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Abstract

The world's climate has already changed measurably in response to accumulated greenhouse gases emissions. These changes, as well as projected future disruptions, such as increase of temperature, have prompted intense research. A significant body of literature on climate change and economic growth signifies a negative relationship between the two. However, considerable uncertainty surrounds the effect of increasing temperatures combined with releases of anthropogenic emissions to the atmosphere. By applying detailed country level data in the 1961-2013 period this paper documents the relationship between weather variables, CO_2 emissions, share of renewable energy sources, gross domestic product and total factor productivity in a standard Cobb-Douglas production function by using an instrumental variable approach. Our findings suggest that economic growth has been positively affected by temperature and CO_2 emissions, while climate vulnerability varies significantly between rich-poor countries. Furthermore, as soon as we take into account renewable sources as an instrument, the negative effect on CO_2 emissions demonstrates its impact for optimal environmental policies design. Finally, our results also provide evidence for the existence of an inverted U-shaped relationship for temperature and emissions.
keywords: Climate Change, Countries' TFP, CO_2 emissions, Renewable Energy Sources, Temperature.

JEL Classifications: Q54, C26, O44

1 Introduction

One of the most critical issues contemporaneous generations are faced with is that of climate crisis that has emerged over the past decades. Not only does climate change create unfriendly environmental conditions for citizens, cities and regions that are influenced by extreme weather conditions, but it also has an impact on the economy of countries both at regional and country level (Nordhaus, 1991; Cline, 1992). Several studies (Frankhauser, 1996; Tol, 2009, 2010) have proven that climate change through rising temperature records has a negative impact on the economy. Also, if humanity fails to mitigate the warming effect that is currently being conducted, the economic impact will also be persistent and more damaging for poor countries (Nordhaus and Boyer, 2000; Stern, 2007). To deal with the problem many countries signed the Paris agreement; a transnational convention that aims to increase the capability of all governments to manage the implications deriving from climate change, obtain stable economies harmonized with low carbon emissions, and become resistant to the problem of climate change. Moreover, in a very recent reaction European Union (EU) has come to a European Green Deal, the most ambitious package of measures that should enable European citizens and businesses to benefit from sustainable green transition.

By using the term climate change we refer to the human made change of meteorological or natural phenomena that holds for long time periods causing global warming, deforestation, melting of permafrost and other risky effects that result in dangerous paths (Stern, 2006). Furthermore, increasing atmospheric concentrations of greenhouse gases (GHG's) over the past decades are the main contributor to the deterioration of environmental quality (Stern, 2007). Greenhouse gases trap heat in the lower atmosphere and keep earth warmer causing many disasters (Stern, 2006). Thus, many scientists argue that the increase of anthropogenic GHGs alters the climate producing changes in surface temperature and precipitation (Brown et al., 2016). From their side, economists (Frankhauser, 1996; Tol, 2005, 2018) consider these effects as of increasing interest for countries' economic growth and total factor productivity. The most commonly used GHGs are carbon dioxide (CO_2) (Caron and Fally, 2018; Pindyck, 2020), methane (CH_4) (Benavides et al., 2017) and particulate matters ($PM_{2.5}$ or PM_{10}) (Chen et al., 2018) in order to investigate the risk derived from increasing emissions and their impact on the economy.

The uncontrollable environmental pollution, mainly from pollutant releases of the transportation and industry sector, has caused the greenhouse effect which is responsible for the increase of temperature and the climate change that is being conducted. Climate change risks can also cause economic shocks, meaning unpredictable events that bring significant harm within an economy (Batten, 2018), especially on the agricultural sector, which is the most vulnerable sector of the economy due to the nature of its work (Mendelsohn et al., 1994; Cline, 2007; Deschenes and Greenstone, 2007; Mendelsohn, 2008; Ji et al., 2020). Hence, an issue of critical importance in climate, environmental and development economics involves understanding the economic impact and consequences of changes in surface temperatures. Consequently, when estimating the impact of climate change on gross domestic product (GDP) and total factor productivity (TFP), temperature can not be considered as strictly exogenous (Kahn et al., 2019).

It is a fact that year to year temperature variations constitute the most common determinant factor to specify the change of climate harmony and its effect on the economy (Nordhaus, 2006; Dell et al., 2012; Letta and Tol, 2018). Other than temperature variations, studies use the Wet Bulb Globe Temperature (Somanathan et al., 2015), which is a metric that combines temperature, humidity, precipitation and wind direction. Precipitation (annual cumulative amount of rainfall) is the second most common analytical tool used to define climate change (Dell et al., 2014; Damania et al., 2019). The significance of other climatic variables, such as wind speed, sunshine duration and evaporation (Zhang et al., 2017), has recently been examined. But the vast majority of available studies investigate the relationship between climate change -expressed as temperature and/or rainfall- and economic development.

