat{\phi} = -1$ the adjustment takes place in 1 unit of time (a year, in our case), if $-2 < \hat{\phi} < -1$ the adjustment is overshooting. (Engle and Granger (1987), Kremers et al. (1992), Banerjee et al. (1993))

[9] Specifically, the PMG coefficients are calculated through a maximum likelihood approach using the Newton-Raphson numerical method.

[10] See Peersman and Van Robays (2012) for a discussion of the comparison of macroeconomic consequences of oil shocks across different countries.

[11] See Section 2.3.1 for an overview of the clusterization method and Table 2.8 for the list of countries within each group.

Table 2.13: Long-Run Effects on the GDP per capita Growth Rate, 1971-2014

	Whole Sample	Energy Exporters	Energy Importers
Long-run			
ΔP_e	-0.0246***	0.0820***	-0.0271***
	(0.01)	(0.02)	(0.01)
$\Delta Inst$	0.0004	-0.0009	0.0009
	(0.00)	(0.00)	(0.00)
$\hat{\phi}$	-0.5552***	-0.5162***	-0.5602***
	(0.04)	(0.06)	(0.05)
$N \times T$	1920	640	1280

Notes: The regression in Eq. 2.1 is performed on the whole sample and on energy exporter and energy importer countries. All estimations are obtained using the PMG estimator. Long-run coefficients and the error correction term, i.e. $\hat{\phi}$, are reported, while Short-run coefficients and the cross-sectionally augmented variables are included but not reported. The lag order is set to 3.
t statistics in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

in major energy-exporting countries, i.e. countries in ED1, to being negative in major energy-importing countries, i.e. countries in ED5. Specifically, it is negative in the whole sample, namely -0.0308, but ranges from 0.1212 to -0.0882 across clusters, while remaining significant at the 1% level.

This is a relevant finding because it suggests that countries can reduce the long-run impact of energy price fluctuations on economic growth by changing their degree of energy dependency, moving from extreme quintiles to more central ones. For example, major energy importer countries may limit the negative effects of an energy price increase by reducing their degree of energy dependency, and major energy exporter countries may reduce the negative effect caused by a rise in energy price volatility.

Indeed, the latter countries suffer an adverse impact from increasing energy price volatility that is larger than the positive effect of a higher energy price. It is worth noting that the bigger size of the negative impact of volatility with respect to the positive effect of increasing energy price changes is supported by De V. Cavalcanti et al. (2015), Mohaddes and Raissi (2017) and Jarrett et al. (2019), but it is experienced only by major energy exporter countries -i.e. ED1-, while the others are unaffected by volatility variations.

Moreover, we notice an overall positive effect of increasing institutions quality, which stands out for countries in ED3, probably due to the presence of emerging countries as India and Brazil. Finally, we show the cross-section dependence (CD) test (Pesaran et al. (2004), Pesaran (2015)) of residuals of the estimated regressions. The CD statistic is asymptotically distributed and it does not reject the null hypothesis of no cross-sectional dependence of errors.

With our long-run analysis, we contribute to the resource curse paradox literature, supporting the idea that fossil sources abundance does not damage economic growth, while an unwise management of these resources may lead to a negative outcome over time. Specifically, we show that the price volatility of resources harms long-run growth, as suggested by several recent studies (De V. Cavalcanti et al. (2015), Mohaddes and Raissi (2017) and Jarrett et al. (2019)). These studies also recommend a better quality of institutions and the correct use of sovereign wealth funds as main strategies to limit the price volatility negative effects. Following this

Table 2.14: Long-Run Effects on the GDP Growth Rate, 1971-2014

	Whole Sample	ED1	ED2	ED3	ED4	ED5
Long-run						
ΔP_e	-0.0250***	0.0998***	0.0581***	-0.0106	-0.0384***	-0.0602***
	(0.01)	(0.03)	(0.02)	(0.01)	(0.01)	(0.01)
Vol	-0.0088	-0.1775**	0.0179	-0.0336	-0.0098	-0.0017
	(0.01)	(0.07)	(0.04)	(0.03)	(0.03)	(0.03)
$\Delta Inst$	0.0021***	0.0020	-0.0018	0.0033***	-0.0010	0.0007
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\hat{\phi}$	-0.5256***	-0.5268***	-0.4497***	-0.6572***	-0.5458***	-0.4744***
	(0.04)	(0.09)	(0.07)	(0.07)	(0.07)	(0.10)
CD test	4.24***	-3.09***	-2.51**	-1.54*	-2.26***	-3.49***
$N \times T$	1872	351	390	390	390	351

Notes: The regression in Eq. 2.1 is performed on the whole sample and on several sub-samples, i.e. ED1, ED2, ED3, ED4 and ED5. Countries are divided in five clusters (ED1, ED2, ED3, ED4 and ED5) on the basis of their degree of energy dependency over time, as explained in Section 2.3.1. All estimations are obtained using the PMG estimator. Long-run coefficients and the error correction term, i.e. $\hat{\phi}$, are reported, while Short-run coefficients and the cross-sectionally augmented variables are included but not reported. The lag order is set to 3.

t statistics in parentheses.

* $p<0.10$, ** $p<0.05$, *** $p<0.01$

advice, major energy exporter countries could rely less on produced quantity adjustments to counterbalance government budget losses.

Furthermore, we show that only countries with an unbalanced degree of energy dependency, either being major exporter or importer of energy commodities, are significantly influenced by energy price changes, thus narrowing the economic and political debate around this issue. Only countries having a degree of energy dependency which is above a certain threshold should concern about that. For example, energy dependency is and has been an important political issue in the US, but the USA is clustered as an energy balanced country, so they do not suffer an energy dependency effect.

If we exclude the energy price volatility from Equation 2.1 and we re-estimate the model on the whole sample and on the five clusters of energy dependency, we still see that major energy exporter benefit from increasing energy price in the long-run, while major energy importers are hit by this change, and countries in ED3 remains unaffected. This finding is consistent with our robustness checks (Section 2.5.3).

Table 2.15: Long-Run Effects on the GDP Growth Rate, 1971-2014

	Whole Sample	ED1	ED2	ED3	ED4	ED5
Long-run						
ΔP_e	-0.0308***	0.1212***	-0.0366***	-0.0073	-0.0239*	-0.0882***
	(0.01)	(0.04)	(0.01)	(0.01)	(0.01)	(0.02)
$\Delta Inst$	0.0007	-0.0008	-0.0013	0.0024***	-0.0025	0.0019
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\hat{\phi}$	-0.5747***	-0.5399***	-0.5717***	-0.7723***	-0.5556***	-0.4717***
	(0.04)	(0.09)	(0.09)	(0.07)	(0.06)	(0.10)
CD test	4.01***	-3.24***	-2.33*	-2.26*	-2.55**	-3.51***
$N \times T$	1920	360	400	400	400	360

Notes: The regression in Eq. 2.1 is performed on the whole sample and on several sub-samples, i.e. ED1, ED2, ED3, ED4 and ED5. Countries are divided in five clusters (ED1, ED2, ED3, ED4 and ED5) on the basis of their degree of energy dependency over time, as explained in Section 2.3.1. All estimations are obtained using the PMG estimator. Long-run coefficients and the error correction term, i.e. $\hat{\phi}$, are reported, while Short-run coefficients and the cross-sectionally augmented variables are included but not reported. The lag order is set to 3.

t statistics in parentheses.

* p<0.10, ** p<0.05, *** p<0.01

2.5.3 Robustness Checks

To ensure the robustness of our results, we provide various versions of the main regression, using the growth rate of GDP per capita as dependent variable, replacing the institutional quality variable with a political stability variable, excluding the energy price volatility, and using a different clusterization based on quartiles of energy dependency.

Political Quality

In Table 2.16, we substitute the institutional quality variable with the political quality variable. It is worth noting that the two variables are not highly correlated (Table 2.6) supporting the relevance of this robustness check. We see that our main finding, the monotonically decreasing long-run effects of energy price change on GDP growth across quintiles, still holds, although we note some relevant differences with Table 2.14. These differences may suggest that institution quality and political quality do not perfectly substitute each other and that the institution quality variable is more suitable for our analysis. Indeed, the resource curse paradox literature extensively relies on the latter variable.

Furthermore, we see that being in ED2 is the best possible choice since both energy price and energy price volatility cause a positive long-run effect on growth. Countries in ED3 experience a positive effect due to energy price changes but they cannot exploit a positive effect from volatility, while countries in ED5 can. This is an unexpected finding, which is probably due to the high income and level of development of major energy importing countries, giving them the chance to cope with volatility through proper management of energy derivatives and supply contracts. However, assuming that there is no non-linearity in the energy price effect, being in ED4 is preferable since this profile of energy dependency guarantees being unaffected by energy price upward and downward movements.

Table 2.16: Long-Run Effects on the GDP Growth Rate, 1970-2014

	Whole Sample	ED1	ED2	ED3	ED4	ED5
Long-run						
ΔP_e	-0.0094**	0.1328***	0.0432***	0.0313**	-0.0099	-0.0206***
	(0.00)	(0.03)	(0.01)	(0.02)	(0.01)	(0.01)
Vol	0.0214**	-0.1839***	0.0865***	0.0338	0.0178	0.0198*
	(0.01)	(0.07)	(0.02)	(0.03)	(0.02)	(0.01)
ΔPol	0.0009*	-0.0006	0.0024**	0.0009	0.0010	-0.0006
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\hat{\phi}$	-0.7645***	-0.7133***	-0.7972***	-0.7480***	-0.6727***	-0.8789***
	(0.06)	(0.08)	(0.15)	(0.10)	(0.14)	(0.20)
$N \times T$	1680	329	369	333	353	296

Notes: The regression in Eq. 2.1 is performed on the whole sample and on several sub-samples, i.e. ED1, ED2, ED3, ED4 and ED5. Countries are divided in five clusters (ED1, ED2, ED3, ED4 and ED5) on the basis of their degree of energy dependency over time, as explained in Section 2.3.1. All estimations are obtained using the PMG estimator. Long-run coefficients and the error correction term, i.e. $\hat{\phi}$, are reported, while Short-run coefficients and the cross-sectionally augmented variables are included but not reported. The lag order is set to 3.

t statistics in parentheses.

* p<0.10, ** p<0.05, *** p<0.01

GDP per capita as dependent variable

Table 2.17: Long-Run Effects on the GDP per capita Growth Rate, 1971-2014

	Whole Sample	ED1	ED2	ED3	ED4	ED5
Long-run						
ΔP_e	-0.0217***	0.1040***	0.1000***	-0.0205*	-0.0012	-0.0625***
	(0.01)	(0.03)	(0.02)	(0.01)	(0.02)	(0.02)
Vol	-0.0383**	-0.2038**	-0.0199	-0.0680*	-0.0114	-0.0323
	(0.02)	(0.08)	(0.06)	(0.04)	(0.04)	(0.04)
$\Delta Inst$	0.0021***	0.0020	-0.0024	0.0034***	-0.0058***	0.0011
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\hat{\phi}$	-0.4937***	-0.4954***	-0.4254***	-0.6004***	-0.5195***	-0.4679***
	(0.04)	(0.07)	(0.10)	(0.08)	(0.07)	(0.11)
$N \times T$	1872	351	390	390	390	351

Notes: The regression in Eq. 2.1 is performed on the whole sample and on several sub-samples, i.e. ED1, ED2, ED3, ED4 and ED5. Countries are divided in five clusters (ED1, ED2, ED3, ED4 and ED5) on the basis of their degree of energy dependency over time, as explained in Section 2.3.1. All estimations are obtained using the PMG estimator. Long-run coefficients and the error correction term, i.e. $\hat{\phi}$, are reported, while Short-run coefficients and the cross-sectionally augmented variables are included but not reported. The lag order is set to 3.

t statistics in parentheses.

* p<0.10, ** p<0.05, *** p<0.01

In Table 2.17 we use the growth rate of GDP per capita as dependent variable, and we note that (i) our contribution to the resource curse paradox is confirmed, however, the volatility negative effect is much lower, (ii) countries in ED5 are still relevantly negatively affected by rising energy prices, (iii) countries in ED3 are negatively affected by energy price rising and

Table 2.18: Long-Run Effects on the GDP per capita Growth Rate, 1971-2014

	Whole Sample	ED1	ED2	ED3	ED4	ED5
Long-run						
ΔP_e	-0.0246***	0.1149***	-0.0271**	-0.0104	0.0022	-0.0735***
	(0.01)	(0.03)	(0.01)	(0.01)	(0.01)	(0.02)
$\Delta Inst$	0.0004	-0.0009	-0.0010	0.0021***	-0.0055***	0.0015
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\hat{\phi}$	-0.5552***	-0.5365***	-0.5464***	-0.7123***	-0.5415***	-0.5125***
	(0.04)	(0.06)	(0.08)	(0.07)	(0.05)	(0.13)
$N \times T$	1920	360	400	400	400	360

Notes: The regression in Eq. 2.1 is performed on the whole sample and on several sub-samples, i.e. ED1, ED2, ED3, ED4 and ED5. Countries are divided in five clusters (ED1, ED2, ED3, ED4 and ED5) on the basis of their degree of energy dependency over time, as explained in Section 2.3.1. All estimations are obtained using the PMG estimator. Long-run coefficients and the error correction term, i.e. $\hat{\phi}$, are reported, while Short-run coefficients and the cross-sectionally augmented variables are included but not reported. The lag order is set to 3.

t statistics in parentheses.

* $p<0.10$, ** $p<0.05$, *** $p<0.01$

energy price volatility, (iv) ED2 and ED4 are not negatively affected by energy price increase nor by energy price volatility. All these findings suggest that countries in ED3 are vulnerable to energy price changes, in contrast with what was previously found. However, moving from extreme degrees of energy dependency to more moderate degrees can off-set the negative long-run effects of energy price fluctuations, i.e. from ED5 to ED4 or from ED1 to ED2.

These findings remain consistent even if we exclude volatility from this specification (Table 2.18). Moreover, the unexpected negative effect of increasing energy price disappears for countries in ED3.

Thus, we still suggest that having a moderate degree of energy dependency is the most suitable strategy.

Quartiles of Energy Dependency

If we rely on the alternative clusterization based on quartiles of energy dependency, we still see that (i) countries in the first quartile are positively influenced by increasing energy price changes and negatively hit by increasing energy price volatility, (ii) the latter effect is bigger than the first one, (iii) countries in the last quartile are negatively influenced by energy price increases, (iv) countries in central quartiles are unaffected by energy price but exporters experience price volatility negative effect. Bullet points (i) and (ii) hold in all specifications using quartiles of energy dependency (Tables 2.19, 2.20, 2.21 and 2.22).

Overall, these results are consistent with the ones obtained using quintiles of energy dependency, suggesting that a balanced profile of energy dependency is preferable.

Table 2.19: Long-Run Effects on the GDP Growth Rate, 1971-2014

	Whole Sample	ED1	ED2	ED3	ED4
Long-run					
ΔP_e	-0.0250***	0.0946***	-0.0108	-0.0168	-0.0540***
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
Vol	-0.0088	-0.1424***	-0.0863**	0.0071	0.0031
	(0.01)	(0.05)	(0.04)	(0.03)	(0.03)
$\Delta Inst$	0.0021***	0.0011	0.0030***	0.0023	0.0004
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\hat{\phi}$	-0.5256***	-0.5060***	-0.4898***	-0.5917***	-0.4882***
	(0.04)	(0.08)	(0.06)	(0.08)	(0.09)
$N \times T$	1872	507	468	507	390

Notes: The regression in Eq. 2.1 is performed on the whole sample and on several sub-samples, i.e. ED1, ED2, ED3, and ED4. Countries are divided in five clusters (ED1, ED2, ED3, and ED4) on the basis of their degree of energy dependency over time, as explained in Section 2.3.1. All estimations are obtained using the PMG estimator. Long-run coefficients and the error correction term, i.e. $\hat{\phi}$, are reported, while Short-run coefficients and the cross-sectionally augmented variables are included but not reported. The lag order is set to 3.
t statistics in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table 2.20: Long-Run Effects on the GDP per capita Growth Rate, 1971-2014

	Whole Sample	ED1	ED2	ED3	ED4
Long-run					
ΔP_e	-0.0217***	0.1061***	-0.0281**	-0.0003	-0.0579***
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
Vol	-0.0383**	-0.1075**	-0.1190**	-0.0064	-0.0255
	(0.02)	(0.05)	(0.05)	(0.04)	(0.04)
$\Delta Inst$	0.0021***	0.0004	0.0034***	0.0011	0.0008
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\hat{\phi}$	-0.4937***	-0.5260***	-0.4161***	-0.5654***	-0.4579***
	(0.04)	(0.08)	(0.06)	(0.08)	(0.10)
$N \times T$	1872	507	468	507	390

Notes: The regression in Eq. 2.1 is performed on the whole sample and on several sub-samples, i.e. ED1, ED2, ED3, and ED4. Countries are divided in five clusters (ED1, ED2, ED3, and ED4) on the basis of their degree of energy dependency over time, as explained in Section 2.3.1. All estimations are obtained using the PMG estimator. Long-run coefficients and the error correction term, i.e. $\hat{\phi}$, are reported, while Short-run coefficients and the cross-sectionally augmented variables are included but not reported. The lag order is set to 3.
t statistics in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table 2.21: Long-Run Effects on the GDP Growth Rate, 1971-2014

	Whole Sample	ED1	ED2	ED3	ED4
Long-run					
ΔP_e	-0.0308***	0.1086***	-0.0255**	-0.0088	-0.0781***
	(0.01)	(0.03)	(0.01)	(0.01)	(0.02)
$\Delta Inst$	0.0007	-0.0001	0.0013	0.0016	0.0014
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\hat{\phi}$	-0.5747***	-0.4997***	-0.6269***	-0.6309***	-0.4643***
	(0.04)	(0.08)	(0.06)	(0.08)	(0.10)
$N \times T$	1920	520	480	520	400

Notes: The regression in Eq. 2.1 is performed on the whole sample and on several sub-samples, i.e. ED1, ED2, ED3, and ED4. Countries are divided in five clusters (ED1, ED2, ED3, and ED4) on the basis of their degree of energy dependency over time, as explained in Section 2.3.1. All estimations are obtained using the PMG estimator. Long-run coefficients and the error correction term, i.e. $\hat{\phi}$, are reported, while Short-run coefficients and the cross-sectionally augmented variables are included but not reported. The lag order is set to 3.
t statistics in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

Table 2.22: Long-Run Effects on the GDP per capita Growth Rate, 1971-2014

	Whole Sample	ED1	ED2	ED3	ED4
Long-run					
ΔP_e	-0.0246***	0.1048***	-0.0257**	0.0073	-0.0702***
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
$\Delta Inst$	0.0004	-0.0005	0.0016	0.0007	0.0013
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\hat{\phi}$	-0.5552***	-0.5382***	-0.5619***	-0.6039***	-0.4818***
	(0.04)	(0.07)	(0.06)	(0.07)	(0.12)
$N \times T$	1920	520	480	520	400

Notes: The regression in Eq. 2.1 is performed on the whole sample and on several sub-samples, i.e. ED1, ED2, ED3, and ED4. Countries are divided in five clusters (ED1, ED2, ED3, and ED4) on the basis of their degree of energy dependency over time, as explained in Section 2.3.1. All estimations are obtained using the PMG estimator. Long-run coefficients and the error correction term, i.e. $\hat{\phi}$, are reported, while Short-run coefficients and the cross-sectionally augmented variables are included but not reported. The lag order is set to 3.
t statistics in parentheses.
* p<0.10, ** p<0.05, *** p<0.01

2.6 Conclusion

In this empirical work, we study whether the business cycle and long-run growth of countries differ depending on a country's degree of energy dependency. Indeed, energy dependency is a great concern for most countries because of its implications on energy security and on macroeconomic stability and growth.

Specifically, we study whether the business cycle of countries with a similar degree of energy dependency shares some basic features - i.e. frequency, duration, and amplitude of recessions and recoveries -, and we analyse the synchronization of their business cycle with the energy price cycle. Moreover, we study the long-run impact of energy price changes on GDP growth.

There are two novel aspects in this paper. First, all energy commodities are considered, not only oil, and second, our work goes beyond the standard distinction between energy importing and exporting countries.

The business cycle analysis is based on Harding and Pagan (2002) and Harding and Pagan (2006), where the authors define the basic features of cycles and how to identify them using an updated version of the Bry and Boschan (1971) algorithm. We investigate the main features of business cycles and energy price cycle of 28 countries from 1979q2 to 2016q4, and their synchronization. Then, we verify whether the long-run effects of oil price changes differ depending on a country's degree of energy dependency, using a cross-sectionally augmented panel autoregressive distributed lag (CS-ARDL) approach in 48 countries from 1971 to 2014.

For the analyses on macroeconomic stability and growth, we cluster the countries in five groups based on their degree of energy dependency, arguing that the division in energy exporting/importing countries does not define homogeneous clusters. The two main sources of heterogeneity are the level of development[12], and the relevant differences in terms of energy dependency among countries within the same sub-sample. For instance, Italy and the US are net energy importers, but Italy imports 80% of its total primary energy consumption while the US imports just about 10%.