The article at hand builds on the potential effects of temperature and precipitation, but also of CO_2 emissions on countries' economic growth estimating a neoclassical production function. Unraveling such a relationship is in line with a theoretical framework (Kahn et al., 2019) and empirical studies that incorporate the effects of climatic variables and CO_2 emissions individually on countries' growth. However, our intention here is to take a step further investigating the effects of CO_2 emissions and temperature in light of instrumental variables using a Cobb-Douglas production function. We argue that CO_2 emissions and temperature have an indirect impact on countries' economic growth through an endogenous relationship. We consider temperature, precipitation and renewable energy sources (RES) as instruments for the CO_2 emissions case, while we assume precipitation and CO_2 emissions as potential determinants of temperature. This would allow us to understand not only the specific role of classical variables of production may have on countries' growth under this perspective, but also to demonstrate how CO_2 emissions and temperature flows are linked with countries' growth and how they affect their climate change policies proposing an alternative mechanism.

The literature attempts to quantify the effects of climate change on economic growth are relatively recent. For example, Dell et al. (2012) using country level data find that a 1^oC temperature increase in a given year reduces that year's economic growth by 1.3 percentage points but only in poor countries. Another finding is that higher temperatures in poor countries tend to reduce not only the output levels, but also the growth rates of the economy. Nordhaus (2006) detects a negative relationship between temperature and output when it is measured on a per capita basis, and a positive relationship when it is measured on a per area basis. Leppänen et al. (2017) provide evidence in regional level that increase of temperature reduces public expenditures for cold and hot regions, thus implying non-linear effects. Temperatures and extreme weather conditions, such as cyclones, are expected to reduce economic output by 2.5% according to Hsiang (2010).

In the same line of research, Letta and Tol (2018) investigate the relationship between annual temperature shocks and annual Total Factor Productivity (TFP) growth. In agreement with Dell et al. (2012) they found a negative relationship only in poor countries, where a 1^oC annual increase in temperature decreases TFP growth rates by about 1.1-1.8 percentage points. They also find that temperature lags have an effect on countries' economic growth implying a persistence of weather in the medium run. They do not find existing non-linear effects of temperature shocks on TFP. The nexus between temperature and firm productivity is of great importance but research attempts on industry level are scarce. Zhang et al. (2018) for half a million manufacturing plants give evidence for the existence of an inverted U-shaped relationship between temperature and TFP. More specifically, they estimate that an extra day with temperature exceeding 32^oC reduces output by 0.45%. Somanathan et al. (2015) provide similar evidence, concluding that productivity declines when temperature is higher than 27 degrees and that worker absenteeism increases when hot days are consecutive. Cai et al. (2018) controlling for labor productivity show that it has an inverted U-shaped relationship with temperature, decreasing with temperature records above 26^oC. Recent evidence (Cook and Heyes, 2020) explains that cognitive workers, despite not working outdoors, are impacted when cold temperatures are existing outdoors.

In order to focus the attention on factors of the production function most studies explore the short-run relationship between pollution and labor supply, mainly through work hours (Graff Zivin and Neidell, 2012; Hanna and Oliva, 2015). Another part of the literature explores the long-run impacts of pollution, or contamination, mainly through diseases and illnesses (**?**Qiu et al., 2018) that are in fact a spin-off of the pollution. Common finding in studies investigating the impact of air pollution on worker productivity is that emissions have a negative impact on productivity. When investigating for economic growth instead, the results indicate that emissions increase economic outcomes. It is also a matter of fact that pollution can be detrimental for infants and people suffering from other diseases. In this line of research, Zhang et al. (2018), findings support the fact that decreases in $PM_{2.5}$ and SO_2 increase labor productivity and also manufacturing output. Hanna and Oliva (2015) present similar results for Mexico City suggesting that decrease of SO_2 emissions leads to increase of hours worked per week by

3.5%. Many could argue that the effect of emissions on labor productivity can only be found on jobs that require human presence in open space. Chang et al. (2019) investigate the effect of pollution on worker productivity for call centers and find a negative relationship between the variables of interest. Similar evidence is provided by a handful of other studies (Koundouri et al., 2010; Graff Zivin and Neidell, 2012; He et al., 2019) suggesting that air pollution has significant negative impacts on worker productivity.