Indeed, we show that the business cycle of energy exporter countries is statistically different from the one of energy importer countries, and that the business cycles of emerging economies are sharper than the ones of advanced economies, as suggested by the literature (see Claessens et al. (2012) and Aguiar and Gopinath (2007) among others).

Therefore, as explained before, we analyse the key features of the business cycles of five clusters of countries. We note that the duration and amplitude of both recessions and recoveries of countries in the five clusters are significantly different, but their business cycles are similarly synchronized with the energy price cycle. The business cycles of countries with a balanced profile of energy dependency have shorter and more moderate recessions with respect to the other countries, either energy exporter or importer countries. Moreover, they show shorter but stronger recoveries with respect to energy major and moderate importer countries. However, major and moderate energy exporter countries show more pronounced recoveries.

On the other side, the energy price cycle has more frequent downturns (i.e. recessions) and upturns (i.e. recoveries) with respect to business cycles, characterized by longer and deeper downturns, and longer but shallower upturns.

From the synchronization analysis, we see that the business cycles of countries in different quintiles of energy dependency are similarly synchronized with the energy price cycle, and that there is not a clear link between the two cycles. However, when analysing only recessions and expansions, clusters show a statistically different synchronization with the energy price cycle. The probability of business cycles and energy price cycle being both in expansion is similar to a coin toss, while it shrinks to 10% while considering the cycles being simultaneously

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[12] Energy exporting countries are mainly emerging countries with the exceptions of Canada, Australia, and Norway, while energy importing countries are mostly developed countries with the exceptions of Chile, India, Senegal, and Brazil.

in recession. This result could suggest an asymmetry in the effects of energy price movements on business cycles.

The panel approach suggests that energy price changes have negative effects on the economic growth of major energy importer countries and that major energy exporters benefit from increasing energy price, while being damaged by its volatility. This analysis contributes to the resource curse paradox literature supporting the idea that the economic growth of resource-rich countries is harmed by resource price volatility, not by abundance per se, as in De V. Cavalcanti et al. (2011), De V. Cavalcanti et al. (2015), Mohaddes and Pesaran (2016), Jarrett et al. (2019) and Van Eyden et al. (2019). Moreover, this analysis shows that major importing and exporting countries are the most affected countries, narrowing the economic and political debate around energy dependency. Hence, energy dependency is an important political issue in the US, but we show that the degree of energy dependency becomes relevant only beyond a certain threshold. The USA does not suffer an energy dependency effect because they have an energy dependency balanced profile.

An interesting future development of the main model could be a Dynamic Panel Quantile Model, within a panel CS-ARDL framework, that could permit to avoid the ex-ante clusterization of the sample (Harding et al. (2020) is a frontier model). Otherwise, it could be interesting to estimate a Dynamic Panel Threshold Model, as Chudik et al. (2017), to empirically find the existence of an energy dependency threshold and to quantify the coefficients change above and beyond this threshold.

Overall, we find that countries with a more balanced energy dependency seem to be not or less affected by energy price fluctuations and energy price volatility in the long-run. Moreover, the countries with a balanced degree of energy dependency have the lowest amplitude and the shortest duration of recessions, and their recoveries have a higher amplitude with respect to the ones of countries with a more energy dependent profile.

These results have several policy implications. If exporter countries were able to limit the negative effects of energy price volatility, for example working on their financial institutions (i.e. sovereign wealth funds) as suggested by Jarrett et al. (2019) and Mohaddes and Raissi (2017), they will significantly improve their macroeconomic stability conditions without extensively relying on adjustment in energy production. The stabilization of global energy production from fossil sources would improve the global energy security conditions with noticeable geopolitical advantages. Another suggested policy for major energy exporter countries refers to the diversification of the energy production sector via renewable sources. This strategic choice should allow them to continue to play a pivotal role in the global energy supplier market in the light of a transitioning world. On the other side, major energy importers may reduce their degree of energy dependency augmenting renewable energy production to diversify their energy mix and augment their own energy production while reducing their energy consumption via increasing energy efficiency and decreasing energy intensity.

These changes would enhance a more competitive and diversified energy sector and a lower global energy per capita utilisation, diminishing the vulnerability of countries to energy price and supply shocks. Finally, a key implication that emerges is that converging to a moderate degree of energy dependency through the above-mentioned energy policies have important consequences on energy-related emissions and thus on climate change. Indeed, significant shifts from a high degree of energy dependence to a moderate energy dependence situation may be possible only through major changes toward less carbon intensive economies and an effective energy transition at global level.

2.A Appendix

2.A.1 Business Cycle: an Alternative Clusterization

The standard approach in the business cycle literature relies on the division of countries into advanced and emerging ones, while we divide them using their degree of energy dependency. In Table 2.23, we report the main features of the business cycles of countries that are divided into energy exporters and importers, and then again by level of development[13]. We appreciate that the level of development cleavage is relevant, although there is not a statistically significant difference in the duration of recoveries.

Table 2.23: Business Cycle: Basic Features, Alternative Clusterization

	N° of Events	Duration	Amplitude
Recessions			
Energy exporter countries	45	4.68	-4.00
Advanced countries	14	4.54	-1.66
Emerging countries	31	4.80^{***}	-5.58^{***}
Energy importer countries	111	4.10	-2.23
Advanced countries	86	4.36	-1.87
Emerging countries	25	3.18^{***}	-3.21^{***}
Recoveries			
Energy exporter countries	47	4.49	6.09
Advanced countries	15	3.42	2.98
Emerging countries	32	4.96	7.36^{***}
Energy importer countries	109	4.40	4.18
Advanced countries	85	4.37	2.86
Emerging countries	24	4.52	8.13^{***}

Notes: Duration is in quarters, while Amplitude is in percentage. Duration for recessions is the number of quarters between peak and trough. Duration for recoveries is the time it takes to attain the level of output at previous peak after the trough. Amplitude for recessions is based on the decline in output from peak to trough. Amplitude for recoveries is based on the one-year change in output after the trough.
Significance refers to the difference between advanced and emerging countries, using advanced countries as a reference.
t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

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[13] There are not enough countries to split the five energy dependency clusters by level of development.

2.A.2 Leading and Lagging Coincidence Indexes

$$LeadingCI = \frac{1}{T}\left[\sum I(S_{GDP,t} = 1; S_{Pe,t+1} = 1) + \sum I(S_{GDP,t} = 0; S_{Pe,t+1} = 0)\right]$$

$$LaggingCI = \frac{1}{T}\left[\sum I(S_{GDP,t} = 1; S_{Pe,t-1} = 1) + \sum I(S_{GDP,t} = 0; S_{Pe,t-1} = 0)\right]$$

Table 2.24: Concordance Indexes, with leading Energy Price Cycle

	$LeadingCI$	$LeadingCI_{exp}$	$LeadingCI_{rec}$
Full Sample	0.569	0.481	0.091
Energy exporter countries	0.561	0.468	0.096
Energy importer countries	0.572	0.487^{***}	0.089^{***}
ED1	0.539	0.426^{***}	0.116^{***}
ED2	0.562	0.489^{***}	0.077
ED3	0.557	0.477	0.083
ED4	0.557	0.483^{*}	0.107^{***}
ED5	0.581	0.493^{***}	0.092^{***}

Notes: Significance refers to the difference between energy exporter countries and energy importer countries and to the difference between each quintile (i.e. ED1, ED2, ED4, ED5) and the third quintile (i.e. ED3).

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table 2.25: Concordance Indexes, with lagging Energy Price Cycle

	$LaggingCI$	$LaggingCI_{exp}$	$LaggingCI_{rec}$
Full Sample	0.562	0.478	0.087
Energy exporter countries	0.572	0.474	0.102
Energy importer countries	0.558	0.480^{***}	0.082^{***}
ED1	0.539	0.426^{***}	0.116^{***}
ED2	0.568	0.492^{***}	0.080
ED3	0.549	0.474	0.078
ED4	0.561	0.471	0.094^{***}
ED5	0.578	0.492^{***}	0.090^{***}

Notes: Significance refers to the difference between energy exporter countries and energy importer countries and to the difference between each quintile (i.e. ED1, ED2, ED4, ED5) and the third quintile (i.e. ED3).

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

2.A.3 An Alternative Model using the Energy Dependency Index

For completeness, we show the results obtained using a panel CS-ARDL model that embeds the Energy Dependency Index as an explanatory variable. From Table 2.26, it is possible to see that the energy dependency index does not have a direct effect on growth, but these effects appear when it is interacted. This finding supports the idea that the Energy Dependency Index is a suitable variable to cluster countries because it is no explanatory power and a small variability over time and countries. In addition, this finding implies that the clusterization of countries is necessary to appreciate the heterogeneous long-run effects on growth of changes in the energy price index and in its volatility, as shown in Section 2.5.2.

$$\begin{aligned}\Delta y_{i,t} = \alpha_i + \sum_{l=1}^{p} \gamma_{il} \Delta y_{i,t-l} + \sum_{l=0}^{p} \delta_{il} \Delta ED_{i,t-l} + \sum_{l=0}^{p} \beta_l \Delta Pe_{t-l} + \sum_{l=0}^{p} \psi_{il} (\Delta Pe_{t-l} \times ED_{i,t-l}) + \\ + \sum_{l=0}^{p} \eta_{il} (Vol_{t-l} \times ED_{i,t-l}) + \sum_{l=0}^{p} \varphi_{il} \overline{\Delta y}_{i,t-l} + \varepsilon_{i,t}\end{aligned} \tag{2.2}$$

where $\Delta y_{i,t}$ is growth rate of real GDP in country i at time t, α_i is the country-specific fixed effect, $ED_{i,t-l}$ is the energy dependency index in country i at time t, ΔPe_t is the growth rate of the energy price at time t, Vol_t is the energy price index volatility at time t, $\overline{\Delta y}_{i,t-l}$ is the cross-sectional average of the GDP growth rate, and $\varepsilon_{i,t}$ is the serially uncorrelated idiosyncratic error. $\Delta Pe_{t-l} \times ED_{i,t-l}$ and $Vol_{t-l} \times ED_{i,t-l}$ are the interaction terms.

Table 2.26: Long-Run Effects on the GDP Growth Rate using the Energy Dependency Index, 1971-2014

	GDP growth rate	GDP growth rate	GDP growth rate	GDP growth rate
Long-run				
ED	0.0000	0.0000	-0.0000	
	(0.0013)	(0.0000)	(0.0000)	
ΔP_e		-0.0089	-0.0194***	-0.0267***
		(0.0066)	(0.0065)	(0.0060)
$\Delta P_e \times ED$		-0.0002**	-0.0002***	-0.0001**
		(0.0001)	(0.0001)	(0.0000)
$Vol \times ED$		-0.0000		
		(0.0001)		
$\hat{\phi}$	-0.8802***	-0.5943***	-0.6251***	-0.6122***
	(0.0465)	(0.0426)	(0.0406)	(0.0407)
$N \times T$	1920	1920	1920	1920

Notes: The regression in Eq. 2.2 is performed on the whole sample of countries. All estimations are obtained using the PMG estimator. Long-run coefficients and the error correction term, i.e. $\hat{\phi}$, are reported, while Short-run coefficients and the cross-sectionally augmented variables are included but not reported. The lag order is set to 3.

t statistics in parentheses.

* p<0.10, ** p<0.05, *** p<0.01

2.A.4 The Degree of Energy Dependency of G7 and BRIIC countries

Figure 2.12: The Degree of Energy Dependency of G7 countries.

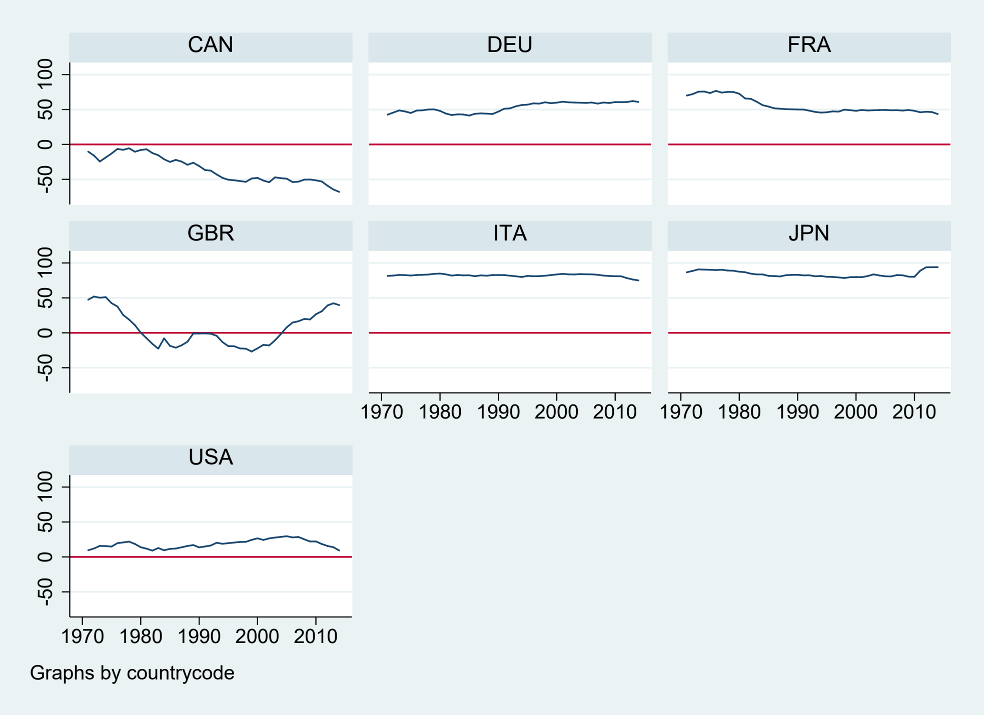
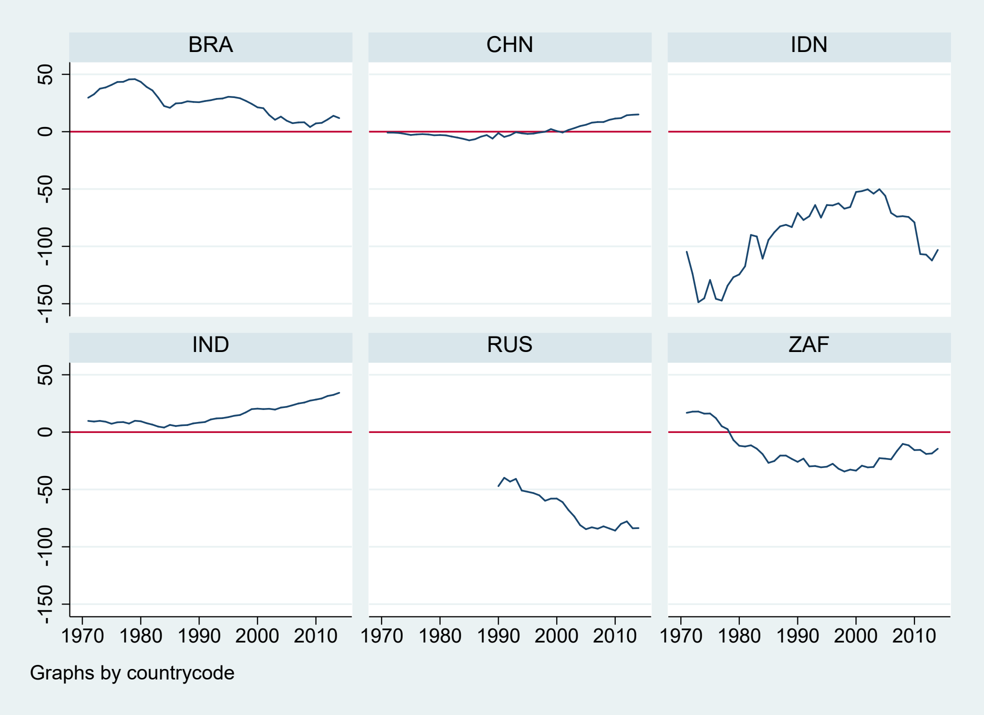


Figure 2.13: The Degree of Energy Dependency of Briics.



Chapter 3

Macroeconomic Effects of Climate Change: Evidence from the European Regions

Co-authored with Professor Kamiar Mohaddes

Macroeconomic Effects of Climate Change: Evidence from the European Regions

Co-authored with Dr. Kamiar Mohaddes

Abstract

We investigate the long-term macroeconomic effects of climate change on output and labour productivity of European industrial sectors, using a panel data set composed of the 281 European regions at NUTS 2 administration level from 1980 to 2017. Moreover, we analyse the main transmission channels through which climate change influences European economic activity, shedding some light on its impact on investments, employment and hours worked.

Overall, we do not find evidence of adverse or favourable effects of climate change on European economic growth at aggregate level, although all sectors and regions are diversely influenced by temperature and precipitation variations from their historical norms. Furthermore, we study the climate change effects in more and less developed regions, finding that the two sub-samples are differently affected and that the overall impact on economic growth in less developed regions is not higher than in more developed ones.

Finally, we notice that labour productivity is the main driver of climate change effects on growth and that agriculture, construction, and financial services sectors - the latter through the insurance industry - are the most affected sectors.

Keywords: Economic growth, Climate change, Heterogeneous panel, Sector data, Adaptation, NUTS, Europe.

JEL Codes: C33, O40, O44, O52, Q51, Q54, R11.

3.1 Introduction

The annual global average temperature has significantly increased in the last decades and the process is even accelerating. Indeed, the NOAA[1] classifies 2020 as the second-hottest year in centuries, just after 2016 (NOAA (2020)). However, global warming is only one of the numerous manifestations of climate change, which include changing temperature and precipitation patterns and more frequent extreme weather events, leading to droughts and floods, to melting glaciers and desertification, to rising sea levels and sea acidity, to wildfires and other disruptive events. These phenomena affect several aspects of our societies, from key macroeconomic indicators to relevant issues as health (Basu and Samet (2002)), political stability (Hsiang (2010), Dell et al. (2012) among many others), migrations (Falco et al. (2019), Feng et al. (2010)), and energy demand (Auffhammer and Mansur (2014), Wenz et al. (2017), Deschênes and Greenstone (2011)). This is a heavy burden since the last IPCC (2021) report demonstrates unequivocally the anthropogenic nature of climate change.

Cross-country empirical literature has found evidence of global - but asymmetrically distributed - effects, across countries (Burke et al. (2015), Acevedo et al. (2020), Dell et al. (2012), among others) and sectors (Hsiang (2010), Jones and Olken (2010), Dell et al. (2012), Agrawala et al. (2011), Kahn et al. (2019)). Indeed, scholars have established that output in both indoor and outdoor sectors is affected, mainly via labour productivity (Deryugina and Hsiang (2014), Behrer and Park (2017), Hsiang (2010), Hsiang et al. (2013), Deschenes (2014)). Nevertheless, empirical and theoretical papers suggest that climate change has an effect on labour supply (Graff Zivin and Neidell (2014), Graff Zivin et al. (2018)) and on investments (Fankhauser et al. (1997), Moore and Diaz (2015), Behrer and Park (2017), Henseler and Schumacher (2019), Acevedo et al. (2020)). Furthermore, scholars have studied the role of income heterogeneity, finding that poor countries and poor regions are more hit by climate change with respect to the rich ones (Dell et al. (2012), Newell et al. (2021), Letta and Tol (2019), Henseler and Schumacher (2019), Tol (2020), Olper et al. (2021)).

The stream of literature studying the macroeconomic impact of climate change is broad and rapidly increasing because precise estimates of these effects are fundamental for the design and evaluation of optimal adaptation and mitigation policies, at national and international level. Indeed, these policies rely on the scenarios created by the Integrated Assessment Models (IAMs), which, in turn, are calibrated and parametrized on empirical macroeconomic works. For instance, Stern et al. (2006) indicates IAMs as the best models to estimate global costs and risks of climate change. Therefore, a continuous improvement of the methodologies and a better comprehension of the economic channels through which climate change affects our societies is crucial to produce reliable estimates of the impact of climate change in the next decades.
However, there is not a large consensus on the pointwise estimates of the effects of climate change. For instance, Burke et al. (2015) estimates a positive impact on European GDP in the long-run, while Kahn et al. (2019) finds a negative impact.
Moreover, another highly debated issue concerns the functional relationship between climate change and GDP (Newell et al. (2021), Diffenbaugh and Burke (2019a), Rosen (2019), Diffenbaugh and Burke (2019b)). This is a key issue considering that growth effects have a persistent and cumulative impact on GDP, while level effects are temporary and may be reabsorbed in a few years.

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[1] NOAA is the US National Oceanic and Atmospheric Administration.

Our work aims to shed some lights on the long-term macroeconomic effects of climate change in Europe, with a particular focus on the channels of transmissions. Our dataset covers the gross value added, labour productivity, employment, hours worked and gross fixed capital formation of the 281 NUTS2[2] European regions, from 1980 to 2017. Moreover, for each indicator, we have sector-level data, following the NACE Revision 2 classification.

By exploiting the within-country variation in the data, we are able to investigate diverse countries, where country-averaged data cannot fully capture the heterogeneity and sparsity of climate features and where national macroeconomic indicators do not completely represent the different regional economic characteristics. Indeed, recent literature is questioning the reliability of country-level climate data and it is now focusing on within-country data analysis (Deryugina and Hsiang (2014), Burke and Tanutama (2019), Kalkuhl and Wenz (2020), and Damania et al. (2020)). Relying on sub-national data, we cast some lights on the relevance of precipitations, solving the puzzle of their significant effect in microeconometric studies, which is not found in many macroeconometric studies.

Moreover, we study the long-term climate change effects on gross value added, labour productivity, and other macroeconomic indicators, such as employment, hour worked and gross fixed capital formation, to verify which are the most relevant channels of transmission of temperature and precipitation changes, and which are the most affected sectors. As already said, these components are investigated at total and sectoral level.

Finally, we investigate whether income heterogeneity is a relevant issue, even though Europe is a rich and developed area[3], analysing the effects on more and less developed regions.

For all specifications, we estimate the climate change-economic growth relationship in European regions because even limited but persistent growth effects cause significant cumulative damages to economic activity over time, while level effects can be reabsorbed in a few years. To our knowledge, this is the first work that studies the long-term macroeconomic impact of climate change in Europe with such a complete, granular, and long dataset.

The rest of the papers is organized as follows. Section 2 is a literature review. Section 3 presents the data, and the empirical strategy, as well as the historical climate patterns of temperature and precipitations in Europe. Section 4 shows the main results of our analysis and Section 5 provides a focus on the channels of impact of climate change. Section 6 concludes.

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[2] The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU for the collection, development, and harmonisation of European regional statistics. The current NUTS 2016 classification is valid from 1 January 2018 and lists 104 regions at NUTS1, 281 regions at NUTS2, and 1348 regions at NUTS3 level. Eurostat.

[3] The IMF consider Bulgaria, Croatia, Romania, Poland, and Hungary as the only developing countries in the EU, representing 41 regions, which is the 14.8% of the total (IMF (2018)).

3.2 Related Literature

Among many other works, it is worth reading Dell et al. (2014) to understand how scholars have approached the study of the socio-economic effects of climate change. First, with Carleton and Hsiang (2016) and Kolstad and Moore (2020) it is a recent literature review on climate change economics, then it presents the main features of geo-referenced climate data and the most common econometric techniques used in this field. It shows that several aspects of our societies are affected by climate variations and extreme weather events, such as key macroeconomic indicators and other relevant issues as health (Basu and Samet (2002)), political stability (Hsiang (2010), Dell et al. (2012) and others), migrations (Falco et al. (2019), Feng et al. (2010)) and energy demand (Auffhammer and Mansur (2014), Wenz et al. (2017), Deschênes and Greenstone (2011)).

Specifically, this paper sheds some light on the manifold effects on the economy, showing that empirical works (i) have estimated significant impacts on aggregate GDP (Nordhaus (2006), Dell et al. (2009), Kalkuhl and Wenz (2020)) or specific sectors, mainly agriculture (Burke and Emerick (2016), Van Passel et al. (2017), Deschênes and Greenstone (2007), Schlenker and Roberts (2009), Hidalgo et al. (2010), Jones and Olken (2010), Hsiang (2010), Agrawala et al. (2011), Cachon et al. (2012), Dell et al. (2012)), (ii) have investigated the role of several channels of transmission, such as labour productivity (Deryugina and Hsiang (2014), Behrer and Park (2017), Tol (2020), among others), and that (iii) the impacts may be different due to the climate and income heterogeneity of considered countries.

Indeed, cross-country empirical analyses, which are the most relevant for our purpose, have underlined that hot and poor countries are more vulnerable to climate fluctuations (Dell et al. (2012), Burke et al. (2015), Newell et al. (2021), Letta and Tol (2019), Henseler and Schumacher (2019), Acevedo et al. (2020) and Tol (2020)). Among them, Kahn et al. (2019) presents an innovative econometric approach, investigating the macroeconomic impacts of climate change on the global GDP growth rate and the US sectoral GDP growth rate. One of the main contributions of that paper is its theoretical model warranting an effect on growth which is, by construction, persistent. Consequently, even small significant growth effects imply large damages over time. Moreover, this framework allows the authors to avoid the issue of trended climate data discussed in Kahn et al. (2019) and Mendelsohn (2016).

However, there is no consensus on the functional form of the climate-economy relationship (Newell et al. (2021), Diffenbaugh and Burke (2019a), Rosen (2019), Diffenbaugh and Burke (2019b)), with scholars debating on three forms: level-level relationship, growth-level, and growth-growth relationship.

Another open issue concerning the specification of the climate-economy relationship refers to the inclusion of precipitation changes. While the cross-model validation work of Newell et al. (2021) empirically suggests that embedding precipitations do not improve the estimation results, Auffhammer et al. (2013), Dell et al. (2014) and Tol (2020) underline that it is better to include them to avoid the risk of omitted variable bias. Moreover, recent studies show that the lack of significance in the precipitation effects on economic variables in cross-country empirical works depends on the reliance on country-level climate data. Indeed, Damania et al. (2020) shows that the precipitation puzzle - the presence of a relevant impact of precipitation effects in micro studies and its absence in macro studies - is solved using sub-national climate and economic data, avoiding country-level data aggregation.

Thus, the use of within-country data is more and more frequent, as in Deryugina and Hsiang (2014), Burke and Tanutama (2019), Kalkuhl and Wenz (2020), Hertel and de Lima (2020), and the increasing granularity of datasets, from national to gridded climate and economic data, is more and more appreciated in this field.

Focusing on the European case, García-León (2015) and Holtermann and Rische (2020) are the only two papers investigating the temperature and precipitation effects on the economy of EU regions, with the first one concerning the NUTS 2 regions of the five largest Western European countries and the latter concerns NUTS 3 regions in 15 EU countries. These two papers analyse the climate change effects on economic activity at aggregate and sectoral level, using three sub-groups of sectors - agriculture, industry, and services -, but they do not focus on the channels of transmission, which are a highly discussed issue.

In fact, most of the empirical literature investigates the impact on productivity and labour supply, while a few papers focus on physical capital. Among many others, it is worth citing Deryugina and Hsiang (2014), Behrer and Park (2017) and Letta and Tol (2019), that concentrate on productivity, Graff Zivin and Neidell (2014) and Graff Zivin et al. (2018) that estimate the effects on labour supply, and Acevedo et al. (2020) that focuses on investments. Moreover, only a couple of papers investigate the effects of climate change on several channels of transmissions, such as Henseler and Schumacher (2019), which estimates the effects on total factor productivity, employment, and capital in a large pool of countries, and Zhang et al. (2018), which adopts a firm-level perspective.

3.3 Data and Empirical Approach

We estimate the long-run relationship between climate change and economic growth in Europe, using sub-national sectoral data, aiming at shedding some light on the channels of impact.

We build the population-weighted climate variables from the Matsuura and Willmott (2018) gridded temperature and precipitation series and the CIESIN (2016) population density in 2015. The within-country economic data are obtained from the ARDECO European Commission dataset and refer to gross value added, employment, hours worked and gross fixed capital formation of the 281 NUTS2[4] European regions for the 1980-2017 period. Moreover, we build two indexes of labour productivity dividing the gross value added of each region by their employment and hours worked.

The ARDECO dataset has annual frequency, and it is composed of sectoral level data, following the NACE Revision 2 classification, as in Table 3.17. For the following analysis, we use an unbalanced panel with an average $T \approx 33$ and $N = 276$, since the economic data of former soviet countries have some missing observations in the first part of the series. We decide to exclude the 5 French *Outre-mer* regions[5] for their very peculiar economic and climate characteristics.

We use a long-run approach to analyze the effects of climate change, since an approach based on identification would end up quantifying the impact of the considered extreme weather event, leaving aside the manifold and inertial nature of this phenomenon (Tol (2020)). Hence, a panel approach adapted for long-run analysis is the most suitable methodology to investigate climate change.

The proposed methodology is inspired by Kahn et al. (2019) and consists in estimating a cross-sectionally augmented panel ARDL model for each industrial sector, using an economic performance measure as dependent variable and the positive and negative deviations of temperature and precipitations from their historical norms as climate variables.

This scheme is proposed for several measures of economic performance - labour productivity, gross value added, employment, hours worked and gross fixed capital formation - to fully in-

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[4] The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU for the collection, development, and harmonisation of European regional statistics. The current NUTS 2016 classification is valid from 1 January 2018 and lists 104 regions at NUTS1, 281 regions at NUTS2, and 1348 regions at NUTS3 level. Eurostat.

[5] We are not considering the NUTS2 regions outside geographical Europe: Mayotte, La Reunion, Guadalupe, Martinique, Guyana. These regions have a tropical climate and economic characteristics.

vestigate how climate change impacts the European economic growth in the long run.
This approach is consistent with the literature and fits with the data, taking into account for the dynamics and feedback effects among climate and economic variables, for the non-linearity of their relationship, for the cross-sectional dependence in the data, and for the heterogeneity over sectors and income.
Moreover, our dataset gives us the possibility to investigate diverse countries, where country-averaged data cannot fully capture the heterogeneity and sparsity of climate features and where national macroeconomic indicators do not completely represent the different regional economic characteristics. Indeed, the reliability of country-level climate data has been questioned in several papers and literature is now focusing on within-country data analysis (Deryugina and Hsiang (2014), Burke and Tanutama (2019), Kalkuhl and Wenz (2020), and Damania et al. (2020)).

We rely on this panel ARDL approach because it fits for long-run analysis and because of its properties, clearly exposed by Pesaran in a series of papers (Pesaran and Smith (1995), Pesaran (1997) and Pesaran and Shin (1998)) showing that this approach is robust to the omitted variable bias, to the I(0) or I(1) nature of the considered variables, and that it allows for feedback effects among variables.
Furthermore, the produced estimates are consistent if a sufficient number of lags is used (Chudik et al. (2016)). After considering different lag orders, we decide to use 3 lags for all variables, avoiding any data mining critique due to the use of a different number of lags for the variables. This choice is endorsed by several applied econometrics works, i.e. Chudik et al. (2016), Kahn et al. (2019) and Mohaddes and Williams (2020).
As in Kahn et al. (2019), we rely on the half-panel Jackknife fixed effect estimator (HPJFE) because it does not suffer from the Nickell bias[6] due to the large time dimension of data. The properties of this estimator, shown in Chudik et al. (2018), fit particularly well our dataset.
Moreover, we add the cross-sectional augmentation of the dependent variable to account for the presence of cross-sectional dependence in our data.
Following the literature, we assume that the error has a multi-factor structure

$$u_{i,t} = \lambda_i f_t + \varepsilon_{i,t}$$

where f_t are the unobserved common factors, λ_i are their loadings, and $\varepsilon_{i,t}$ is the serially uncorrelated idiosyncratic error with zero mean. As proposed in Pesaran et al. (2015), we proxy the unobserved common factors term, $\lambda_i f_t$, with the cross-sectional average of the dependent variable.

Turning to the climate variables, we use the positive and negative deviations of temperature and precipitation from their historical norms, and their lags. This choice allows us to investigate whether there is a non-linearity in the climate change-economic growth relationship, avoiding the problems related to the presence of a trend in climate data, i.e. Kahn et al. (2019).
Although Newell et al. (2021) concludes that specifications embedding temperature only perform better, our main specification includes both temperature and precipitation. Indeed, several paper using within country data find a significant precipitation effect. To ensure the robustness of our choice, we test different climate specifications. First, we check for alternative definitions of historical norms of temperature and precipitation in Table 3.10. Second, we control for a linear relationship between climate change and economic growth, using absolute deviations of temperature and precipitations from their historical norms (Table 3.14). Since we

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[6] Nickell (1981) demonstrates that the standard Fixed Effect estimator produces biased estimates in dynamic panel data sets.

note that including precipitation changes do not significantly modify the impact of temperature changes on the labour productivity growth of European regions and that these changes have a significant effect in the long-run (Panel A and B, Table 3.15), we conclude that excluding precipitation variations lead to an underestimation of the long-run economic damages caused by climate change. Therefore, we keep precipitation changes in our main specification.

For all specifications, we do not include the key variables used in growth theory, such as human capital and institutional quality, following the standard literature approach. The exclusion of these variables from the regressions is aimed at avoiding the bias due to "bad controls", since they may, in turn, be determined by climate variables (see Angrist and Pischke (2009), Hsiang et al. (2013), Dell et al. (2014) for a comprehensive explanation). However, the standard literature approach uses fixed effects and time-region fixed effects to account for individual time-invariant factors and common trends. Analogously, we employ individual fixed effects and the cross-sectional augmentation of the dependent variable to account for all these features.

We estimate the following panel CS-ARDL model for each sector, for each considered economic performance indicator:

$$\Delta y_{i,t} = \alpha_i + \sum_{l=1}^{p} \gamma_l \Delta y_{i,t-l} + \sum_{l=0}^{p} \beta_l \Delta \mathbf{x}_{i,t-l} + \sum_{l=0}^{p} \varphi_l \Delta \bar{y}_{t-l} + \varepsilon_{i,t} \tag{3.1}$$

where $y_{i,t}$ is the log of the economic performance measure (i.e. labour productivity) in administrative unit i at time t, α_i is the region-specific fixed effect, $\bar{y}_t$ is the log of the cross-sectional average of the economic performance measure at time t, $\mathbf{x}_{i,t}$ is the vector of the deviations of climate variables from their historical norms and $\varepsilon_{i,t}$ is the serially uncorrelated idiosyncratic error. The climate change vector, $\mathbf{x}_{i,t}$, is:

$$\mathbf{x}_{i,t} = \left(\left(\mathbf{C}_{i,t} - \mathbf{C}^{*}_{i,t-1}\right)^{+} ; \left(\mathbf{C}_{i,t} - \mathbf{C}^{*}_{i,t-1}\right)^{-} \right)$$

where $\mathbf{C}_{i,t}$ is the vector of population-weighted temperature, $T_{i,t}$, and precipitations, $P_{i,t}$, while $\mathbf{C}^{*}_{i,t-1}$ is the vector of their historical norms: $\mathbf{C}_{i,t} = \left(T_{i,t}, P_{i,t}\right)$ and $\mathbf{C}^{*}_{i,t} = \left(T^{*}_{i,t}, P^{*}_{i,t}\right)$.

Following Arguez et al. (2012) and Vose et al. (2014), we use the 30 years moving average as measure of the historical norms of climate variables, but we check for the robustness of our choice in Table 3.10

$$\mathbf{C}^{*}_{i,t-1} = \left(\frac{1}{30}\right) \left[\sum_{s=1}^{30} \mathbf{C}_{i,t-s} \right]$$

Since our focus is on the long-run effects of climate change, we compute the average long-run coefficients, θ, from the short-run coefficients in Equation 3.1:

$$\theta = \frac{\sum_{l=0}^{p} \beta_l}{1 - \sum_{l=1}^{p} \gamma_l}$$

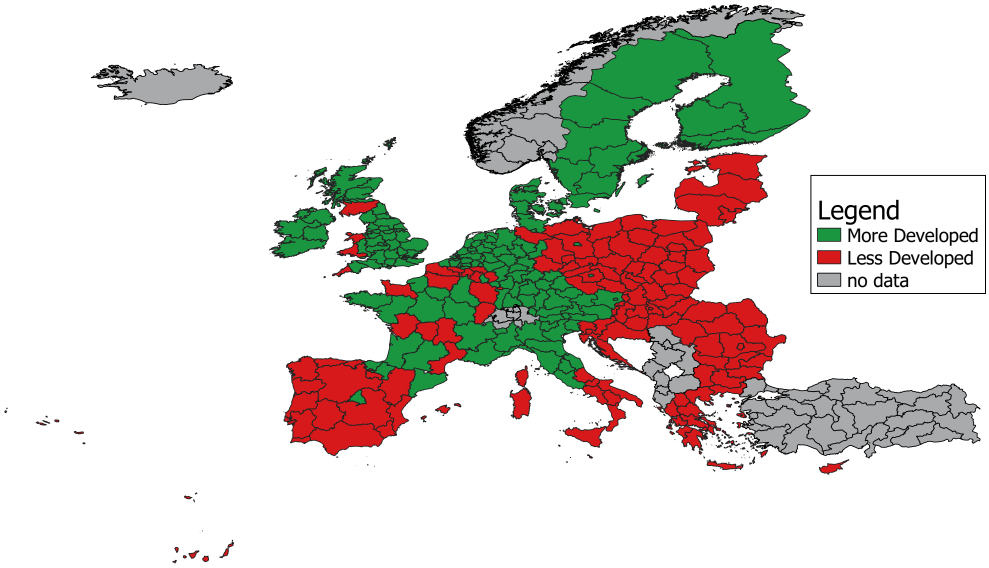
It is worth noting that our approach implies households and firms adapt to changes in historical norms of temperature and precipitations, but they are affected by fluctuations of climate variables above and below it. Consequently, unlike most of the literature, we are not estimating the effects of temperature rises and falls, but the long-run effects of temperature fluctuations around their historical norm.

Moreover, we concentrate on growth effects because, following Dell et al. (2012), they are not mean-reversing, cause permanent damages, and can be estimated as changes in productivity growth. On the other side, level effects are temporary, caused by specific weather shocks, and can be estimated by variations in output level. In other words, the first ones are long-lasting and imply large consequences over time, while the second ones are short-lived and reabsorbed in a few years.

To enrich our analysis, we estimate the effects of climate change on two sub-samples to study if these effects are different in more and less developed regions[7]. A region i is defined less (more) developed if its PPP gross regional product per capita is below (above) the European median over the 1980-2017 period. This criterion defines 122 less developed regions and 154 more developed regions, as in Figure 3.1.

We check the robustness of our results using different classifications of less and more developed regions, without encountering significant differences. In particular, we estimate the climate change effects on less developed, transitional and more developed European regions, as defined by the EU funding criteria for the distribution of the 2014-2020 European Social Fund and the European Regional Development Fund[8].

Figure 3.1: Less and more developed regions.



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[7] Indeed, literature has established that income heterogeneity is more relevant than temperature heterogeneity, showing that poor countries and regions are hit harder by climate change with respect to hot ones (Dell et al. (2012), Burke et al. (2015), Newell et al. (2021), Burke and Tanutama (2019), Henseler and Schumacher (2019), Letta and Tol (2019), Acevedo et al. (2020), Tol (2020), Olper et al. (2021)). This is partially due to the almost complete overlapping of poor and hot countries that complicates the identification of the effects of climate change in the two sub-samples. However, in our dataset, just 46% of hot regions are considered poor.

[8] This classification is based on income per capita and it is different from ours for mainly three reasons. First, the regions are divided into three groups, i.e more developed, transitional, less developed regions, while we split them into two groups, i.e. more and less developed regions. Second, it is based on the 2010 NUTS2 classification, while ours is based on the most recent one, which is the 2016 NUTS2 classification. Third, the income threshold(s) are set on different criteria. In this work, a region is defined more (less) developed if its gross regional product per capita in PPP is below (above) the European median over the 1980-2017 period, to take into account for the relevant dynamics of regions over time. On the other side, the EU divides less developed, transitional and more developed regions based on a three-year average of income per capita, which is renewed every seven years, because the allocation of European funds is based on a seven-year rolling window. Although this two classification methods are very different, the estimations suggest similar effects in all sectors and a mainly non-linear climate change-economic growth relationship.

3.3.1 Climate Change: European Historical Patterns

Europe lies in a comfortable climate zone and it has been less affected by climate change with respect to other areas of the world. However, the effects of climate change are quite remarkable, since we see temperatures growing all over Europe (Figures 3.2 and 3.3) and that this upward pressure is even accelerating over time (Table 3.2). In particular, temperatures are rising in almost every region - 275 over 276 -, but following different paths. For example, cold areas, such as Scandinavia, northern Italy, and eastern European regions, are heating up faster than the others (Figure 3.3).

Tables 3.3 and 3.4 show that temperature are rising in all the considered sub-sample, and that they are stationary around an increasing trend.

Turning to precipitations, they are increasing in eastern Europe and decreasing in central Europe, in Spain, and in part of Ireland and the UK. Indeed, floods and droughts are becoming more frequent phenomena in Europe (Blöschl et al. (2017), Blöschl et al. (2019) as regards to floods and Hisdal et al. (2001), Feyen and Dankers (2009) and Spinoni et al. (2018) as regards to droughts).

Table 3.1: Temperature and Precipitation, 1980-2017

	Observations $N \times T$	Mean	Median	Standard Deviation	Skewness	Kurtosis
Temperature	10488	10.30338	9.878817	2.969316	.4973715	3.631177
Precipitation	10488	7.601473	7.224855	2.445982	.8772053	4.412259

Temperature in Celsius degrees. Precipitation in total deciliters.