Finally, precipitation is whether a weak significant and positive estimator of economic productivity (Dell et al., 2012) or not significant at all (Letta and Tol, 2018). Damania et al. (2019) focus on the impact that rainfall has on gross domestic product. Rainfall is expressed as the total amount of precipitation that has fallen during a year and they find that it can bring positive and statistically significant changes in gross domestic product if the latter is calculated in sub-national levels, unlikely with other research works that use aggregate national levels.

While important, the relationship between emissions and countries' economic growth and also the relationship between emissions and RES are not well documented in the existing literature. Kalaitzidakis et al. (2018), examine the relationship between SO_2 emissions and TFP growth for countries belonging to OECD. They ascertain an increasing relationship between emissions and output and that SO_2 emissions contribute on average about 0.063% to productivity growth in the countries of their sample. Empora and Mamuneas (2011) make use of the TFP growth of U.S. states combined with the effect of sulphur dioxide and nitrogen oxides and for both pollutants they conclude that TFP is positively affected. Regarding renewable sources Le et al. (2020) find that the use of RES helps limit emissions but only in developed countries. The results they provide also indicate that GHG emissions (testing for a set of different types of GHGs) have a significantly positive effect on economic growth. It is a rational result, which is aligned with the results we provide. Apergis and Payne (2010), testing for OECD countries, find a positive and statistically significant nexus between renewable energy consumption and economic growth detecting bidirectional causality for the two variables of interest.

We contribute to the climate change economy growth literature along the following dimensions. Firstly, we make use of a standard Cobb-Douglas production function and add emissions and weather variables as determinants of growth. We consider temperature effects along with emissions which according to the available literature has been attempted only once (Fu et al., 2018). Secondly, knowing that emissions and temperature are responsible for climate change, it was of high importance to include both of them in an equation describing the impacts of climate change. In order to achieve this we make use of an instrumental variable regression and consider emissions and temperature as endogenous variables. Finally, we proceed with a number of alternative specification, such as robustness checks, to examine the diversification of rich vs poor countries and possible quadratic effects.

Drawing information from various databases and appropriately modifying it, we construct a balanced panel dataset for the 1961-2013 period that contains 110 countries. Our main findings indicate that temperature and emissions are negatively impacting economic development but only when we control for poor countries, implying substantial heterogeneity between rich and poor countries. As poor countries have to face the climate change problem more intensively, it constitutes an extra obstacle on their way to converge with richer countries (Dell et al., 2012; Letta and Tol, 2018; Zhang et al., 2018; Zhao et al., 2018). We also find that TFP is declining with increasing CO_2 emissions, while factors of production have the expected signs. Non-linearity is also checked and exists for both temperature and CO_2 emissions. Existence of temperature non-linearity is aligned with Burke et al. (2015) and Dell et al. (2012) and CO_2 emissions' non-linearity is aligned with Kalaitzidakis et al. (2018). Finally, we find a steadily negative relationship between emissions and share of RES. This implies that the growing part of renewable energy can diminish the CO_2 emissions concentration and help manage the greenhouse effect (Le et al., 2020). Thus, optimal policies should focus on clean energy generation in order to tackle emissions.

The rest of the paper is organized as follows. Section "Methodology and empirical strategy" presents the empirical background for our analysis. Section "Data and variables" describes data sources and provides summary statistics. Section "Empirical results and discussion presents our results while Section "Conclusions" concludes.

2 Methodology and empirical strategy

In this section we present the methodological route we followed in order to ground the relationship among countries' economic growth, capital, labor, energy, carbon dioxide emissions, temperature, precipitation and share of RES for a set of countries covering the 1961-2013 period. Based merely on Dell et al. (2012) we consider a production function in logs estimating our primary econometric model of the following form:

$$Y_{it} = f(K_{it}, L_{it}, E_{it}) + \beta_1 W_{it} + \beta_2 CO2_{it} + \alpha_i + \pi_t + \varepsilon_{it} \tag{1}$$

where W_{it} is a vector of weather variables including annual mean temperature and annual mean cumulative precipitation, while β_2 captures the effect of countries' emissions on their economic growth. α_i depicts country fixed effects that are caused by time invariant country characteristics and affect GDP growth. Year fixed effects (π_t) capture annual transnational shocks to countries' economic growth, such as macroeconomic effects. ε_{it} is the error term and captures time variant country characteristics that are unobservable and not included in the parameters of the estimation, but affect countries' economic growth. In robustness checks we allow for continents fixed effects instead of countries in order to condense information that concerns countries with similarities.