Figure 3.2: Temperature distribution of European regions over time.

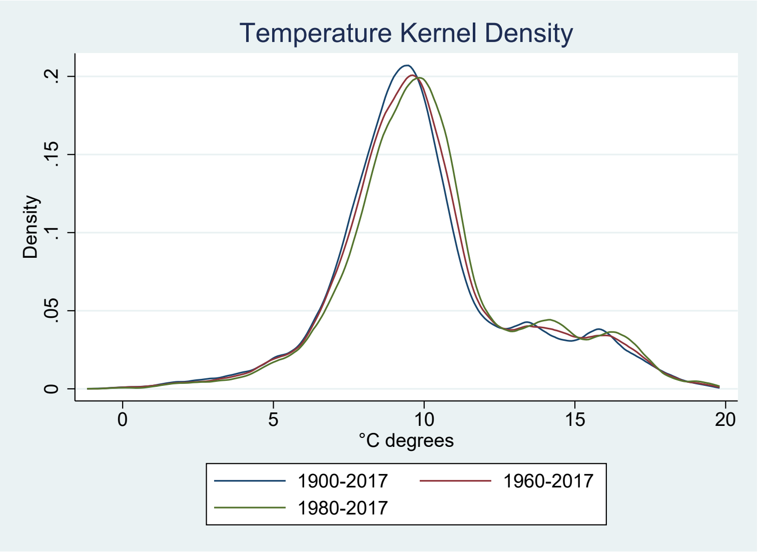


Table 3.2: Temperature Average Yearly Rise in European regions

	Whole Sample 1900-2017	Sub-Sample 1960-2017	Sub-Sample 1980-2017
trend	0.0061***	0.0222***	0.0309***
	(0.0002)	(0.0005)	(0.0006)
constant	9.6272***	8.1205***	7.2301***
	(0.0144)	(0.0645)	(0.0407)
$N \times T$	32568	16008	10488

Notes: The estimates are based on the following equation: $T_{i,t} = \alpha_i + \beta_i t + u_{i,t}$ where $T_{i,t}$ is the population-weighted average temperature in °C and t is the time trend. Asterisks indicate statistical significance at the 10% (*), 5% (**), 1% (***) levels.

Table 3.3: Panel Unit Root Tests, Temperatures

Time Span	Method	Form	Statistic value	p-value
Whole Sample 1900-2017	IPS	trend, no lags	-100.0020	0.0000
Sub Sample 1960-2017	IPS	trend, no lags	-66.6043	0.0000
Sub Sample 1980-2017	IPS	trend, no lags	-52.9388	0.0000

Notes: The IPS is the Im-Pesaran-Shin panel unit root test. The null hypothesis of the IPS test is that all panels contain unit roots, while the alternative is that some panels are stationary.

Table 3.4: Temperature Average Yearly Rise in Less and More Developed Regions

	Less Developed Regions			More Developed Regions		
	Whole Sample 1900-2017	Sub-Sample 1960-2017	Sub-Sample 1980-2017	Whole Sample 1900-2017	Sub-Sample 1960-2017	Sub-Sample 1980-2017
trend	0.0051***	0.0208***	0.0326***	0.0069***	0.0232***	0.0295***
	(0.0004)	(0.0008)	(0.0010)	(0.0003)	(0.0005)	(0.0008)
const	10.7170***	9.2520***	8.0466***	8.7638***	7.2241***	6.5832***
	(0.0219)	(0.0727)	(0.1045)	(0.0182)	(0.0433)	(0.0793)
$N \times T$	14396	7076	4636	18172	8932	5852

Notes: The estimates are based on the following equation: $T_{i,t} = \alpha_i + \beta_i t + u_{i,t}$ where $T_{i,t}$ is the population-weighted average temperature in °C and t is the time trend. Asterisks indicate statistical significance at the 10% (*), 5% (**), 1% (***) levels.

Table 3.5: Descriptive Statistics of Temperature Changes above and below its historical norm

	All Regions		Less Dev. Regions		More Dev. Regions	
	Mean	SD	Mean	SD	Mean	SD
$\Delta\left(T_{i,t} - T^{*}_{i,t-1}\right)^{+}$	0.0041	0.507	0.0022	0.487	0.0031	0.493
$\Delta\left(T_{i,t} - T^{*}_{i,t-1}\right)^{-}$	-0.0038	0.462	-0.0002	0.475	-0.0031	0.478

Table 3.6: Two-sample t-test with unequal variances

Variable 1	Variable 2	Difference in mean	Standard Error	t-test	p-value
$\left(T_{i,t} - T^{*}_{i,t-1}\right)^{+}$ in less dev. regions	$\left(T_{i,t} - T^{*}_{i,t-1}\right)^{+}$ in more dev. regions	0.0017	0.0111	0.1524	0.8788
$\left(T_{i,t} - T^{*}_{i,t-1}\right)^{-}$ in less dev. regions	$\left(T_{i,t} - T^{*}_{i,t-1}\right)^{-}$ in more dev. regions	-0.0018	0.0079	-1.030	0.3027
$\left(T_{i,t} - T^{*}_{i,t-1}\right)^{+}$ in less dev. regions	$\left(T_{i,t} - T^{*}_{i,t-1}\right)^{-}$ in less dev. regions	0.0020	0.0051	0.4054	0.6852
$\left(T_{i,t} - T^{*}_{i,t-1}\right)^{+}$ in more dev. regions	$\left(T_{i,t} - T^{*}_{i,t-1}\right)^{-}$ in more dev. regions	0.0000	0.0049	0.0075	0.9940

Notes: The null hypothesis for the two-sample t-test with unequal variances is that the difference in mean is zero, while the alternative one is that it is statistically different from zero.

As shown in Table 3.5, the temperature fluctuations above and below its historical norm have similar means and standard deviations, in the considered sub-samples. Moreover, the two-sample t-test with unequal variances suggest that the temperature variables, which are used in first differences in our estimations, are not statistically significantly different (Table 3.6).

Figure 3.3: Temperature change over time, 1980-2017.

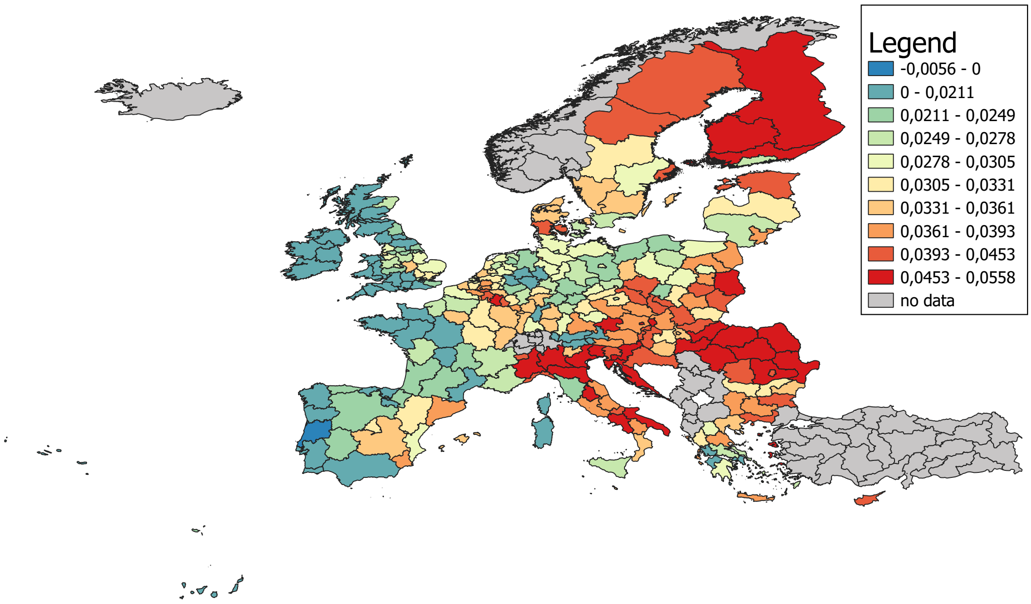
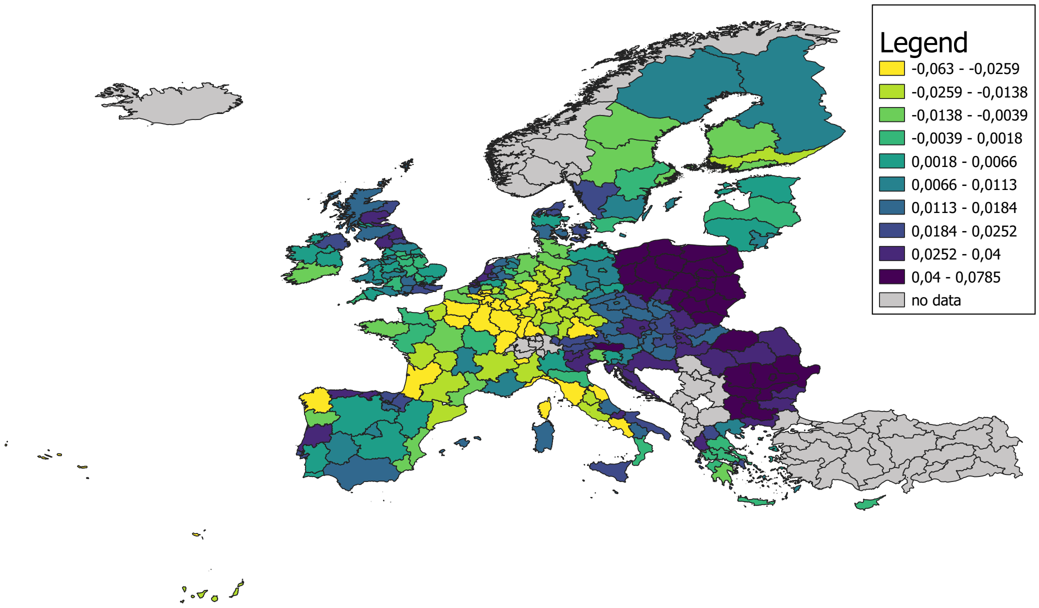


Figure 3.4: Precipitations change over time, 1980-2017.



3.4 Baseline Results

Our main results are summarized in Table 3.7, where it is possible to appreciate widespread statistically significant effects on sectoral gross value added and labour productivity. Moreover, these effects are present in both indoor and outdoor sectors and reveal a prevalent non-linearity in the climate change-economic growth relationship.
However, we do not find evidence of adverse or favorable effects of climate change on European economic growth at aggregate level, although all sectors and regions are diversely influenced by temperature and precipitation variations from their historical norms. The lack of a significant long-run macroeconomic impact of climate change on aggregate economic growth is comprehensible considering that Europe is a rich and developed area, and that the positive and negative effects may counter-balanced themselves. Indeed, the European economic structure is characterized by (i) a prevalence of indoor activities, (ii) a wide utilization and diffusion of air conditioning and advanced machinery, (iii) a skilled labour force, (iv) a developed and globally integrated financial market, and (v) high investments in R&D and adaptive technologies.
Nevertheless, our analysis suggests that the growth rate of gross value added and labour productivity of several sectors is influenced by climate change. Among the most exposed sectors to climate variations, we count the agricultural and the construction sectors because most of the job consists of outdoor tasks (IPCC (2014), ILO (2018)), and the energy, mining, and manufacturing industry because "facilities are typically not climate-controlled and the production process often generates considerable heat" for the US National Institute for Occupational Safety and Health (NIOSH) Behrer and Park (2017)).

Focusing on the long-run effects of climate change on the agricultural sector, we notice that most scholars estimate the variations in land production (Schlenker and Roberts (2009), Burke and Emerick (2016), Auffhammer and Schlenker (2014)), leaving aside the impacts on labour productivity, despite the labour-intensive nature of the agricultural sector (Hertel and de Lima (2020)). Thus, our analysis sheds some light on an under-investigated issue, like the effects of climate change on agricultural labour productivity in a rich and developed area, such as Europe, where Olesen and Bindi (2002) and Olper et al. (2021) are the only examples of paper studying that issue.
Our estimates suggest that temperature fluctuations above and below its historical norm, i.e. $\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{+}}$ and $\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{-}}$, negatively affect the agricultural gross value added (Panel A, Table 3.7) and labour productivity (Panel B and C, Table 3.7) while positively affecting the construction sector. These findings are supported by the signs, magnitudes, and statistical significance of the coefficients of an alternative index of labour productivity (Panel C, Table 3.7). Moreover, literature finds non-linear effects of temperature movements on agriculture (Deschênes and Greenstone (2007), Schlenker and Roberts (2009), Deryugina and Hsiang (2014)). Interestingly, Panel B in Table 3.7 suggests that heat and cold stress influence working conditions, as well as rising precipitations. This positive and significant (at 5% level) impact of increasing precipitation that is supported by Fishman (2016).

As previously discussed, global warming causes significant damages in the agricultural sector, but it seems to be detrimental even for the manufacturing, energy, and mining sector, which has a more relevant share in European output (Table 3.18). Indeed, we notice a negative effect of temperature fluctuations above its historical norm, i.e. $\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{+}}$, on gross value added and labour productivity, consisting in respectively -0.0163 and -0.0137 (Panel A and C, Table 3.7). This negative effect on the manufacturing, energy, and mining sector has been found in several works (Cachon et al. (2012), Dell et al. (2012), Sudarshan and Tewari (2014), Barreca et al. (2016)) and it is mostly driven by manufacturing, since it represents around the 85% of that sector, leaving the rest to energy and mining industries. For instance, Kahn et al. (2019) confirms the adverse and significant impact of climate change on US manufacturing and mining sectors. However, the literature is not unanimous on the warming impact on mining and energy industries, even though the latter is considered as one of the most vulnerable industries (Hsiang (2010)). Zhang et al. (2018) finds a non-significant effect of warming on coal mining and on ferrous and non-ferrous metal mining in China, Colacito et al. (2019) estimates a positive impact of rising temperature on the US mining and utilities industries, and Hsiang (2010) finds a negative significant impact on mining and utilities sector in Caribbean countries. Overall, it is possible to assess that global warming causes a long-term negative and significant effect on the European manufacturing, energy, and mining sector, which is mainly driven by the manufacturing industry.

Nevertheless, climate change positively affects specific European sectors in the long-run. For instance, labour productivity in the construction and business and financial services sectors is positively affected by rising temperature. Specifically, labour productivity in the construction sector is favorably influenced by temperature changes, while being negatively affected by rising precipitations. The beneficial impact of increasing temperature on construction labour productivity may be counter-intuitive but comprehensible for several reasons. First, warming may increase labour productivity in cold regions. Second, the ILO (2019) report indicates that some European countries, either developed or developing such as Germany and Romania, have specific unemployment benefits which are paid in case of work interruptions due to unfavorable weather conditions. This may result in increased labour productivity at the resumptions of works since the downside effects are avoided[9]. Third, Hallegatte and Vogt-Schilb (2016) shows that there is a rise in the US construction employees' compensation in the aftermath of extreme event shocks, due to the effort in adaptation and mitigation of buildings and infrastructures disposed to cope with climate change. This effort results in an increased sectoral output, which is supported by ILO (2019), underlying its beneficial effect on construction value added and employment through increasing investments in adaptation and climate-resilient infrastructures. Tables 3.7 and 3.11 confirm this finding for the European case. Fourth, the ILO (2019) report indicates that, although agricultural and construction workers are the most hit by warming, a smarter urban planning, a continuous building site monitoring of the weather conditions, "enhanced information sharing and communication, and technological improvements can enable construction workers and their employers to adapt more effectively to heat stress". Indeed, Europe is at the frontier in the implementation of these advances, which are beneficial even in terms of mitigation and adaptation to climate change effects on labour productivity.

Interestingly, the business and financial services sector can extract profit from climate change, probably through the insurance industry. Specifically, temperature changes above and below its historical norm and precipitation changes above its historical norm have a significant positive effect on the gross value added of this sector. Moreover, the effects of $\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$ and $\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^+}$ on labour productivity are positive too. This evidence is consistent with the estimation results in Kahn et al. (2019) for the US business and financial sector, suggesting that the rise in the gross value added is due to the higher insurance premiums asked to hedge against climate risks. Indeed, Colacito et al. (2019) finds that the US insurance industry is affected by climate change, while the other industries within the same sector, namely financial, real estate,

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[9] Nonetheless, alongside these welfare provisions, construction and agricultural sectors are characterized by a high level of informality, implying that the working conditions in the declared and undeclared labour market may react differently to climate change.

and business services industries, are not significantly influenced. This peculiar positive effect is probably due to the level of development of the financial markets in the US and the EU, but it is likely to change in the next future since climate change is accelerating and more frequent extreme weather events will put a lot of pressure on these industries.
At the same time, this is a mainly indoor sector, then its labour productivity is less vulnerable to climate change.

We now turn our attention to the effects on the wholesale trade, retail trade, transport, food and accommodation, information and communication sectors, e.g. WTRAFIC, and in non-market services sectors. The interpretation of the estimated coefficients is difficult, as well as their comparison with the coefficient obtained in other empirical works, because these sectors are composed of numerous and heterogeneous industries. However, we see that rising temperature positively influence the gross value added in the non-market services sector as in Kahn et al. (2019). Nonetheless, we notice that the labour productivity in both sectors is positively affected by decreasing temperature, $\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-} > 0$, and that the non-market services sector is positively affected by decreasing precipitations too.
In this case, as in many others, our estimates show that precipitation changes have remarkable impacts on economic activity, casting some lights on the precipitation puzzle. As underlined by Damania et al. (2020), microeconometric studies find evidence of significant precipitation effects, while most macroeconometric studies do not find them. The latter typically rely on country-level data to make cross-country comparisons, unaware that this level of data aggregation reduces or sterilizes the impacts of precipitations on macroeconomic indicators.
However, a few macroeconomic studies do find a significant impact of precipitation on annual labour productivity growth (Henseler and Schumacher (2019), Letta and Tol (2019)) and gross domestic product growth (Dell et al. (2012)).

To fully capture the complexity of the macroeconomic effects of climate change on economic growth, we extend the analysis by studying the main channels of transmission of climate variations on economic activity, i.e. employment, hours worked, gross fixed capital formation, and investigating whether these climate fluctuations have heterogeneous effects in more and less developed European regions[10].
To this end, we investigate the presence of income heterogeneity in the long-term macroeconomic effects of climate change on gross value added and labour productivity (Tables 3.8 and 3.9), and we discuss these effects on employment, hours worked and gross fixed capital formation in Section 3.5.

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[10] The classification in more and less developed regions is discussed in Section 3.3 and it is based on regional income per capita, defining 122 less developed regions and 154 more developed regions, as shown in Figure 3.1.