Fixed effects estimators are better than the standard regression estimators because they are less biased and more reasonable as a method, albeit the estimators may still be biased. More specifically, there still might exist unobserved time varying differences across countries, thus implying selection bias. Using a large dataset with a period of time of more than half a century, can lead to structural changes within countries. These changes can derive from emissions and pollution policies or changes in labor legislation. A second problem that gives rise to potential bias is the reverse causality that results from the link between emissions and growth (Kahn et al., 2019; Kalaitzidakis et al., 2018). It is a matter of fact that emissions are the outcome of the production process and the more output a country has, the more pollutants it emits. Developing economies on their way to become developed use more emission intensive technologies and end up being more polluted. This reverse causality problem leads to simultaneity bias when estimated using a fixed effects method.

We apply an instrumental variable regression strategy to remedy both of the above mentioned biases. We consider that the link between emissions temperature and economic growth is not only straightforward as it has been described in the majority of recent literature. According to Kaufmann et al. (2006), the relationship between temperature and emissions does not only derive from the fact that emissions' concentration changes surface temperature, but also from the fact that increases in surface temperature have caused carbon dioxide emissions' concentration to increase. Thus, we test whether temperature, precipitation and share of RES have an impact on carbon dioxide emissions, on the first stage regressions (2) and if so, we regress economic growth on CO_2 emissions, capital, labor, energy for a given country in a given year (1):

$$CO2_{it} = \rho_0 + \rho_1 W_{it} + \rho_2 RE_{it} + \alpha_i + \pi_t + \mu_{it} \tag{2}$$

where RE_{it} is share of RES and ρ_2 the slope of the variable depicting the way that renewable sources impact CO_2 emissions. μ_{it} is the error term and the rest of the variables have been explained at equation (1). Instruments must be correlated with the endogenous variable, CO_2 emissions in our case and have an indirect change on the dependent variable through the endogenous. Temperature and precipitation variables together with the share of RES are being used as instruments for the first stage of regression. Normally, when a country increases the quantity of energy produced from renewable sources, it is because they want to face the increased demand for energy use or because they want to replace the classic type of energy production with green energy from sustainable energy sources. In both cases, the aftermath is that the share of RES increases. This can lead to a decrease in CO_2 emissions, since it is the most common pollutant, emitted during the production process and has to be reduced in order to prevent temperature rise and climate change.

Finally, using the same logic we also consider that temperature operates as an instrumental variable in Eq. (1) and examine if precipitation, denoted as PRE_{IT} and CO_2 emissions influence countries' economic growth in the following form:

$$Temp_{it} = \rho_0 + \rho_1 C02_{it} + \rho_2 PRE_{it} + \alpha_i + \pi_t + \mu_{it} \tag{3}$$

At this point we want to emphasize 5 notes. First, we choose output-side real GDP and TFP as measures of economic growth and output. GDP, as an index that incorporates the final market value of all goods and services, is very useful in our era to understand the way that economic growth gets impacted by CO_2 emissions and rising temperatures. On the other hand, TFP, which is the ratio of aggregate output to aggregate inputs, can reveal the effect that emissions and temperature have on output and productivity. TFP reveals the reactions of productivity and combined with the fact that we use a Cobb Douglas production function to estimate the results, it will let us have a sneak peek on more productive characteristics of the economy. Second, we take advantage of the reverse causality between CO_2 emissions and temperature and treat them alternately as endogenous variables and instruments. The fact that it has been proved that not only CO_2 emissions increase temperature, but also temperature increases CO_2 emissions' concentration allows to test on the endogeneity problem with two variables. Third, we try to unravel the effects of share of RES, CO_2 emissions and temperatures using continents fixed effects. We consider that the broader geographic areas can absorb some peculiarities that are common characteristics in countries of the same continent. Fourth, following Dell et al. (2012) we create a poor dummy in order to separate the existing country dataset in poor and rich countries. The approach we adopt here is different and we consider a country as poor if their GDP is below the mean GDP of all countries for that year. Thus, we do not create only one mean GDP (that of the first year) and categorize the countries according to it, but every year's GDP helps identify better the rich and poor countries. Fifth, we estimate non linear effects of temperature and precipitation in order to explore the inverted U-shaped relationship between temperature and economic growth (Letta and Tol, 2018).

3 Data and Variables

We construct a unique panel dataset for world countries over the 1961-2013 period. More specifically, the country-year GDP and TFP data are derived from Penn World Table version 9.1 dataset (Feenstra et al., 2015), concerning a set of 110 countries from 1961 to 2013. We make use of variables such as output side real GDP (at chained PPP's and also in million 2011 US $) and TFP level at current PPP's that are being used as the dependent variables for our estimations. Furthermore, we make use of the capital stock (expressed at 2011 national prices) and the number of persons engaged (in millions) for every country, in order to create a classic Cobb-Douglas production function for estimation purposes.

Furthermore, data concerning energy is obtained from the World Bank database. We collect data for energy use (kg of oil equivalent per capita) to represent the energy consumed by country and by year. Energy use refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport. Data covers the years from 1960 to 2015 but we focus on 1961-2013 for 110 countries. In addition, using the World Bank database we collect combustible renewables and waste dataset (expressed as a percentage of energy). The specific dataset includes energy from solid biomass, liquid biomass, biogas, industrial waste, and municipal waste being used in a country and measured as a percentage of total energy use. Another innovative part of our research is making use of a second RES dataset. More specifically, we refer to clean alternative and nuclear energy, such as hydropower, nuclear, geothermal, and solar power. Hence, we make use of two distinct datasets when controlling for the impact of RES on countries' economic activity.

In addition, CO_2 emissions data (metric tons per capita) is also derived from the World Bank and includes the country-year quantities of CO_2 emissions during consumption of solid, liquid and gas fuels and gas flaring. Carbon dioxide emissions are a by-product of fossil fuel combustion and biomass burning and constitute the most common anthropogenic emissions affecting Earth's radiative balance. Carbon dioxide atmospheric concentrations have increased rapidly since the industrial revolution and the machine introduction at the production chain. As discussed above, we focus on the 1961-2013 period for 110 countries.

The climatic variables of temperature and precipitation have been derived from Matsuura and Willmott (Matsuura and Willmott, 2016) and appropriately modified in gridded cells method (Nordhaus, 2006). Once collected, data are presented on a monthly level and represent recorded temperature and precipitation from several weather stations that have been converged into one record for a particular geographical area according to the coordinates. Surface bounded by 0.5^o latitude and by 0.5^o longitude contours (approximately 90x90 kilometers on equator) depicts a terrestrial unit or otherwise called, gridded cell. The specific database covers the period 1900-2018 and with appropriate handling temperature and precipitation data can be easily extracted for the period of our interest (1961-2013). We convert monthly temperatures and precipitation records to annual average temperature and annual
cumulative precipitation. Then, we match them to country boundaries and con-

struct annual average temperature and annual average cumulative precipitation for 110 countries and 53 years. According to Nordhaus (2006), *"The grid cell is selected because it is the unit for which data, particularly on population, are most plentiful. From a practical point of view there is no alternative to a grid measurement system"*. The specific method has been used in other researches (Nordhaus, 2006; Somanathan et al., 2015) and is preferred to the method that makes use of data that refer to one single number giving national evidence, because it can provide more detailed information and also the geographic heterogeneity can be dismissed.

We have to note that energy, emissions and renewable sources datasets contain an unbalanced panel dataset of 290 countries for the 1950-2018 period. After unifying the three separate datasets, we reduce the chronicle scale of our sample to 1961-2013[1]. We end up having 130 countries on our dataset. Next, we merge with the temperature and precipitation data [2]. Thus, the panel dataset consists of 5830 observations covering 110 countries for 53 years. Table 1 presents the logarithmic values of the variables of GDP, TFP, labor, capital, energy and CO_2 emissions, which are used instead of their natural values. For all the above mentioned variables, plus the one representing renewable sources of energy, in order to avoid outliers (high and low values) we replace the 0.005% highest and lowest values with the next value counting inwards from the extremes.

4 Results and discussion

4.1 OLS and 2SLS Results

We begin by presenting the results of OLS regression together with the results of instrumental variable regression. Table 2 is organized as follows. Panel (a) provides the results of the first stage of the 2SLS method, while panel (b) provides the results of the second stage and the OLS results. Each column represents a different regression. In column (1), we provide the results of Eq.(1) which actually is an Ordinary Least Squares method using a fixed effects strategy. As expected (Arceo et al., 2016; Fu et al., 2018), the fixed effects estimation results are smaller and tend to be upward toward or above zero. Columns (2), (3), (4) and (5) present the results from the two stage regression.