Table 3.7: Long-Term Effects of Climate Change on the Sectoral Output and Labour Productivity Growth in European regions, 1980-2017

	Total	Agriculture, Forestry, Fishing	Manufacturing, Energy, Mining	Construction	WTRAFIC	Financial, Business Services	Non-market Services
Panel A: Gross Value Added							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$	0.0019	-0.0355***	-0.0163*	0.0425***	-0.0050	0.0203***	0.0104*
	(0.0044)	(0.0107)	(0.0086)	(0.0107)	(0.0053)	(0.0060)	(0.0063)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-}$	-0.0045	-0.0409**	-0.0004	0.0814***	0.0219***	0.0320***	0.0061
	(0.0071)	(0.0190)	(0.0132)	(0.0153)	(0.0076)	(0.0088)	(0.0101)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^+}$	0.0002	-0.0015	0.0030	-0.0089	0.0006	0.0079**	-0.0001
	(0.0020)	(0.0068)	(0.0046)	(0.0056)	(0.0027)	(0.0032)	(0.0030)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^-}$	0.0024	-0.0067	0.0079	-0.0050	-0.0041	0.0059	0.0019
	(0.0033)	(0.0062)	(0.0057)	(0.0063)	(0.0033)	(0.0037)	(0.0041)
$N \times T$	8336	8158	8164	8164	8164	8164	8164
Panel B: Labour Productivity (based on employment)							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$	0.0016	-0.0333***	0.0004	0.0138*	-0.0027	0.0169**	0.0090
	(0.0038)	(0.0125)	(0.0063)	(0.0078)	(0.0053)	(0.0071)	(0.0062)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-}$	-0.0027	-0.0418**	-0.0020	0.0279***	0.0156**	0.0069	0.0173*
	(0.0059)	(0.0196)	(0.0100)	(0.0106)	(0.0079)	(0.0104)	(0.0095)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^+}$	0.0014	0.0129*	-0.0001	-0.0094**	0.0002	0.0121***	-0.0010
	(0.0019)	(0.0070)	(0.0035)	(0.0043)	(0.0028)	(0.0037)	(0.0033)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^-}$	0.0015	-0.0032	0.0018	-0.0047	-0.0029	0.0056	0.0067*
	(0.0026)	(0.0076)	(0.0037)	(0.0044)	(0.0033)	(0.0038)	(0.0040)
$N \times T$	8196	8006	8116	8116	8116	8116	8116
Panel C: Labour Productivity (based on hours worked)							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$	0.0039	-0.0391***	-0.0137**	0.0253***	0.0029	0.0135	0.0018
	(0.0038)	(0.0126)	(0.0069)	(0.0082)	(0.0072)	(0.0087)	(0.0071)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-}$	0.0063	-0.0531***	-0.0107	0.0335***	0.0145	0.0277**	0.0153
	(0.0060)	(0.0197)	(0.0114)	(0.0113)	(0.0106)	(0.0126)	(0.0108)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^+}$	0.0040**	-0.0010	-0.0052	-0.0132***	-0.0006	0.0107***	0.0057
	(0.0020)	(0.0071)	(0.0038)	(0.0042)	(0.0037)	(0.0042)	(0.0037)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^-}$	0.0011	-0.0062	-0.0002	-0.0115**	-0.0006	0.0133***	0.0113***
	(0.0025)	(0.0075)	(0.0040)	(0.0045)	(0.0042)	(0.0048)	(0.0043)
$N \times T$	7988	6896	6902	6902	6902	6902	6902

Notes: The estimates are based on Equation 3.1: $\Delta y_{i,t} = \alpha_i + \sum_{l=1}^{p}\gamma_l \Delta y_{i,t-l} + \sum_{l=0}^{p}\beta_l \Delta \mathbf{x}_{i,t-l} + \sum_{l=0}^{p}\varphi_l \Delta \bar{y}_{t-l} + \varepsilon_{i,t}$, where $y_{i,t}$ is the log of the economic performance measure in region i at time t, α_i is the region-specific fixed effect, $\bar{y}_t$ is the log of the cross-sectional average of the economic performance measure at time t, and $\mathbf{x}_{i,t}$ is the vector of climate variables, defined as follows $\mathbf{x}_{i,t} = \left[\left(T_{i,t} - T^*_{i,t-1}\right)^+; \left(T_{i,t} - T^*_{i,t-1}\right)^-; \left(P_{i,t} - P^*_{i,t-1}\right)^+; \left(P_{i,t} - P^*_{i,t-1}\right)^-\right]$, where $T_{i,t}$ and $P_{i,t}$ are population-weighted average temperature and precipitation of region i at time t, and $T^*_{i,t-1}$ and $P^*_{i,t-1}$ are their historical norms (based on moving averages of the past 30 years). The long-run effects, $\widehat{\theta}$, are calculated from the OLS estimates of the short-run coefficients: $\theta = \frac{\sum_{l=0}^{p}\beta_l}{1-\sum_{l=1}^{p}\gamma_l}$. The lag order, p, is set to 3. WTRAFIC is wholesale, transportation, retail, food and accommodation, information and communication sectors. The standard errors are clustered as proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 10% (*), 5% (**), 1% (***) levels.

Turning to the estimation results in Tables 3.8 and 3.9, we notice that the long-run effects of climate change on the gross value added and labour productivity are widespread over sectors, but diverse. Although we do not find any discordance comparing significant effects of climate change in the two sub-samples of regions, it is worth noting that some sectors are influenced by temperature and precipitation changes in one sub-sample and unaffected in the other one, or vice versa. For instance, the agricultural gross value added in less developed regions is significantly affected by climate change, while in more developed regions it is not. However, we cannot claim that less developed regions are associated with slower aggregate economic growth. Indeed, even noticing that the magnitude of these effects vary in the two sub-samples in specific sectors, the confidence intervals of several coefficients overlap in more and less developed regions.

The most relevant difference in the effects of climate change between more and less developed regions refers to temperature changes below their historical norm[11], emphasizing once again that climate change is a complex phenomenon, and that global warming is just one of its manifestations. Specifically, we see a significant negative effect on aggregate labour productivity in less developed regions which is caused by temperature changes below their historical norm, and mainly driven by labour productivity in the manufacturing, energy and mining sector. Indeed, the 2021 Texas power crisis[12] shows that cold waves cause disruptive effects on economic activity, and that they are particularly harmful to this sector. Furthermore, Bloesch and Gourio (2015) studies the consequences of the 2015 US cold wave, shedding some lights on its channels of transmission and reporting several disruptions, such as slowed commuting, delayed construction, interrupted supply chains, delayed shopping days, and higher heating costs.

This negative effect on labour productivity and gross value added is coupled with large confidence intervals that are probably due to the presence of both southern - generally hot - and eastern - generally cold - regions in the sub-sample of less developed regions.

However, the effects of temperature and precipitation fluctuations above and below their historical norms on labour productivity (Panel B, Tables 3.8 and 3.9) are statistically significant across all sectors in less developed regions, ranging from -0.0585 in agriculture to 0.0660 in construction, and suggesting an interesting capacity of benefiting from climate variations. On the other hand, only some sectors of more developed regions are affected, and the magnitude of coefficients is generally smaller than the one of less developed regions. For instance, the coefficient proxying the effect of warming on agricultural labour productivity, $\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{+}}$, is -0.0315 in more developed regions, and -0.0375 in less developed ones. These results are consistent with the ones obtained using another index of labour productivity (Panel C, Tables 3.8 and 3.9), although the difference between the coefficients is larger (i.e. they are respectively -0.0515 and -0.0319). This is an interesting finding suggesting that more developed European regions have not experienced a benefit in labour productivity from rising temperature. However, we note that agricultural gross value added in less developed regions is negatively affected by rising temperature while being unaffected in more developed regions.

To deepen our comprehension of the impact of temperature and precipitation changes on aggregate and sectoral economic growth and to explain some empirical findings that emerged from the previous analysis on gross value added and labour productivity, we extend our investigation to the long-run effects of climate change on other channels of transmission in Section 3.5.

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[11] This empirical finding is supported by Kahn et al. (2019) and Olper et al. (2021). However, it is probably due to the smaller frequency of temperature fluctuations below its historical norm with respect to the one of the fluctuations above it. Moreover, this pattern may be exacerbated by increasing global warming.

[12] During 10-17 February 2021, several cities in Texas have reported lower temperatures than in Alaska.

Table 3.8: Long-Term Effects of Climate Change on the Output and Labour Productivity Growth of Several Sectors in Less Developed European regions, 1980-2017

	Total	Agriculture, Forestry, Fishing	Manufacturing, Energy, Mining	Construction	WTRAFIC	Financial, Business Services	Non-market Services
Panel A: Gross Value Added							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$	-0.0086	-0.0533***	-0.0208	0.0610***	-0.0046	0.0259**	-0.0034
	(0.0083)	(0.0142)	(0.0190)	(0.0201)	(0.0086)	(0.0101)	(0.0105)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-}$	-0.0488**	-0.0290	-0.0159	0.1529***	0.0321**	0.0395**	-0.0179
	(0.0194)	(0.0299)	(0.0338)	(0.0346)	(0.0160)	(0.0182)	(0.0207)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^+}$	0.0032	-0.0055	0.0215*	0.0030	0.0053	0.0049	0.0042
	(0.0038)	(0.0073)	(0.0115)	(0.0102)	(0.0043)	(0.0050)	(0.0045)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^-}$	0.0080	-0.0282***	0.0343**	0.0070	0.0019	0.0065	0.0101
	(0.0074)	(0.0086)	(0.0157)	(0.0128)	(0.0063)	(0.0072)	(0.0075)
$N \times T$	3196	3048	3048	3048	3048	3048	3048
Panel B: Labour Productivity (based on employment)							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$	-0.0027	-0.0375*	-0.0037	0.0297**	-0.0023	0.0203*	-0.0123
	(0.0076)	(0.0192)	(0.0120)	(0.0149)	(0.0100)	(0.0123)	(0.0083)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-}$	-0.0283*	-0.0585*	-0.0494*	0.0660***	0.0461**	0.0211	0.0020
	(0.0154)	(0.0351)	(0.0253)	(0.0228)	(0.0189)	(0.0222)	(0.0151)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^+}$	0.0046	0.0035	0.0051	-0.0071	0.0087*	0.0104*	0.0036
	(0.0037)	(0.0097)	(0.0063)	(0.0075)	(0.0047)	(0.0057)	(0.0041)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^-}$	0.0057	-0.0135	0.0022	-0.0080	0.0028	0.0039	0.0137**
	(0.0058)	(0.0108)	(0.0070)	(0.0084)	(0.0065)	(0.0066)	(0.0058)
$N \times T$	3062	2990	3002	3002	3002	3002	3002
Panel C: Labour Productivity (based on hours worked)							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$	-0.0026	-0.0515***	-0.0188	0.0495***	0.0002	0.0241	-0.0130
	(0.0084)	(0.0197)	(0.0139)	(0.0158)	(0.0115)	(0.0164)	(0.0118)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-}$	-0.0113	-0.0526	-0.0253	0.0784***	0.0149	0.0346	0.0227
	(0.0166)	(0.0414)	(0.0301)	(0.0279)	(0.0243)	(0.0306)	(0.0233)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^+}$	0.0124***	-0.0128	-0.0052	-0.0105	0.0080	0.0183**	0.0139**
	(0.0045)	(0.0104)	(0.0076)	(0.0078)	(0.0063)	(0.0073)	(0.0057)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^-}$	0.0082	-0.0174*	-0.0012	-0.0219***	0.0002	0.0173*	0.0279***
	(0.0061)	(0.0103)	(0.0080)	(0.0084)	(0.0076)	(0.0097)	(0.0073)
$N \times T$	2982	2616	2616	2616	2616	2616	2616

Notes: The estimates are based on Equation 3.1: $\Delta y_{i,t} = \alpha_i + \sum_{l=1}^{p} \gamma_l \Delta y_{i,t-l} + \sum_{l=0}^{p} \beta_l \Delta \mathbf{x}_{i,t-l} + \sum_{l=0}^{p} \varphi_l \Delta \bar{y}_{t-l} + \varepsilon_{i,t}$, where $y_{i,t}$ is the log of the economic performance measure in region i at time t, α_i is the region-specific fixed effect, $\bar{y}_t$ is the log of the cross-sectional average of the economic performance measure at time t, and $\mathbf{x}_{i,t}$ is the vector of climate variables, defined as follows $\mathbf{x}_{i,t} = \left[\left(T_{i,t} - T^*_{i,t-1}\right)^+ ; \left(T_{i,t} - T^*_{i,t-1}\right)^- ; \left(P_{i,t} - P^*_{i,t-1}\right)^+ ; \left(P_{i,t} - P^*_{i,t-1}\right)^-\right]$, where $T_{i,t}$ and $P_{i,t}$ are population-weighted average temperature and precipitation of region i at time t, and $T^*_{i,t-1}$ and $P^*_{i,t-1}$ are their historical norms (based on moving averages of the past 30 years). The long-run effects, $\widehat{\theta}$, are calculated from the OLS estimates of the short-run coefficients: $\theta = \frac{\sum_{l=0}^{p} \beta_l}{1-\sum_{l=1}^{p} \gamma_l}$. The lag order, p, is set to 3. WTRAFIC is wholesale, transportation, retail, food and accommodation, information and communication sectors. The standard errors are clustered as proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 10% (*), 5% (**), 1% (***) levels.

Table 3.9: Long-Term Effects of Climate Change on the Output and Labour Productivity Growth of Several Sectors in More Developed European regions, 1980-2017

	Total	Agriculture, Forestry, Fishing	Manufacturing, Energy, Mining	Construction	WTRAFIC	Financial, Business Services	Non-market Services
Panel A: Gross Value Added							
$\widehat{\theta}_{\Delta(T_{i,t}-T^*_{i,t-1})^+}$	0.0013	-0.0238	-0.0215***	0.0221**	0.0017	0.0063	0.0179**
	(0.0042)	(0.0149)	(0.0082)	(0.0097)	(0.0061)	(0.0072)	(0.0071)
$\widehat{\theta}_{\Delta(T_{i,t}-T^*_{i,t-1})^-}$	0.0098	-0.0285	-0.0178	0.0433***	0.0130	0.0207**	0.0321***
	(0.0064)	(0.0236)	(0.0120)	(0.0146)	(0.0087)	(0.0097)	(0.0098)
$\widehat{\theta}_{\Delta(P_{i,t}-P^*_{i,t-1})^+}$	-0.0002	0.0030	-0.0027	-0.0159***	0.0051	0.0074*	-0.0046
	(0.0019)	(0.0111)	(0.0043)	(0.0055)	(0.0033)	(0.0039)	(0.0040)
$\widehat{\theta}_{\Delta(P_{i,t}-P^*_{i,t-1})^-}$	-0.0015	0.0124	-0.0049	-0.0098*	-0.0007	0.0020	-0.0019
	(0.0020)	(0.0088)	(0.0042)	(0.0054)	(0.0030)	(0.0036)	(0.0041)
$N \times T$	5140	5110	5116	5116	5116	5116	5116
Panel B: Labour Productivity (based on employment)							
$\widehat{\theta}_{\Delta(T_{i,t}-T^*_{i,t-1})^+}$	-0.0019	-0.0315*	-0.0102	-0.0120	-0.0001	0.0103	0.0103
	(0.0036)	(0.0166)	(0.0066)	(0.0076)	(0.0058)	(0.0081)	(0.0091)
$\widehat{\theta}_{\Delta(T_{i,t}-T^*_{i,t-1})^-}$	0.0001	-0.0197	-0.0080	-0.0082	0.0045	-0.0033	0.0253*
	(0.0056)	(0.0238)	(0.0099)	(0.0114)	(0.0086)	(0.0126)	(0.0133)
$\widehat{\theta}_{\Delta(P_{i,t}-P^*_{i,t-1})^+}$	0.0010	0.0084	0.0006	-0.0050	0.0047	0.0037	-0.0055
	(0.0019)	(0.0100)	(0.0040)	(0.0048)	(0.0032)	(0.0047)	(0.0051)
$\widehat{\theta}_{\Delta(P_{i,t}-P^*_{i,t-1})^-}$	-0.0011	0.0080	-0.0010	0.0036	0.0006	-0.0013	-0.0020
	(0.0018)	(0.0106)	(0.0039)	(0.0047)	(0.0030)	(0.0046)	(0.0051)
$N \times T$	5134	5016	5114	5114	5114	5114	5114
Panel C: Labour Productivity (based on hours worked)							
$\widehat{\theta}_{\Delta(T_{i,t}-T^*_{i,t-1})^+}$	0.0029	-0.0319*	-0.0181***	0.0078	0.0227**	-0.0023	0.0088
	(0.0035)	(0.0172)	(0.0069)	(0.0072)	(0.0090)	(0.0079)	(0.0085)
$\widehat{\theta}_{\Delta(T_{i,t}-T^*_{i,t-1})^-}$	0.0047	-0.0412*	-0.0152	0.0156	0.0334***	0.0084	0.0120
	(0.0054)	(0.0226)	(0.0108)	(0.0106)	(0.0127)	(0.0125)	(0.0127)
$\widehat{\theta}_{\Delta(P_{i,t}-P^*_{i,t-1})^+}$	0.0008	0.0021	-0.0026	-0.0059	0.0010	-0.0012	0.0004
	(0.0019)	(0.0102)	(0.0038)	(0.0043)	(0.0043)	(0.0043)	(0.0048)
$\widehat{\theta}_{\Delta(P_{i,t}-P^*_{i,t-1})^-}$	-0.0015	0.0067	-0.0040	-0.0019	0.0012	-0.0046	-0.0035
	(0.0018)	(0.0111)	(0.0041)	(0.0043)	(0.0043)	(0.0043)	(0.0051)
$N \times T$	5006	4280	4286	4286	4286	4286	4286

Notes: The estimates are based on Equation 3.1: $\Delta y_{i,t} = \alpha_i + \sum_{l=1}^{p}\gamma_l \Delta y_{i,t-l} + \sum_{l=0}^{p}\beta_l \Delta \mathbf{x}_{i,t-l} + \sum_{l=0}^{p}\varphi_l \Delta \bar{y}_{t-l} + \varepsilon_{i,t}$, where $y_{i,t}$ is the log of the economic performance measure in region i at time t, α_i is the region-specific fixed effect, $\bar{y}_t$ is the log of the cross-sectional average of the economic performance measure at time t, and $\mathbf{x}_{i,t}$ is the vector of climate variables, defined as follows $\mathbf{x}_{i,t} = \left[\left(T_{i,t} - T^*_{i,t-1}\right)^+; \left(T_{i,t} - T^*_{i,t-1}\right)^-; \left(P_{i,t} - P^*_{i,t-1}\right)^+; \left(P_{i,t} - P^*_{i,t-1}\right)^-\right]$, where $T_{i,t}$ and $P_{i,t}$ are population-weighted average temperature and precipitation of region i at time t, and $T^*_{i,t-1}$ and $P^*_{i,t-1}$ are their historical norms (based on moving averages of the past 30 years). The long-run effects, $\widehat{\theta}$, are calculated from the OLS estimates of the short-run coefficients: $\theta = \frac{\sum_{l=0}^{p}\beta_l}{1-\sum_{l=1}^{p}\gamma_l}$. The lag order, p, is set to 3. WTRAFIC is wholesale, transportation, retail, food and accommodation, information and communication sectors. The standard errors are clustered as proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 10% (*), 5% (**), 1% (***) levels.

3.4.1 Different Definitions of Historical Norms

To ensure the robustness of our analysis, we show in Table 3.10 that the long-run macroeconomic effects of climate change on labour productivity are substantially stable using alternative definitions of historical norms of the temperature and precipitations in European regions. Focusing on agricultural sector, which is one of the most affected by climate change, it is possible to see that the sign and magnitude of coefficients are very similar over Panel A, B, and C. We have based our analysis on the 30 years moving average of climate variables, as suggested by Arguez et al. (2012) and Vose et al. (2014), and considered the 20 and 40 years moving averages as robustness checks.

Table 3.10: Long-Term Effects of Climate Change on the Labour Productivity Growth of Several Sectors in European regions, 1980-2017 (Historical Norms as the Moving Averages of Past 20, 30 and 40 Years)

	Total	Agriculture, Forestry, Fishing	Manufacturing, Energy, Mining	Construction	WTRAFIC	Financial, Business Services	Non-market Services
Panel A: 20 years Moving Average							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{+}}$	0.0057	-0.0394***	0.0116*	0.0191**	0.0024	0.0201***	0.0071
	(0.0039)	(0.0130)	(0.0066)	(0.0081)	(0.0055)	(0.0074)	(0.0064)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{-}}$	0.0037	-0.0387**	0.0130	0.0369***	0.0217***	-0.0037	0.0061
	(0.0053)	(0.0179)	(0.0093)	(0.0099)	(0.0075)	(0.0093)	(0.0082)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^{*}_{i,t-1}\right)^{+}}$	0.0010	0.0101	0.0011	-0.0068	0.0006	0.0124***	-0.0009
	(0.0019)	(0.0069)	(0.0035)	(0.0044)	(0.0028)	(0.0037)	(0.0032)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^{*}_{i,t-1}\right)^{-}}$	0.0011	-0.0017	0.0022	-0.0033	-0.0020	0.0064*	0.0054
	(0.0023)	(0.0078)	(0.0036)	(0.0044)	(0.0031)	(0.0037)	(0.0037)
$N \times T$	8196	8006	8116	8116	8116	8116	8116
Panel B: 30 years Moving Average							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{+}}$	0.0016	-0.0333***	0.0004	0.0138*	-0.0027	0.0169**	0.0090
	(0.0038)	(0.0125)	(0.0063)	(0.0078)	(0.0053)	(0.0071)	(0.0062)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{-}}$	-0.0027	-0.0418**	-0.0020	0.0279***	0.0156**	0.0069	0.0173*
	(0.0059)	(0.0196)	(0.0100)	(0.0106)	(0.0079)	(0.0104)	(0.0095)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^{*}_{i,t-1}\right)^{+}}$	0.0014	0.0129*	-0.0001	-0.0094**	0.0002	0.0121***	-0.0010
	(0.0019)	(0.0070)	(0.0035)	(0.0043)	(0.0028)	(0.0037)	(0.0033)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^{*}_{i,t-1}\right)^{-}}$	0.0015	-0.0032	0.0018	-0.0047	-0.0029	0.0056	0.0067*
	(0.0026)	(0.0076)	(0.0037)	(0.0044)	(0.0033)	(0.0038)	(0.0040)
$N \times T$	8196	8006	8116	8116	8116	8116	8116
Panel C: 40 years Moving Average							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{+}}$	-0.0028	-0.0348***	-0.0057	0.0087	-0.0060	0.0233***	0.0038
	(0.0038)	(0.0121)	(0.0062)	(0.0076)	(0.0052)	(0.0070)	(0.0061)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{-}}$	-0.0078	-0.0395**	-0.0076	0.0188*	0.0084	0.0165	0.0136
	(0.0060)	(0.0192)	(0.0098)	(0.0103)	(0.0077)	(0.0104)	(0.0097)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^{*}_{i,t-1}\right)^{+}}$	0.0018	0.0133*	0.0020	-0.0114***	-0.0003	0.0119***	0.0003
	(0.0019)	(0.0071)	(0.0035)	(0.0043)	(0.0027)	(0.0037)	(0.0033)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^{*}_{i,t-1}\right)^{-}}$	0.0022	-0.0016	0.0040	-0.0071	-0.0037	0.0045	0.0088**
	(0.0025)	(0.0075)	(0.0036)	(0.0044)	(0.0034)	(0.0039)	(0.0040)
$N \times T$	8196	8006	8116	8116	8116	8116	8116

Notes: The estimates are based on Equation 3.1: $\Delta y_{i,t} = \alpha_i + \sum_{l=1}^{p}\gamma_l \Delta y_{i,t-l} + \sum_{l=0}^{p}\beta_l \Delta \mathbf{x}_{i,t-l} + \sum_{l=0}^{p}\varphi_l \Delta \bar{y}_{t-l} + \varepsilon_{i,t}$, where $y_{i,t}$ is the log of the economic performance measure in region i at time t, α_i is the region-specific fixed effect, $\bar{y}_t$ is the log of the cross-sectional average of the economic performance measure at time t, $\mathbf{x}_{i,t}$ is the vector of climate variables, defined as follows $\mathbf{x}_{i,t} = \left[\left(T_{i,t} - T^{*}_{i,t-1}\right)^{+}; \left(T_{i,t} - T^{*}_{i,t-1}\right)^{-}; \left(P_{i,t} - P^{*}_{i,t-1}\right)^{+}; \left(P_{i,t} - P^{*}_{i,t-1}\right)^{-}\right]$, where $T_{i,t}$ and $P_{i,t}$ are population-weighted average temperature and precipitation of region i at time t, and $T^{*}_{i,t-1}$ and $P^{*}_{i,t-1}$ are their historical norms (based on moving averages of the past 20, 30, 40 years). The long-run effects, $\widehat{\theta}$, are calculated from the OLS estimates of the short-run coefficients: $\theta = \frac{\sum_{l=0}^{p}\beta_l}{1-\sum_{l=1}^{p}\gamma_l}$. The lag order, p, is set to 3. WTRAFIC is wholesale, transportation, retail, food and accommodation, information and communication sectors. The standard errors are clustered as proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 10% (*), 5% (**), 1% (***) levels.

3.5 Channels of Transmission

Since European output and labour productivity response to climate change has been studied in Section 3.4, here we investigate the relationship between employment, hours worked and gross fixed capital formation with climate change. We show that these macroeconomic measures are largely affected by climate change, causing relevant and persistent effects in the long-run. Indeed, Tables 3.11, 3.12 and 3.13 show that climate variables broadly affect these indicators across all sectors and regions and that the relationship between these production factors and changes in temperature and precipitation is generally non-linear.

Moreover, we note that the statistically significant effects of climate change are generally higher in gross fixed capital formation (ranging across sectors between -0.0324 and 0.0832) than employment (between -0.0103 and 0.0420), and hours worked (between -0.0086 and 0.0274).

This evidence supports the idea that the effects of climate change on human labor are mostly driven by labour productivity, rather than employment and hours worked, as previously suggested in Section 3.4. For instance, the effects of temperature and precipitation changes on agricultural gross value added are more consistent with the ones on labour productivity (Table 3.7, Panel A and B), rather than the ones on agricultural employment and hours worked (Tables 3.11, Panel A and B).

The empirical investigation of the impacts on the extensive and intensive margins of the labour market at sectoral level is one of the main contributions of this work, although there exists a vast amount of the literature that studies the relationship between climate change and labour supply from different points of view (mortality and human health as in Deschenes (2014), heat waves as in Graff Zivin and Neidell (2014), Deryugina and Hsiang (2014), Behrer and Park (2017), Graff Zivin et al. (2018), or cold waves, extreme weather events, and many other climate features as in Dell et al. (2014) literature review).

However, we find some interesting results, like a significant and positive effect of temperature fluctuations below its historical norm, namely $\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{-}}$, on aggregate employment and hours worked, while fluctuations above its historical norm do not have it. Furthermore, Greene (2018) supports our findings that droughts, e.g. precipitation fluctuations below their historical norms, harm agricultural employment.

Overall, the effects of climate change on employment and hours worked in more and less developed regions are similar, even though the coefficients in Panel A and B in Table 3.12 are generally larger than the ones in Table 3.13. However, as previously discussed, these coefficients may be beneficial or adverse, depending on several factors. Thus, it is not possible to sustain that climate change is associated with slower economic growth in less developed regions rather than in more developed regions.

Turning to the long-run effects of temperature and precipitation variations on gross fixed capital formation, we note that it is diffusely affected by climate change, at both total and sectoral level (Panel C, Table 3.11). We find that temperature changes have positive and negative effects, while precipitation variations have mostly adverse effects in the long-run. Indeed, it is worth saying that gross fixed capital formation can be affected by climate change in different ways. First, it may be directly hit by climate shocks or its rate of return can decrease over time (Fankhauser et al. (1997), Bosetti et al. (2006), Moore and Diaz (2015), Hallegatte and Vogt-Schilb (2016), Zhang et al. (2018)). Second, climate change is a major uncertainty driver on investment decisions. Theoretical and empirical works show that firms and households may decide to lower or postpone their investments in response to climate variations (Fankhauser and Tol (2005), Hallegatte et al. (2012)). Third, investments may be redirected on adaptive capital to cope with climate change. While Behrer and Park (2017)) offers a theoretical investigation of this phenomenon, Mohaddes and Williams (2020) empirically studies it, finding that investing in adaptive capital produces higher benefits from mitigation policies.

Our analysis suggests that increasing temperatures slow down investments in manufacturing and non-market services sectors, while raising them in the construction and business and financial services sectors. Moreover, temperature fluctuations above their historical norm are associated with increasing agricultural gross fixed capital formation in more developed regions, signaling that these regions are coping with warming through investments, regardless of the high cost of adaptation in this sector. On the other hand, agricultural gross fixed capital formation in less developed regions is not significantly affected, suggesting the need for adaptive investments in the next decades to counter-balance the negative effects on labour productivity and gross value added (Table 3.8, Panel A and B).

Finally, we notice the statistically significant adverse effects of climate change on the non-market services sector, signaling a worrying divestment in health and education, which are two of the main components of the sector.

Table 3.11: Long-Term Effects of Climate Change on other Channels of Transmission of Several Sectors in European regions, 1980-2017

	Total	Agriculture, Forestry, Fishing	Manufacturing, Energy, Mining	Construction	WTRAFIC	Financial, Business Services	Non-market Services
Panel A: Employment							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{+}}$	0.0017	-0.0089	-0.0011	0.0328***	0.0042	0.0049	-0.0000
	(0.0034)	(0.0088)	(0.0059)	(0.0101)	(0.0046)	(0.0067)	(0.0050)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{-}}$	0.0093**	-0.0096	0.0031	0.0244*	0.0146**	0.0420***	0.0094
	(0.0044)	(0.0135)	(0.0088)	(0.0136)	(0.0061)	(0.0091)	(0.0068)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^{*}_{i,t-1}\right)^{+}}$	-0.0001	-0.0103**	0.0018	0.0005	0.0006	-0.0040	0.0018
	(0.0018)	(0.0051)	(0.0038)	(0.0054)	(0.0022)	(0.0035)	(0.0023)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^{*}_{i,t-1}\right)^{-}}$	-0.0012	-0.0076	0.0042	0.0045	0.0000	-0.0014	-0.0047*
	(0.0018)	(0.0054)	(0.0041)	(0.0057)	(0.0022)	(0.0033)	(0.0028)
$N \times T$	8474	8370	8474	8474	8474	8474	8474
Panel B: Hours Worked							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{+}}$	0.0021	-0.0047	-0.0066	0.0260**	-0.0083	0.0179***	-0.0023
	(0.0033)	(0.0092)	(0.0065)	(0.0113)	(0.0062)	(0.0060)	(0.0048)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{-}}$	0.0086*	0.0045	-0.0028	0.0077	0.0274***	0.0173*	-0.0097
	(0.0045)	(0.0140)	(0.0107)	(0.0169)	(0.0090)	(0.0092)	(0.0071)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^{*}_{i,t-1}\right)^{+}}$	-0.0025	0.0059	0.0068	0.0058	-0.0011	-0.0026	-0.0039
	(0.0017)	(0.0065)	(0.0046)	(0.0064)	(0.0033)	(0.0033)	(0.0026)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^{*}_{i,t-1}\right)^{-}}$	-0.0021	-0.0036	0.0026	0.0053	0.0004	-0.0072**	-0.0086***
	(0.0019)	(0.0059)	(0.0052)	(0.0068)	(0.0034)	(0.0034)	(0.0028)
$N \times T$	8210	7128	7128	7128	7128	7128	7128
Panel C: Gross Fixed Capital Formation							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{+}}$	-0.0043	0.0140	-0.0324**	0.0374*	0.0004	0.0281*	-0.0424***
	(0.0095)	(0.0162)	(0.0136)	(0.0210)	(0.0140)	(0.0145)	(0.0116)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^{*}_{i,t-1}\right)^{-}}$	0.0279**	0.0213	-0.0060	0.0832***	0.0554***	0.0523***	-0.0043
	(0.0119)	(0.0228)	(0.0166)	(0.0262)	(0.0173)	(0.0177)	(0.0141)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^{*}_{i,t-1}\right)^{+}}$	-0.0086*	-0.0286***	0.0089	0.0023	-0.0099	-0.0244***	-0.0123*
	(0.0051)	(0.0094)	(0.0079)	(0.0126)	(0.0073)	(0.0088)	(0.0063)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^{*}_{i,t-1}\right)^{-}}$	-0.0002	-0.0280***	0.0007	-0.0069	0.0039	-0.0214***	-0.0012
	(0.0049)	(0.0092)	(0.0078)	(0.0125)	(0.0077)	(0.0075)	(0.0064)
$N \times T$	8578	8550	8578	8546	8578	8578	8578

Notes: The estimates are based on Equation 3.1: $\Delta y_{i,t} = \alpha_i + \sum_{l=1}^{p}\gamma_l \Delta y_{i,t-l} + \sum_{l=0}^{p}\beta_l \Delta \mathbf{x}_{i,t-l} + \sum_{l=0}^{p}\varphi_l \Delta \bar{y}_{t-l} + \varepsilon_{i,t}$, where $y_{i,t}$ is the log of the economic performance measure in region i at time t, α_i is the region-specific fixed effect, $\bar{y}_t$ is the log of the cross-sectional average of the economic performance measure at time t, and $\mathbf{x}_{i,t}$ is the vector of climate variables, defined as follows $\mathbf{x}_{i,t} = \left[\left(T_{i,t} - T^{*}_{i,t-1}\right)^{+}; \left(T_{i,t} - T^{*}_{i,t-1}\right)^{-}; \left(P_{i,t} - P^{*}_{i,t-1}\right)^{+}; \left(P_{i,t} - P^{*}_{i,t-1}\right)^{-}\right]$, where $T_{i,t}$ and $P_{i,t}$ are population-weighted average temperature and precipitation of region i at time t, and $T^{*}_{i,t-1}$ and $P^{*}_{i,t-1}$ are their historical norms (based on moving averages of the past 30 years). The long-run effects, $\widehat{\theta}$, are calculated from the OLS estimates of the short-run coefficients: $\theta = \frac{\sum_{l=0}^{p}\beta_l}{1-\sum_{l=1}^{p}\gamma_l}$. The lag order, p, is set to 3. WTRAFIC is wholesale, transportation, retail, food and accommodation, information and communication sectors. The standard errors are clustered as proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 10% (*), 5% (**), 1% (***) levels.

Table 3.12: Long-Term Effects of Climate Change on other Channels of Transmission of Several Sectors in Less Developed European regions, 1980-2017

	Total	Agriculture, Forestry, Fishing	Manufacturing, Energy, Mining	Construction	WTRAFIC	Financial, Business Services	Non-market Services
Panel A: Employment							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$	0.0037	-0.0122	0.0057	0.0394**	0.0065	0.0177	0.0058
	(0.0059)	(0.0160)	(0.0114)	(0.0165)	(0.0077)	(0.0116)	(0.0073)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-}$	0.0136	-0.0195	0.0378	0.0647**	0.0138	0.0508***	0.0071
	(0.0102)	(0.0285)	(0.0246)	(0.0294)	(0.0139)	(0.0193)	(0.0123)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^+}$	0.0007	-0.0137	0.0031	0.0117	-0.0017	-0.0089	0.0012
	(0.0030)	(0.0087)	(0.0073)	(0.0083)	(0.0033)	(0.0059)	(0.0035)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^-}$	0.0031	-0.0215**	0.0240***	0.0266***	-0.0003	-0.0025	-0.0044
	(0.0033)	(0.0097)	(0.0093)	(0.0099)	(0.0037)	(0.0057)	(0.0045)
$N \times T$	3304	3292	3304	3304	3304	3304	3304
Panel B: Hours Worked							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$	0.0076	-0.0221	-0.0034	0.0155	-0.0066	0.0167	-0.0030
	(0.0060)	(0.0185)	(0.0132)	(0.0197)	(0.0109)	(0.0110)	(0.0088)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-}$	0.0260**	0.0176	0.0234	0.0458	0.0345	0.0206	-0.0446**
	(0.0117)	(0.0423)	(0.0295)	(0.0436)	(0.0218)	(0.0195)	(0.0179)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^+}$	-0.0044	0.0101	0.0098	0.0123	-0.0007	-0.0097*	-0.0085*
	(0.0029)	(0.0113)	(0.0094)	(0.0108)	(0.0059)	(0.0051)	(0.0044)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^-}$	-0.0001	-0.0153	0.0173	0.0373***	0.0010	-0.0090	-0.0156***
	(0.0037)	(0.0106)	(0.0113)	(0.0129)	(0.0059)	(0.0057)	(0.0049)
$N \times T$	3168	2786	2786	2786	2786	2786	2786
Panel C: Gross Fixed Capital Formation							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$	-0.0112	-0.0067	-0.0439*	0.0116	-0.0049	0.0282	-0.0616***
	(0.0161)	(0.0272)	(0.0246)	(0.0384)	(0.0234)	(0.0248)	(0.0213)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-}$	0.0430	0.0239	0.0508	0.0499	0.1417***	0.1009**	0.0012
	(0.0263)	(0.0451)	(0.0381)	(0.0573)	(0.0408)	(0.0404)	(0.0356)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^+}$	-0.0039	-0.0163	0.0068	0.0144	-0.0150	-0.0382**	0.0100
	(0.0092)	(0.0160)	(0.0160)	(0.0234)	(0.0133)	(0.0160)	(0.0110)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^-}$	0.0085	-0.0167	0.0060	0.0385*	0.0030	-0.0380***	0.0200*
	(0.0089)	(0.0163)	(0.0159)	(0.0227)	(0.0135)	(0.0134)	(0.0114)
$N \times T$	3402	3396	3402	3396	3402	3402	3402

Notes: The estimates are based on Equation 3.1: $\Delta y_{i,t} = \alpha_i + \sum_{l=1}^{p}\gamma_l \Delta y_{i,t-l} + \sum_{l=0}^{p}\beta_l \Delta \mathbf{x}_{i,t-l} + \sum_{l=0}^{p}\varphi_l \Delta \bar{y}_{t-l} + \varepsilon_{i,t}$, where $y_{i,t}$ is the log of the economic performance measure in region i at time t, α_i is the region-specific fixed effect, $\bar{y}_t$ is the log of the cross-sectional average of the economic performance measure at time t, and $\mathbf{x}_{i,t}$ is the vector of climate variables, defined as follows $\mathbf{x}_{i,t} = \left[\left(T_{i,t} - T^*_{i,t-1}\right)^+; \left(T_{i,t} - T^*_{i,t-1}\right)^-; \left(P_{i,t} - P^*_{i,t-1}\right)^+; \left(P_{i,t} - P^*_{i,t-1}\right)^-\right]$, where $T_{i,t}$ and $P_{i,t}$ are population-weighted average temperature and precipitation of region i at time t, and $T^*_{i,t-1}$ and $P^*_{i,t-1}$ are their historical norms (based on moving averages of the past 30 years). The long-run effects, $\widehat{\theta}$, are calculated from the OLS estimates of the short-run coefficients: $\theta = \frac{\sum_{l=0}^{p}\beta_l}{1-\sum_{l=1}^{p}\gamma_l}$. The lag order, p, is set to 3. WTRAFIC is wholesale, transportation, retail, food and accommodation, information and communication sectors. The standard errors are clustered as proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 10% (*), 5% (**), 1% (***) levels.

Table 3.13: Long-Term Effects of Climate Change on other Channels of Transmission of Several Sectors in More Developed European regions, 1980-2017

	Total	Agriculture, Forestry, Fishing	Manufacturing, Energy, Mining	Construction	WTRAFIC	Financial, Business Services	Non-market Services
Panel A: Employment							
$\widehat{\theta}_{\Delta(T_{i,t}-T^*_{i,t-1})^+}$	-0.0002	-0.0046	-0.0127**	0.0192	0.0008	-0.0101	0.0039
	(0.0034)	(0.0105)	(0.0058)	(0.0119)	(0.0050)	(0.0065)	(0.0053)
$\widehat{\theta}_{\Delta(T_{i,t}-T^*_{i,t-1})^-}$	0.0079*	-0.0093	-0.0027	0.0461***	0.0113*	0.0157	0.0086
	(0.0043)	(0.0147)	(0.0073)	(0.0154)	(0.0067)	(0.0102)	(0.0080)
$\widehat{\theta}_{\Delta(P_{i,t}-P^*_{i,t-1})^+}$	-0.0018	0.0007	-0.0036	-0.0145**	-0.0005	0.0031	0.0009
	(0.0019)	(0.0060)	(0.0033)	(0.0066)	(0.0027)	(0.0037)	(0.0028)
$\widehat{\theta}_{\Delta(P_{i,t}-P^*_{i,t-1})^-}$	-0.0009	0.0064	-0.0029	-0.0184***	0.0006	0.0043	0.0011
	(0.0018)	(0.0064)	(0.0035)	(0.0063)	(0.0026)	(0.0037)	(0.0028)
$N \times T$	5170	5078	5170	5170	5170	5170	5170
Panel B: Hours Worked							
$\widehat{\theta}_{\Delta(T_{i,t}-T^*_{i,t-1})^+}$	-0.0039	-0.0014	-0.0166***	0.0209*	-0.0114	0.0160***	0.0065
	(0.0033)	(0.0124)	(0.0058)	(0.0117)	(0.0072)	(0.0056)	(0.0048)
$\widehat{\theta}_{\Delta(T_{i,t}-T^*_{i,t-1})^-}$	-0.0021	0.0044	-0.0123	0.0050	-0.0129	0.0157	0.0062
	(0.0043)	(0.0140)	(0.0087)	(0.0169)	(0.0102)	(0.0106)	(0.0071)
$\widehat{\theta}_{\Delta(P_{i,t}-P^*_{i,t-1})^+}$	-0.0017	0.0075	0.0028	-0.0005	-0.0011	0.0070*	-0.0031
	(0.0019)	(0.0077)	(0.0035)	(0.0066)	(0.0036)	(0.0038)	(0.0026)
$\widehat{\theta}_{\Delta(P_{i,t}-P^*_{i,t-1})^-}$	-0.0006	0.0049	0.0005	-0.0169***	-0.0025	0.0026	0.0022
	(0.0019)	(0.0076)	(0.0039)	(0.0059)	(0.0037)	(0.0037)	(0.0028)
$N \times T$	5042	4342	4342	4342	4342	4342	4342
Panel C: Gross Fixed Capital Formation							
$\widehat{\theta}_{\Delta(T_{i,t}-T^*_{i,t-1})^+}$	0.0061	0.0348**	-0.0054	0.0683***	0.0085	0.0289**	-0.0102
	(0.0086)	(0.0170)	(0.0120)	(0.0173)	(0.0136)	(0.0115)	(0.0098)
$\widehat{\theta}_{\Delta(T_{i,t}-T^*_{i,t-1})^-}$	0.0319***	0.0203	0.0248*	0.0896***	0.0229	0.0356**	0.0107
	(0.0115)	(0.0249)	(0.0148)	(0.0227)	(0.0154)	(0.0150)	(0.0112)
$\widehat{\theta}_{\Delta(P_{i,t}-P^*_{i,t-1})^+}$	-0.0087**	-0.0362***	0.0048	-0.0185*	-0.0031	-0.0142**	-0.0239***
	(0.0042)	(0.0107)	(0.0064)	(0.0110)	(0.0059)	(0.0062)	(0.0065)
$\widehat{\theta}_{\Delta(P_{i,t}-P^*_{i,t-1})^-}$	-0.0117***	-0.0330***	0.0010	-0.0441***	-0.0048	-0.0143**	-0.0205***
	(0.0043)	(0.0096)	(0.0062)	(0.0122)	(0.0063)	(0.0061)	(0.0070)
$N \times T$	5176	5154	5176	5150	5176	5176	5176

Notes: The estimates are based on Equation 3.1: $\Delta y_{i,t} = \alpha_i + \sum_{l=1}^{p}\gamma_l \Delta y_{i,t-l} + \sum_{l=0}^{p}\beta_l \Delta \mathbf{x}_{i,t-l} + \sum_{l=0}^{p}\varphi_l \Delta \bar{y}_{t-l} + \varepsilon_{i,t}$, where $y_{i,t}$ is the log of the economic performance measure in region i at time t, α_i is the region-specific fixed effect, $\bar{y}_t$ is the log of the cross-sectional average of the economic performance measure at time t, and $\mathbf{x}_{i,t}$ is the vector of climate variables, defined as follows $\mathbf{x}_{i,t} = \left[\left(T_{i,t} - T^*_{i,t-1}\right)^+; \left(T_{i,t} - T^*_{i,t-1}\right)^-; \left(P_{i,t} - P^*_{i,t-1}\right)^+; \left(P_{i,t} - P^*_{i,t-1}\right)^-\right]$, where $T_{i,t}$ and $P_{i,t}$ are population-weighted average temperature and precipitation of region i at time t, and $T^*_{i,t-1}$ and $P^*_{i,t-1}$ are their historical norms (based on moving averages of the past 30 years). The long-run effects, $\widehat{\theta}$, are calculated from the OLS estimates of the short-run coefficients: $\theta = \frac{\sum_{l=0}^{p}\beta_l}{1-\sum_{l=1}^{p}\gamma_l}$. The lag order, p, is set to 3. WTRAFIC is wholesale, transportation, retail, food and accommodation, information and communication sectors. The standard errors are clustered as proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 10% (*), 5% (**), 1% (***) levels.