In column (2) we consider CO_2 emissions as the endogenous variable, meaning that it is correlated with the error term. Endogeneity occurs because of simultaneity and selection bias in our case. Thus, we use CO_2 as the endogenous variable and regress it on the instruments and the exogenous variables included in our

[1]We take standard procedures in the literature regarding our dataset. We drop observations with missing values, remove outliers and reduce the number of countries by keeping those that have at least 40 years of non-missing data on CO_2 emissions.

[2]For instance we find that 20 countries have no records (mainly small countries like Samoa, Singapore and Cape Verde but also Pakistan which has very few records)

empirical method. As instruments of the endogenous CO_2 we pick a vector of weather variables, including annual mean temperature and annual mean cumulative precipitation, and the share of RES. We find that temperature has a positive and statistically significant effect on CO_2 emissions concentration, unlike precipitation which has a negative and statistically significant effect, but very small in magnitude -a 1% rise in a country's mean cumulative precipitation decreases CO_2 by 0.0001%. Renewables' estimates on the other hand, imply that they have a strong negative effect on CO_2 emissions' concentration with a 1% increase of their share bringing a drop in CO_2 by 2.27%. On the second stage, where we estimate the regression model including the fitted values of the instrumental variable, we find that the three components of the production function are statistically significant. We also find that CO_2 is a positive and statistically significant estimator of GDP.

The identification tests for the specific model explain that it is well identified. First, we reject the hypothesis that reduced form coefficients are underidentified at 1% level. Second, we test for weak identification of all instruments using the effective F statistic and reject the null hypothesis, concluding that all instruments are strong (Olea et al., 2013; Pflueger and Wang, 2015).

In column (3), we change our approach in instrumental variable and consider temperature as endogenous. According to Kaufmann et al. (2006) not only does CO_2 emissions' concentration increase temperature, but also high temperatures have changed the way that CO_2 emissions flow in the atmosphere, thus increasing atmospheric concentration. The fact that CO_2 and temperature are being used as instrumental variables and instruments can be explained by two facts. First, by their relevance or in other words when each of them is used as an instrument, they constitute a determinant factor for the endogenous. Second, as instruments they are both conditionally uncorrelated with the error term (Cameron and Trivedi, 2005). The instruments used for the endogenous temperature are precipitation and CO_2. Precipitation is a positive and statistically significant estimator of temperature, but with a very small magnitude and CO_2 is positive and statistically significant. At the second stage of the regression, fitted values of the first stage reveal a positive relationship between temperature and GDP. More specifically, a 1^oC increase of temperature increases GDP by 0.16%. We also detect that a country's capital stock, its labor force and total amount of energy used are positive and significant at the 1% level. The effective F statistic of Montiel-Pflueger robust weak identification test rejects the null of weak instruments for a weak instrument threshold of 5% worst case bias. The underidentification test is significant at 1% level, thus rejecting the null hypothesis that the equation is underidentified.

In column (4), the instrumental variable is CO_2 but this time the dependent variable is countries' TFP instead of countries' GDP. At the first stage of the regression, we regress CO_2 on temperature, precipitation and the share of

RES. Temperature is a positive estimator of CO_2, while the share of RES has a strong and negative effect on the endogenous CO_2. The precipitation holds a small negative effect on the endogenous variable. A possible explanation of the small magnitude that precipitation estimators have is proposed by Damania et al. (2019). They give evidence that when precipitation data is given in large spatial scales (country means) the impact gets negligible. It is worth mentioning that in all specifications adopted here, the share of RES was steadily negatively related with the CO_2 emissions concentrations. At the second stage of the regression, the intriguing result is that if CO_2 increases by 1%, the TFP decreases by 0.093%. In contrast with the CO_2-GDP relationship, when using TFP as a dependent variable we get a negative and statistically significant estimator. TFP is a factor that encapsulates capital and labor through the use of standard production function. Thus, TFP allows interpretation of the consequences of climate variability on more productive characteristics of the economy. Effective F statistic is large, thus rejecting the null hypothesis that instruments are weak (Pflueger and Wang, 2015). Last, the equation is well identified since the null hypothesis of underidentification is rejected.

In column (5), temperature is the instrumental variable and TFP is the dependent variable once again. First stage results indicate a negative effect of CO_2 on temperature and a small positive effect of precipitation on temperature. The second stage results do not provide significant evidence as the only significant estimators are energy and temperature, which has a negative effect on TFP. In fact, 1^oC increase of temperature decreases TFP by 0.017%. In this specification the effective F statistic of Montiel-Pflueger rises above the 5% of worst case bias respectively.