3.6 Conclusion

We investigate the long-term macroeconomic effects of climate change in Europe using sectoral data for the 281 NUTS2[13] European regions from 1980 to 2017.

Thanks to our within-country level dataset, we estimate the long-term effects of temperature and precipitation changes on the growth rates of the main macroeconomic indicators, i.e. gross value added, labour productivity, employment, hours worked and gross fixed capital formation, at both aggregate and sectoral level.

To ensure the robustness of our analysis, we provide the estimation results using different specifications, showing that our econometric approach - which takes into account for short-run and long-run effects, bi-directional feedbacks among climate and economic variables, accelerating climate fluctuations, and cross-sectional dependence in economic data - is broadly consistent.

Overall, we do not find evidence that European gross value added is affected by climate change at aggregate level, although all sectors and regions are diversely influenced by variations in temperature and precipitations from their historical norm.

Moreover, we show that the main components of the production function, i.e. labour productivity, labour supply, and investments, are influenced, at least at sectoral level, suggesting that climate change affects growth through several transmission channels.

Besides, we note that the effects of climate change on the gross value added are more consistent with the ones on labour productivity, rather than the ones on employment, hours worked and gross fixed capital formation, supporting the idea that labour productivity is the main driver of climate change effects on economic growth, as suggested by the literature.

The effects estimated in our analysis may be beneficial or adverse depending on the considered sector and indicator, and remain generally significant in more and less developed regions. The impacts of climate change on these two sub-samples are heterogeneous in some cases, but we cannot associate less developed regions with a slower aggregate economic growth rate because the negative effects caused by temperature and precipitation fluctuations in specific sectors are counter-balanced by the positive effects in other sectors.

Therefore, we do not estimate larger effects on economic growth in regions with a lower income per capita, but different effects, according to the sectoral economic and climate features of the considered regions.

This finding is supported by Tol (2020), suggesting that long-run effects in poor and rich countries are similar, but contrasted by other works, such as Dell et al. (2012), Newell et al. (2021), Letta and Tol (2019), Henseler and Schumacher (2019), Kahn et al. (2019). Most likely, this result depends on the fact that Europe is mainly composed of rich regions since only 14% of European regions belong to developing countries[14].

To summarize, we show that analyses based on aggregate indicators do not fully capture the complexity of long-term macroeconomic effects of climate change in Europe since all sectors - both indoor and outdoor sectors - are affected. Moreover, we suggest that macroeconomic models should take into account the impacts on the labour and capital markets because we find evidence of significant effects in employment, hours worked and gross fixed capital formation, at both aggregate and sectoral level.

Furthermore, we advocate that within-country data are crucial to identify the effects on geographically concentrated industries and to quantify the effects of precipitation changes, which

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[13] The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU for the collection, development, and harmonisation of European regional statistics. The current NUTS 2016 classification is valid from 1 January 2018 and lists 104 regions at NUTS1, 281 regions at NUTS2, and 1348 regions at NUTS3 level. Eurostat.

[14] The IMF considers Bulgaria, Croatia, Romania, Poland, and Hungary as the only developing countries in the EU, representing 41 regions, which is 14.8% of the total (IMF (2018)).

are statistically significant. Finally, macroeconomic models should consider income heterogeneity since our investigation has revealed that more and less developed regions are both influenced, but diversely.

In the light of our analysis, the European economic structure should be renewed to cope with climate change effects and to continue to guarantee an acceptable growth level, with particular attention to a just transition for people and territories.
Thus, adaptation and mitigation policies need to be designed on regional climate and economic features and implemented in close collaboration among European, national and local governmental levels. However, being a rich and developed area, Europe has the responsibility to face the long-run challenges posed by a globally (and locally) accelerating climate change, and the economic and political strength to deal with them and to foster compelling international agreements to lead the world in a decarbonisation process, which is consistent with the sustainable IPCC (2014) climate scenarios.

3.A Appendix

3.A.1 Different Specifications of Climate Change

Robustness Check: Absolute Deviations from Historical Norms

Table 3.14: Long-Term Effects of Climate Change on the Labour Productivity Growth of Several Sectors in European regions, 1980-2017 (Using Absolute Value of Deviations from their Historical Norm)

	Total	Agriculture, Forestry, Fishing	Manufacturing, Energy, Mining	Construction	WTRAFIC	Financial, Business Services	Non-market Services
Panel A: Positive and negative deviations of temperature and precipitation							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$	0.0016	-0.0333***	0.0004	0.0138*	-0.0027	0.0169**	0.0090
	(0.0038)	(0.0125)	(0.0063)	(0.0078)	(0.0053)	(0.0071)	(0.0062)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-}$	-0.0027	-0.0418**	-0.0020	0.0279***	0.0156**	0.0069	0.0173*
	(0.0059)	(0.0196)	(0.0100)	(0.0106)	(0.0079)	(0.0104)	(0.0095)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^+}$	0.0014	0.0129*	-0.0001	-0.0094**	0.0002	0.0121***	-0.0010
	(0.0019)	(0.0070)	(0.0035)	(0.0043)	(0.0028)	(0.0037)	(0.0033)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^-}$	0.0015	-0.0032	0.0018	-0.0047	-0.0029	0.0056	0.0067*
	(0.0026)	(0.0076)	(0.0037)	(0.0044)	(0.0033)	(0.0038)	(0.0040)
$N \times T$	8196	8006	8116	8116	8116	8116	8116
Panel B: Absolute deviations of temperature and precipitation							
$\widehat{\theta}_{\Delta\left\|T_{i,t}-T^*_{i,t-1}\right\|}$	0.0015	-0.0248**	0.0024	0.0200***	-0.0005	0.0155**	0.0075
	(0.0037)	(0.0124)	(0.0062)	(0.0076)	(0.0052)	(0.0069)	(0.0061)
$\widehat{\theta}_{\Delta\left\|P_{i,t}-P^*_{i,t-1}\right\|}$	0.0009	0.0065	-0.0002	-0.0078**	-0.0009	0.0090***	0.0010
	(0.0019)	(0.0061)	(0.0031)	(0.0037)	(0.0025)	(0.0033)	(0.0031)
$N \times T$	8196	8006	8116	8116	8116	8116	8116

Notes: The estimates are based on Equation 3.1: $\Delta y_{i,t} = \alpha_i + \sum_{l=1}^{p}\gamma_l \Delta y_{i,t-l} + \sum_{l=0}^{p}\beta_l \Delta \mathbf{x}_{i,t-l} + \sum_{l=0}^{p}\varphi_l \Delta \bar{y}_{t-l} + \varepsilon_{i,t}$, where $y_{i,t}$ is the log of the economic performance measure in region i at time t, α_i is the region-specific fixed effect, $\bar{y}_t$ is the log of the cross-sectional average of the economic performance measure at time t, $\mathbf{x}_{i,t}$ is the vector of the deviations of climate variables from their historical norms, defined as follows $\mathbf{x}_{i,t} = \left[\left(T_{i,t} - T^*_{i,t-1}\right)^+; \left(T_{i,t} - T^*_{i,t-1}\right)^-; \left(P_{i,t} - P^*_{i,t-1}\right)^+; \left(P_{i,t} - P^*_{i,t-1}\right)^-\right]$, where $T_{i,t}$ and $P_{i,t}$ are population-weighted average temperature and precipitation of region i at time t, and $T^*_{i,t-1}$ and $P^*_{i,t-1}$ are their historical norms (based on moving averages of the past 30 years). Panel B shows an alternative specification that uses the absolute deviations of climate variables from their historical norms: $\mathbf{x}_{i,t} = \left[\left|T_{i,t} - T^*_{i,t-1}\right|; \left|P_{i,t} - P^*_{i,t-1}\right|\right]$. The long-run effects, $\widehat{\theta}$, are calculated from the OLS estimates of the short-run coefficients: $\theta = \frac{\sum_{l=0}^{p}\beta_l}{1-\sum_{l=1}^{p}\gamma_l}$. The lag order, p, is set to 3. WTRAFIC is wholesale, transportation, retail, food and accommodation, information and communication sectors. The standard errors are clustered as proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 10% (*), 5% (**), 1% (***) levels.

Controlling for the non-linearity in the climate change-economic growth relationship is important since the majority of sectors experience a significant long-run effect with only positive or negative variations of temperature and precipitation.

Robustness Check: Temperature only

Table 3.15: Long-Term Effects of Climate Change on the Labour Productivity Growth of Several Sectors in European regions, 1980-2017 (Using Only Temperature Deviations from their Historical Norm)

	Total	Agriculture, Forestry, Fishing	Manufacturing, Energy, Mining	Construction	WTRAFIC	Financial, Business Services	Non-market Services
Panel A: Positive and negative deviations of temperature and precipitation							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$	0.0016	-0.0333***	0.0004	0.0138*	-0.0027	0.0169**	0.0090
	(0.0038)	(0.0125)	(0.0063)	(0.0078)	(0.0053)	(0.0071)	(0.0062)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-}$	-0.0027	-0.0418**	-0.0020	0.0279***	0.0156**	0.0069	0.0173*
	(0.0059)	(0.0196)	(0.0100)	(0.0106)	(0.0079)	(0.0104)	(0.0095)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^+}$	0.0014	0.0129*	-0.0001	-0.0094**	0.0002	0.0121***	-0.0010
	(0.0019)	(0.0070)	(0.0035)	(0.0043)	(0.0028)	(0.0037)	(0.0033)
$\widehat{\theta}_{\Delta\left(P_{i,t}-P^*_{i,t-1}\right)^-}$	0.0015	-0.0032	0.0018	-0.0047	-0.0029	0.0056	0.0067*
	(0.0026)	(0.0076)	(0.0037)	(0.0044)	(0.0033)	(0.0038)	(0.0040)
$N \times T$	8196	8006	8116	8116	8116	8116	8116
Panel B: Positive and negative deviations of temperature							
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^+}$	0.0002	-0.0278**	-0.0008	0.0114	-0.0033	0.0162**	0.0074
	(0.0037)	(0.0123)	(0.0062)	(0.0077)	(0.0053)	(0.0070)	(0.0062)
$\widehat{\theta}_{\Delta\left(T_{i,t}-T^*_{i,t-1}\right)^-}$	-0.0051	-0.0376*	-0.0013	0.0255**	0.0136*	0.0032	0.0168*
	(0.0057)	(0.0193)	(0.0098)	(0.0104)	(0.0077)	(0.0103)	(0.0093)
$N \times T$	8196	8006	8116	8116	8116	8116	8116

Notes: The estimates are based on Equation 3.1: $\Delta y_{i,t} = \alpha_i + \sum_{l=1}^{p}\gamma_l \Delta y_{i,t-l} + \sum_{l=0}^{p}\beta_l \Delta \mathbf{x}_{i,t-l} + \sum_{l=0}^{p}\varphi_l \Delta \bar{y}_{t-l} + \varepsilon_{i,t}$, where $y_{i,t}$ is the log of the economic performance measure in region i at time t, α_i is the region-specific fixed effect, $\bar{y}_t$ is the log of the cross-sectional average of the economic performance measure at time t, $\mathbf{x}_{i,t}$ is the vector of the deviations of climate variables from their historical norms and $\varepsilon_{i,t}$ is the serially uncorrelated idiosyncratic error. Therefore, $\mathbf{x}_{i,t} = \left[\left(T_{i,t} - T^*_{i,t-1}\right)^+; \left(T_{i,t} - T^*_{i,t-1}\right)^-; \left(P_{i,t} - P^*_{i,t-1}\right)^+; \left(P_{i,t} - P^*_{i,t-1}\right)^-\right]$, where $T_{i,t}$ and $P_{i,t}$ are population-weighted average temperature and precipitation of region i at time t, and $T^*_{i,t-1}$ and $P^*_{i,t-1}$ are their historical norms (based on moving averages of the past 30 years). Panel B shows an alternative specification that drops the precipitation variables from the baseline model. The long-run effects, $\widehat{\theta}$, are calculated from the OLS estimates of the short-run coefficients in Eq. 3.1: $\theta = \frac{\sum_{l=0}^{p}\beta_l}{1-\sum_{l=1}^{p}\gamma_l}$. The lag order, p, is set to 3. WTRAFIC is wholesale, transportation, retail, food and accommodation, information and communication sectors. The standard errors are clustered as proposed in Proposition 4 of Chudik et al. (2018). Asterisks indicate statistical significance at the 10% (*), 5% (**), 1% (***) levels.

Controlling for precipitations does not significantly change the impact of temperature changes on labour productivity growth of European regions, apart from the construction sector. However, precipitations have a long-run effect, so excluding them may lead to a downgrade in the amount and heterogeneity of the economic damages caused by climate change.

3.A.2 Data

Table 3.16: Data Sources

Main Variables	Data Source	Unit
Temperature (Grid level)	Matsuura and Willmott (2018)	Celsius Degree, Annual Mean
Precipitation (Grid level)	Matsuura and Willmott (2018)	Total Millimeters per Year
Population density in 2015 (Grid level)	CIESIN (2016)	Persons per 5 km^2
Total Regional Population	ARDECO dataset	Persons
Gross Regional Product	ARDECO dataset	Millions, EUR, at constant 2015 price
GVA, sector a	ARDECO dataset	Millions, EUR, at constant 2015 price
GVA, sector b-e	ARDECO dataset	Millions, EUR, at constant 2015 price
GVA, sector f	ARDECO dataset	Millions, EUR, at constant 2015 price
GVA, sector g-j	ARDECO dataset	Millions, EUR, at constant 2015 price
GVA, sector k-n	ARDECO dataset	Millions, EUR, at constant 2015 price
GVA, sector o-u	ARDECO dataset	Millions, EUR, at constant 2015 price
GVA, total	ARDECO dataset	Millions, EUR, at constant 2015 price
GFCF, sector a	ARDECO dataset	Millions, EUR, at constant 2015 price
GFCF, sector b-e	ARDECO dataset	Millions, EUR, at constant 2015 price
GFCF, sector f	ARDECO dataset	Millions, EUR, at constant 2015 price
GFCF, sector g-j	ARDECO dataset	Millions, EUR, at constant 2015 price
GFCF, sector k-n	ARDECO dataset	Millions, EUR, at constant 2015 price
GFCF, sector o-u	ARDECO dataset	Millions, EUR, at constant 2015 price
GFCF, total	ARDECO dataset	Millions, EUR, at constant 2015 price
Hours worked, sector a	ARDECO dataset	Thousands of Hours Worked
Hours worked, sector b-e	ARDECO dataset	Thousands of Hours Worked
Hours worked, sector f	ARDECO dataset	Thousands of Hours Worked
Hours worked, sector g-j	ARDECO dataset	Thousands of Hours Worked
Hours worked, sector k-n	ARDECO dataset	Thousands of Hours Worked
Hours worked, sector o-u	ARDECO dataset	Thousands of Hours Worked
Hours worked, total	ARDECO dataset	Thousands of Hours Worked
Employment, sector a	ARDECO dataset	Thousands of Employed Persons
Employment, sector b-e	ARDECO dataset	Thousands of Employed Persons
Employment, sector f	ARDECO dataset	Thousands of Employed Persons
Employment, sector g-j	ARDECO dataset	Thousands of Employed Persons
Employment, sector k-n	ARDECO dataset	Thousands of Employed Persons
Employment, sector o-u	ARDECO dataset	Thousands of Employed Persons
Employment, total	ARDECO dataset	Thousands of Employed Persons

Notes: The time span of all climate variable is 1900-2017. The time span of economic variables is 1980-2017.

Table 3.17: NACE Revision 2 Classification

Code	Sector	Industries
A	Agriculture, Forestry and Fishing	Agriculture, Forestry and Fishing
B-E	Industry - excluding Construction	Mining, Quarrying, Manufacturing, Electricity, Gas, Air Conditioning, Water Supply
F	Construction	Construction
G-J	WRTAFIC	Wholesale, Retail, Transport, Accommodation & Food Services, Information and Communication
K-N	Financial & Business Services	Financial and Insurance activities, Real Estate, Legal, Accounting, Management, Scientific Research, Administrative and Support Service activities
O-U	Non-market Services	Non-market Services are general public services, Education, Health and Research provided by the Government and Private Non-Profit Institutions

Table 3.18: Average Sectoral Share of GVA per capita from 1980 to 2017.

	Agriculture, Forestry, Fishing	Manufacturing, Energy, Mining	Construction	WTRAFIC	Financial, Business Services	Non-market Services
Whole Europe	0.021	0.141	0.066	0.219	0.201	0.345
Western Europe	0.019	0.198	0.070	0.234	0.248	0.226
Eastern Europe	0.025	0.057	0.061	0.196	0.131	0.522
Less developed	0.027	0.099	0.067	0.209	0.157	0.435
More developed	0.013	0.202	0.065	0.234	0.264	0.215
Top 50% hottest	0.023	0.104	0.064	0.217	0.189	0.397
Top 50% coldest	0.017	0.226	0.071	0.222	0.227	0.227

Notes: Eastern European regions have missing observations from 1980 to 1994.

Bibliography

S. Acevedo, M. Mrkaic, N. Novta, E. Pugacheva, and P. Topalova. The effects of weather shocks on economic activity: What are the channels of impact? *Journal of Macroeconomics*, page 103207, 2020.

S. Agrawala, M. Carraro, N. Kingsmill, E. Lanzi, M. Mullan, and G. Prudent-Richard. Private sector engagement in adaptation to climate change: approaches to managing climate risks. 2011.

M. Aguiar and G. Gopinath. Emerging market business cycles: The cycle is the trend. *Journal of political Economy*, 115(1):69–102, 2007.

B. W. Ang, W. L. Choong, and T. S. Ng. Energy security: Definitions, dimensions and indexes. *Renewable and sustainable energy reviews*, 42:1077–1093, 2015.

J. D. Angrist and J.-S. Pischke. Mostly harmless econometrics: An empiricist's companion. *Princeton University Press*, 2009.

A. Arguez, I. Durre, S. Applequist, R. S. Vose, M. F. Squires, X. Yin, R. R. Heim Jr, and T. W. Owen. Noaa's 1981–2010 us climate normals: an overview. *Bulletin of the American Meteorological Society*, 93(11):1687–1697, 2012.

B. S. Atasoy. Testing the environmental kuznets curve hypothesis across the us: Evidence from panel mean group estimators. *Renewable and Sustainable Energy Reviews*, 77:731–747, 2017.

M. Auffhammer and E. T. Mansur. Measuring climatic impacts on energy consumption: A review of the empirical literature. *Energy Economics*, 46:522–530, 2014.

M. Auffhammer and W. Schlenker. Empirical studies on agricultural impacts and adaptation. *Energy Economics*, 46:555–561, 2014.

M. Auffhammer, S. M. Hsiang, W. Schlenker, and A. Sobel. Using weather data and climate model output in economic analyses of climate change. *Review of Environmental Economics and Policy*, 7(2):181–198, 2013.

A. Banerjee, J. J. Dolado, J. W. Galbraith, D. Hendry, et al. Co-integration, error correction, and the econometric analysis of non-stationary data. *OUP Catalogue*, 1993.

A. Barreca, K. Clay, O. Deschenes, M. Greenstone, and J. S. Shapiro. Adapting to climate change: The remarkable decline in the us temperature-mortality relationship over the twentieth century. *Journal of Political Economy*, 124(1):105–159, 2016.

R. Basu and J. M. Samet. Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. *Epidemiologic reviews*, 24(2):190–202, 2002.

A. P. Behrer and J. Park. Will we adapt? temperature, labor and adaptation to climate change. *Harvard Project on Climate Agreements Working Paper*, pages 16–81, 2017.

J. Bloesch and F. Gourio. The effect of winter weather on us economic activity. *Economic Perspectives*, 39(1), 2015.

G. Blöschl, J. Hall, J. Parajka, R. A. Perdigão, B. Merz, B. Arheimer, G. T. Aronica, A. Bilibashi, O. Bonacci, M. Borga, et al. Changing climate shifts timing of european floods. *Science*, 357 (6351):588–590, 2017.

G. Blöschl, J. Hall, A. Viglione, R. A. Perdigão, J. Parajka, B. Merz, D. Lun, B. Arheimer, G. T. Aronica, A. Bilibashi, et al. Changing climate both increases and decreases european river floods. *Nature*, 573(7772):108–111, 2019.

A. Bluszcz. European economies in terms of energy dependence. *Quality & Quantity*, 51(4): 1531–1548, 2017.

E. Bompard, A. Carpignano, M. Erriquez, D. Grosso, M. Pession, and F. Profumo. National energy security assessment in a geopolitical perspective. *Energy*, 130:144–154, 2017.

M. Bortolamedi. Accounting for hidden energy dependency: The impact of energy embodied in traded goods on cross-country energy security assessments. *Energy*, 93:1361–1372, 2015.

V. Bosetti, C. Carraro, M. Galeotti, E. Massetti, and M. Tavoni. A world induced technical change hybrid model. *The Energy Journal*, (Special Issue# 2), 2006.

G. Bry and C. Boschan. Standard business cycle analysis of economic time series. In *Cyclical Analysis of Time Series: Selected Procedures and Computer Programs*, pages 64–150. NBEr, 1971.

M. Burke and K. Emerick. Adaptation to climate change: Evidence from us agriculture. *American Economic Journal: Economic Policy*, 8(3):106–40, 2016.

M. Burke and V. Tanutama. Climatic constraints on aggregate economic output. Technical report, National Bureau of Economic Research, 2019.

M. Burke, S. M. Hsiang, and E. Miguel. Global non-linear effect of temperature on economic production. *Nature*, 527(7577):235–239, 2015.

A. F. Burns and W. C. Mitchell. Measuring business cycles. 1946.

G. P. Cachon, S. Gallino, and M. Olivares. Severe weather and automobile assembly productivity. *Columbia Business School Research Paper*, (12/37), 2012.

T. A. Carleton and S. M. Hsiang. Social and economic impacts of climate. *Science*, 353(6304), 2016.

P. Cashin and C. J. McDermott. The long-run behavior of commodity prices: small trends and big variability. *IMF staff Papers*, 49(2):175–199, 2002.

P. Cashin, C. J. McDermott, and A. Scott. Booms and slumps in world commodity prices. *Journal of development Economics*, 69(1):277–296, 2002.

P. Cashin, K. Mohaddes, M. Raissi, and M. Raissi. The differential effects of oil demand and supply shocks on the global economy. *Energy Economics*, 44:113–134, 2014.

L. Chester. Conceptualising energy security and making explicit its polysemic nature. *Energy policy*, 38(2):887–895, 2010.

A. Chudik, K. Mohaddes, M. H. Pesaran, and M. Raissi. *Long-run effects in large heterogeneous panel data models with cross-sectionally correlated errors*. Emerald Group Publishing Limited, 2016.

A. Chudik, K. Mohaddes, M. H. Pesaran, and M. Raissi. Is there a debt-threshold effect on output growth? *Review of Economics and Statistics*, 99(1):135–150, 2017.

A. Chudik, M. H. Pesaran, and J.-C. Yang. Half-panel jackknife fixed-effects estimation of linear panels with weakly exogenous regressors. *Journal of Applied Econometrics*, 33(6):816–836, 2018.

S. CIESIN. Gridded population of the world, version 4 (gpwv4): population density. Technical report, Technical report, Center for International Earth Science Information Network ..., 2016.

S. Claessens, M. A. Kose, and M. E. Terrones. How do business and financial cycles interact? *Journal of International economics*, 87(1):178–190, 2012.

R. Colacito, B. Hoffmann, and T. Phan. Temperature and growth: A panel analysis of the united states. *Journal of Money, Credit and Banking*, 51(2-3):313–368, 2019.

R. Damania, S. Desbureaux, and E. Zaveri. Does rainfall matter for economic growth? evidence from global sub-national data (1990–2014). *Journal of Environmental Economics and Management*, page 102335, 2020.

T. V. De V. Cavalcanti, K. Mohaddes, and M. Raissi. Does oil abundance harm growth? *Applied Economics Letters*, 18(12):1181–1184, 2011.

T. V. De V. Cavalcanti, K. Mohaddes, and M. Raissi. Commodity price volatility and the sources of growth. *Journal of Applied Econometrics*, 30(6):857–873, 2015.

M. Dell, B. F. Jones, and B. A. Olken. Temperature and income: reconciling new cross-sectional and panel estimates. *American Economic Review*, 99(2):198–204, 2009.

M. Dell, B. F. Jones, and B. A. Olken. Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics*, 4(3):66–95, 2012.

M. Dell, B. F. Jones, and B. A. Olken. What do we learn from the weather? the new climate-economy literature. *Journal of Economic Literature*, 52(3):740–98, 2014.

T. Deryugina and S. M. Hsiang. Does the environment still matter? daily temperature and income in the united states. Technical report, National Bureau of Economic Research, 2014.

O. Deschenes. Temperature, human health, and adaptation: A review of the empirical literature. *Energy Economics*, 46:606–619, 2014.

O. Deschênes and M. Greenstone. The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. *American Economic Review*, 97(1): 354–385, 2007.

O. Deschênes and M. Greenstone. Climate change, mortality, and adaptation: Evidence from annual fluctuations in weather in the us. *American Economic Journal: Applied Economics*, 3(4): 152–85, 2011.

N. S. Diffenbaugh and M. Burke. Global warming has increased global economic inequality. *Proceedings of the National Academy of Sciences*, 116(20):9808–9813, 2019a.

N. S. Diffenbaugh and M. Burke. Reply to rosen: Temperature–growth relationship is robust. *Proceedings of the National Academy of Sciences*, 116(33):16171–16172, 2019b.

R. F. Engle and C. W. Granger. Co-integration and error correction: representation, estimation, and testing. *Econometrica: journal of the Econometric Society*, pages 251–276, 1987.

C. Falco, M. Galeotti, and A. Olper. Climate change and migration: Is agriculture the main channel? *Global Environmental Change*, 59:101995, 2019.

S. Fankhauser and R. S. Tol. On climate change and economic growth. *Resource and Energy Economics*, 27(1):1–17, 2005.

S. Fankhauser, R. S. Tol, and D. W. Pearce. The aggregation of climate change damages: a welfare theoretic approach. *Environmental and Resource Economics*, 10(3):249–266, 1997.

R. C. Feenstra, R. Inklaar, and M. P. Timmer. The next generation of the penn world table. *American economic review*, 105(10):3150–82, 2015.

S. Feng, A. B. Krueger, and M. Oppenheimer. Linkages among climate change, crop yields and mexico–us cross-border migration. *Proceedings of the National Academy of Sciences*, 107(32): 14257–14262, 2010.

L. Feyen and R. Dankers. Impact of global warming on streamflow drought in europe. *Journal of Geophysical Research: Atmospheres*, 114(D17), 2009.

S. Filipović, M. Radovanović, and V. Golušin. Macroeconomic and political aspects of energy security–exploratory data analysis. *Renewable and Sustainable Energy Reviews*, 97:428–435, 2018.

R. Fishman. More uneven distributions overturn benefits of higher precipitation for crop yields. *Environmental Research Letters*, 11(2):024004, 2016.

R. Fuentes, M. Galeotti, A. Lanza, and B. Manzano. Covid-19 and climate change: A tale of two global problems. *Sustainability*, 2020.

D. García-León. Weather and income: Lessons from the main european regions. 2015.

J. Graff Zivin and M. Neidell. Temperature and the allocation of time: Implications for climate change. *Journal of Labor Economics*, 32(1):1–26, 2014.

J. Graff Zivin, S. M. Hsiang, and M. Neidell. Temperature and human capital in the short and long run. *Journal of the Association of Environmental and Resource Economists*, 5(1):77–105, 2018.

C. Greene. Broadening understandings of drought–the climate vulnerability of farmworkers and rural communities in california (usa). *Environmental Science & Policy*, 89:283–291, 2018.

S. Hallegatte and A. Vogt-Schilb. Are losses from natural disasters more than just asset losses? the role of capital aggregation, sector interactions, and investment behaviors. *World Bank working paper series*, 2016.

S. Hallegatte, A. Shah, C. Brown, R. Lempert, and S. Gill. Investment decision making under deep uncertainty–application to climate change. *World Bank Policy Research Working Paper*, (6193), 2012.

D. Harding and A. Pagan. Dissecting the cycle: a methodological investigation. *Journal of monetary economics*, 49(2):365–381, 2002.

D. Harding and A. Pagan. Synchronization of cycles. *Journal of Econometrics*, 132(1):59–79, 2006.

M. Harding, C. Lamarche, and M. H. Pesaran. Common correlated effects estimation of heterogeneous dynamic panel quantile regression models. *Journal of Applied Econometrics*, 35(3): 294–314, 2020.

M. Henseler and I. Schumacher. The impact of weather on economic growth and its production factors. *Climatic Change*, 154(3-4):417–433, 2019.

T. W. Hertel and C. Z. de Lima. Climate impacts on agriculture: Searching for keys under the streetlight. *Food Policy*, 95:101954, 2020.

F. D. Hidalgo, S. Naidu, S. Nichter, and N. Richardson. Economic determinants of land invasions. *The Review of Economics and Statistics*, 92(3):505–523, 2010.

H. Hisdal, K. Stahl, L. M. Tallaksen, and S. Demuth. Have streamflow droughts in europe become more severe or frequent? *International Journal of Climatology*, 21(3):317–333, 2001.

L. Holtermann and M.-C. Rische. The subnational effect of temperature on economic production: A disaggregated analysis in european regions. 2020.

S. M. Hsiang. Temperatures and cyclones strongly associated with economic production in the caribbean and central america. *Proceedings of the National Academy of sciences*, 107(35): 15367–15372, 2010.

S. M. Hsiang, M. Burke, and E. Miguel. Quantifying the influence of climate on human conflict. *Science*, 341(6151), 2013.

IEA. Energy supply security: Emergency response of iea countries. Technical report, 2014.

ILO. The employment impact of climate change adaptation, 2018.

ILO. Working on a warmer planet: The effect of heat stress on productivity and decent work., 2019.

IMF. World economic outlook: Challenges to steady growth. 2018.

IPCC. *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. IPCC, 2014.

IPCC. *Climate change 2021: The Physical Science Basis. Contribution of Working Groups I to the sixth assessment report of the Intergovernmental Panel on Climate Change*. IPCC, 2021.

U. Jarrett, K. Mohaddes, and H. Mohtadi. Oil price volatility, financial institutions and economic growth. *Energy Policy*, 126:131–144, 2019.

B. F. Jones and B. A. Olken. Climate shocks and exports. *American Economic Review*, 100(2): 454–59, 2010.

Ò. Jordà, M. Schularick, and A. M. Taylor. Macrofinancial history and the new business cycle facts. *NBER macroeconomics annual*, 31(1):213–263, 2017.

M. E. Kahn and M. J. Kotchen. Environmental concern and the business cycle: the chilling effect of recession. Technical report, National Bureau of Economic Research, 2010.

M. E. Kahn, K. Mohaddes, R. N. Ng, M. H. Pesaran, M. Raissi, and J.-C. Yang. Long-term macroeconomic effects of climate change: A cross-country analysis. Technical report, National Bureau of Economic Research, 2019.

M. Kalkuhl and L. Wenz. The impact of climate conditions on economic production. evidence from a global panel of regions. *Journal of Environmental Economics and Management*, 103: 102360, 2020.

L. Kilian. The economic effects of energy price shocks. *Journal of Economic Literature*, 46(4): 871–909, 2008.

C. D. Kolstad and F. C. Moore. Estimating the economic impacts of climate change using weather observations. *Review of Environmental Economics and Policy*, 14(1):1–24, 2020.

J. J. Kremers, N. R. Ericsson, and J. J. Dolado. The power of cointegration tests. *Oxford bulletin of economics and statistics*, 54(3):325–348, 1992.

B. Kruyt, D. P. van Vuuren, H. J. de Vries, and H. Groenenberg. Indicators for energy security. *Energy policy*, 37(6):2166–2181, 2009.

F. E. Kydland and E. C. Prescott. Time to build and aggregate fluctuations. *Econometrica: Journal of the Econometric Society*, pages 1345–1370, 1982.

M. Letta and R. S. Tol. Weather, climate and total factor productivity. *Environmental and Resource Economics*, 73(1):283–305, 2019.

Z. Liu, P. Ciais, Z. Deng, R. Lei, S. J. Davis, S. Feng, B. Zheng, D. Cui, X. Dou, B. Zhu, et al. Near-real-time monitoring of global co 2 emissions reveals the effects of the covid-19 pandemic. *Nature communications*, 11(1):1–12, 2020.

M. G. Marshall, T. R. Gurr, and K. Jaggers. Polity iv project: Political regime characteristics and transitions, 1800–2015. Technical report, 2016.

K. Matsumoto, M. Doumpos, and K. Andriosopoulos. Historical energy security performance in eu countries. *Renewable and Sustainable Energy Reviews*, 82:1737–1748, 2018.

K. Matsuura and C. J. Willmott. Terrestrial air temperature: 1900–2017 gridded monthly time series, 2018.

R. Mendelsohn. Measuring weather impacts using panel data. In *ASSA Annual Meeting 2017*, 2016.

K. Mohaddes and M. H. Pesaran. Country-specific oil supply shocks and the global economy: A counterfactual analysis. *Energy Economics*, 59:382–399, 2016.

K. Mohaddes and M. H. Pesaran. Oil prices and the global economy: Is it different this time around? *Energy Economics*, 65:315–325, 2017.

K. Mohaddes and M. Raissi. Do sovereign wealth funds dampen the negative effects of commodity price volatility? *Journal of Commodity Markets*, 8:18–27, 2017.

K. Mohaddes and M. Raissi. The us oil supply revolution and the global economy. *Empirical Economics*, 57(5):1515–1546, 2019.

K. Mohaddes and M. Raissi. Compilation, revision and updating of the global var (gvar) database, 1979q2-2019q4. 2020.

K. Mohaddes and R. J. Williams. The adaptive investment effect: evidence from chinese provinces. 2020.

F. C. Moore and D. B. Diaz. Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change*, 5(2):127, 2015.

R. G. Newell, B. C. Prest, and S. E. Sexton. The gdp-temperature relationship: implications for climate change damages. *Journal of Environmental Economics and Management*, page 102445, 2021.

S. Nickell. Biases in dynamic models with fixed effects. *Econometrica: Journal of the econometric society*, pages 1417–1426, 1981.

NOAA. State of the climate: Global climate report for annual 2020, published online january 2021, retrieved on january 24, 2021 from https://www.ncdc.noaa.gov/sotc/global/202013. Technical report, 2020.

W. D. Nordhaus. Geography and macroeconomics: New data and new findings. *Proceedings of the National Academy of Sciences*, 103(10):3510–3517, 2006.

J. E. Olesen and M. Bindi. Consequences of climate change for european agricultural productivity, land use and policy. *European journal of agronomy*, 16(4):239–262, 2002.

A. Olper, M. Maugeri, V. Manara, and V. Raimondi. Weather, climate and economic outcomes: Evidence from italy. *Ecological Economics*, 189:107156, 2021.

G. Peersman and I. Van Robays. Cross-country differences in the effects of oil shocks. *Energy Economics*, 34(5):1532–1547, 2012.

H. Pesaran et al. General diagnostic tests for cross-sectional dependence in panels. *University of Cambridge, Cambridge Working Papers in Economics*, 435, 2004.

M. H. Pesaran. The role of economic theory in modelling the long run. *The Economic Journal*, 107(440):178–191, 1997.

M. H. Pesaran. Testing weak cross-sectional dependence in large panels. *Econometric reviews*, 34(6-10):1089–1117, 2015.

M. H. Pesaran and Y. Shin. An autoregressive distributed-lag modelling approach to cointegration analysis. *Econometric Society Monographs*, 31:371–413, 1998.

M. H. Pesaran and R. Smith. Estimating long-run relationships from dynamic heterogeneous panels. *Journal of econometrics*, 68(1):79–113, 1995.

M. H. Pesaran, K. Mohaddes, A. Chudik, M. Raissi, et al. Long-run effects in large heterogenous panel data models with cross-sectionally correlated errors. Technical report, Federal Reserve Bank of Dallas, 2015.

G. P. Peters, G. Marland, C. Le Quéré, T. Boden, J. G. Canadell, and M. R. Raupach. Rapid growth in co 2 emissions after the 2008–2009 global financial crisis. *Nature climate change*, 2 (1):2–4, 2012.

R. Pode. Addressing india's energy security and options for decreasing energy dependency. *Renewable and Sustainable Energy Reviews*, 14(9):3014–3022, 2010.

M. Radovanović, S. Filipović, and D. Pavlović. Energy security measurement–a sustainable approach. *Renewable and Sustainable Energy Reviews*, 68:1020–1032, 2017.

M. Radovanović, S. Filipović, and V. Golušin. Geo-economic approach to energy security measurement–principal component analysis. *Renewable and Sustainable Energy Reviews*, 82: 1691–1700, 2018.

R. A. Rosen. Temperature impact on gdp growth is overestimated. *Proceedings of the National Academy of sciences*, page 201908081, 2019.

J. D. Sachs and A. M. Warner. Natural resource abundance and economic growth. Technical report, National Bureau of Economic Research, 1995.

W. Schlenker and M. J. Roberts. Nonlinear temperature effects indicate severe damages to us crop yields under climate change. *Proceedings of the National Academy of sciences*, 106(37): 15594–15598, 2009.

D. E. Sichel. Inventories and the three phases of the business cycle. *Journal of Business & Economic Statistics*, 12(3):269–277, 1994.

A. Sirag, B. T. Matemilola, S. H. Law, and A. Bany-Ariffin. Does environmental kuznets curve hypothesis exist? evidence from dynamic panel threshold. *Journal of environmental economics and policy*, 7(2):145–165, 2018.

J. Spinoni, J. V. Vogt, G. Naumann, P. Barbosa, and A. Dosio. Will drought events become more frequent and severe in europe? *International Journal of Climatology*, 38(4):1718–1736, 2018.

N. H. Stern, S. Peters, V. Bakhshi, A. Bowen, C. Cameron, S. Catovsky, D. Crane, S. Cruickshank, S. Dietz, N. Edmonson, et al. *Stern Review: The economics of climate change*, volume 30. Cambridge University Press Cambridge, 2006.

A. Sudarshan and M. Tewari. The economic impacts of temperature on industrial productivity: Evidence from indian manufacturing. Technical report, Working paper, 2014.

R. S. Tol. The economic impact of weather and climate. 2020.

G. Trotta. Assessing energy efficiency improvements, energy dependence, and co 2 emissions in the european union using a decomposition method. *Energy Efficiency*, 12(7):1873–1890, 2019.

R. Van Eyden, M. Difeto, R. Gupta, and M. E. Wohar. Oil price volatility and economic growth: Evidence from advanced economies using more than a century's data. *Applied Energy*, 233: 612–621, 2019.

S. Van Passel, E. Massetti, and R. Mendelsohn. A ricardian analysis of the impact of climate change on european agriculture. *Environmental and Resource Economics*, 67(4):725–760, 2017.

V. Vivoda. Evaluating energy security in the asia-pacific region: A novel methodological approach. *Energy policy*, 38(9):5258–5263, 2010.

R. S. Vose, S. Applequist, M. Squires, I. Durre, M. J. Menne, C. N. Williams Jr, C. Fenimore, K. Gleason, and D. Arndt. Improved historical temperature and precipitation time series for us climate divisions. *Journal of Applied Meteorology and Climatology*, 53(5):1232–1251, 2014.

M. L. Weitzman. Fat-tailed uncertainty in the economics of catastrophic climate change. *Review of Environmental Economics and Policy*, 5(2):275–292, 2011.

L. Wenz, A. Levermann, and M. Auffhammer. North–south polarization of european electricity consumption under future warming. *Proceedings of the National Academy of Sciences*, 114(38): E7910–E7918, 2017.

P. Zhang, O. Deschenes, K. Meng, and J. Zhang. Temperature effects on productivity and factor reallocation: Evidence from a half million chinese manufacturing plants. *Journal of Environmental Economics and Management*, 88:1–17, 2018.