In Table 3 we extend our research to the way that temperature and emissions impact GDP by making two additions in our work. First, we include temperature and CO_2 first lags in order to detect the cumulative effects that temperature and CO_2 emissions have on GDP. Second, we use quadratic effects of temperature and emissions to find whether there exists a non-linear relationship among our variables of interest and GDP. These two additions are implemented in our baseline instrumental variable model. Thus, both the lagged variables and the quadratic variables are being used as instruments of the endogenous CO_2 emissions and temperature, as they were introduced in previous analysis.

Column (1) of Table 3, first lag of temperature is positioned as an instrument of endogenous CO_2 emissions, together with temperature, precipitation and the share of RES. During first stage regression, neither temperature nor its lag yield significant results, in contrast with RES variable and precipitation, albeit the precipitation estimator is very small. Second stage results provide a positive and significant estimator of endogenous CO_2 emissions and the rest of the estimators results are similar to results in Column (2) of Table 2. Thus, we do not find strong evidence for temperature persistence on CO_2 emissions. In column (2), we change our approach to the endogenous and treat temperature as such. The first stage regression results are close to being considered as significant at 10% level. Second stage results are similar to the results presented in Column (3) of Table 2.

Columns (3) and (4) examine the impact of quadratic values of temperature and emissions, respectively. Quadratic value of temperature enters the first stage regression with CO_2 emissions being regarded as endogenous. We observe that temperature has a positive and statistically significant impact on CO_2 emissions, while quadratic value of temperature is negative and significant at 5% level. At the second stage of the regression, CO_2 emissions are estimated to have a positive and statistically significant coefficient. The result is aligned with Kalaitzidakis et al. (2018). Second stage results are very similar to the baseline results presented in Table 2. When quadratic value of emissions is considered as an instrumental variable of temperature, the results imply non-linearity with CO_2 emissions having a positive value and quadratic CO_2 emissions being negative and significant. At the second stage, temperature has a strong and significant impact on GDP (in accordance with Dell et al. (2012)). In each case, we conclude that temperature and CO_2 emissions have a non-linear effect on growth through the channel of endogeneity that we have established.

In table 4, we insert a dummy variable depicting whether a country is considered poor or not. We do that in order to reveal the existing heterogeneity among countries and how that affects the relationship that we examine. The threshold used to distinguish rich and poor countries is the first quartile of GDP values of all countries over the whole period. A country is defined as poor if its GDP for a given year is less than sample's GDP first quartile. That way, a country can change rich/poor status within years and does not remain rich or poor according to first year comparisons (as in Dell et al. (2012)). It is crucial because we work with a dataset that covers a 53-year period of time and therefore we assume that changes in rich/poor status of countries are certain. Column (1) endogenous variable is the interaction between CO_2 emissions and poor dummy. We find a stronger link between temperature interacted with a poor dummy and the endogenous, than temperature and CO_2 as presented in Table 1. The most interesting result is that when a poor dummy is interacted with CO_2 then its impact on a country's economy becomes negative and statistically significant, thus indicating substantial heterogeneity between rich and poor countries. Specifically, a 1% increase of CO_2 emissions decreases economic growth by 0.021%. Column (2) uses temperature interacted with poor dummy as endogenous variable and at the first stage we get a strong influence of CO_2 interacted with the endogenous. At the second stage of the regression, once again substantial heterogeneity between rich and poor countries is revealed. This time we find a negative and statistically significant temperature interacted with poor dummy and countries' GDP. In fact, a 1^oC rise in temperature decreases GDP by 0.011%. The results presented in Table 4 and having in mind results of Table (2), we conclude that effects of temperature and emissions are only detected in poor countries. For both specifications examined in Table 4, the effective F statistic critical values is large, thus rejecting the null hypothesis that instruments are weak. This conclusion is similar to previous important findings (Dell et al., 2012; Letta and Tol, 2018). Poor countries are facing the dangers of increasing temperatures more intensively than rich countries, but the dangers do not stop there since we provide evidence that increasing CO_2 emissions also deteriorate the position of an economy.

4.2 Robustness checks

Table 5 shows the robustness checks under different assumptions. We start by providing the results from using alternative RES instead of combustible renewables and waste dataset. The specific robustness check results strengthen our baseline results that RES have a strong negative impact on CO_2 emission concentrations by reducing them by 1.79% when the share of RES increases by 1%. Furthermore, on the second stage analysis, we detect a negative relationship between the endogenous variable which is CO_2 and GDP that plays the role of the dependent variable. Increasing CO_2 by 1% brings a drop in GDP by 0.15%, indicating that increasing CO_2 emissions can be harmful for a country's economy. At the same time capital, labor and energy variables, all of them components of a Cobb-Douglas production function, are positive and statistically significant. Regarding the instrumental variable regression and whether the variables used are adequate, we examine the effective F statistic of Montiel-Pflueger and find that the result of the test is large, thus rejecting the null hypothesis that instruments are weak.

In column (2), we consider CO_2 as the endogenous variable and countries' TFP as the dependent variable. Results here are similar to the results presented at column (4) of Table 2. Once again, we find a negative and statistically significant relationship between alternative RES and CO_2 emissions. Also, we reveal that CO_2 at the second stage, have a negative effect on countries' TFP index. Specifically, a 1% increase of emissions, reduces countries' TFP by 0.12%. The effective F statistic of Montiel-Pflueger test, once again rejects the null hypothesis.

In columns (3) and (4) of Table 3, we change the variable depicting carbon emissions and instead of using CO_2 emissions concentration we examine the CO_2 intensity for all countries during the period 1961-2013. We construct carbon emission intensity by dividing the carbon
dioxide emission quantities to each country's GDP per year. It is an index that can be used to measure the carbon emission performance on country level. Thus, we exploit this property and use it as an alternative way of capturing the impact of CO_2 emissions on economic growth. The results remain quite similar with those presented in columns (1) and (2). More specifically, we detect the negative

relationship that exists among alternative RES share and CO_2 emissions intensity. Furthermore, at the second stage regression the endogenous CO_2 intensity has a negative effect on the dependent variable, whether we use GDP or TFP as it. The identification tests are performing well indicating that the IV regression equation is well identified.

5 Conclusions

Many scholars argue that understanding the relationship between precipitation, temperature and CO_2 emissions on economic growth and productivity is critical to the design of optimal mitigation policies. Economists, on their part, have tried to measure the damage of climate change and quantify the relationship between the above-mentioned variables. However, a major conceptual dilemma arises from the relationship among economic growth, temperature and CO_2 emissions, since many authors argue that increased GHGs in the atmosphere alter average temperature and consequently could reduce economic growth. On the other hand, faster economic activity increases GHGs and consequently global average temperature (Nordhaus, 1992).

This paper explores the importance of CO_2 emissions, RES, temperature and precipitation in estimating the economic growth of climate change in a sample of world countries. We employ a standard Cobb-Douglas production function and add weather variables and CO_2 emissions as factors. We investigate if weather conditions affect gross domestic product and total factor productivity using a production function. Also, we argue that anthropogenic emissions are responsible for the increase of temperature that has been conducted since the industrial revolution (Kaufmann et al., 2006) and that the use of RES should alter the climate change phenomenon. Thus, we employ an instrumental variable approach where CO_2 emissions and temperature affect GDP and TFP through the use of instruments such as weather variables, share of RES and also emissions.

In our study we exploit of a data set composed of 110 countries for the 1961-2013 period. Our findings confirm the positive effect of emissions and temperature on countries' economic growth while disentangling the specific effect when we account for poor vs rich countries. In that specification it is revealed that poor countries are more vulnerable to CO_2 emissions and temperature increases and this distinction is considered to be an important factor of inequality. Therefore, we can assume that temperature and emissions are two so far underestimated, yet important factors of countries' inequality. Actually, if a country is considered poor then a 1% increase of CO_2 emissions decreases economic growth by 0.021% and a 1^oC rise in temperature decreases GDP by 0.011%. The magnitude of the RES estimator in all baseline regressions was exceeding 1.7% while having a negative effect. That is a strong estimator implying that a 1% increase of RES share can have a drop in CO_2 emissions concentration by at least 1.78%. The importance of RES for the combat against climate change is underlined by our results. In fact, for all specifications the share of RES was used as an instrument for endogenous CO_2 provided a negative estimator and an interpretation for this is that RES decrease CO_2 emissions concentration and increase of their share in total amount of energy used could mean less CO_2 and better environmental conditions. Finally, our results also provide evidence for the existence of an inverted U-shaped relationship for temperature and emissions while the factors of production appear to have the expected signs.

A possible future research we would like to conduct is the effect of carbon emissions and weather variables on gross domestic product on a regional level. The regional level cross-examination will detect deeper and more precisely the impact of emissions and rising temperatures on growth. The smaller geographical areas will reveal much more detailed relationships for the variables of interest and will lead us to more secure estimators. A second research question that arouses our curiosity is what will happen if instead of a Cobb-Douglas, we use an alternative production function.

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Appendix

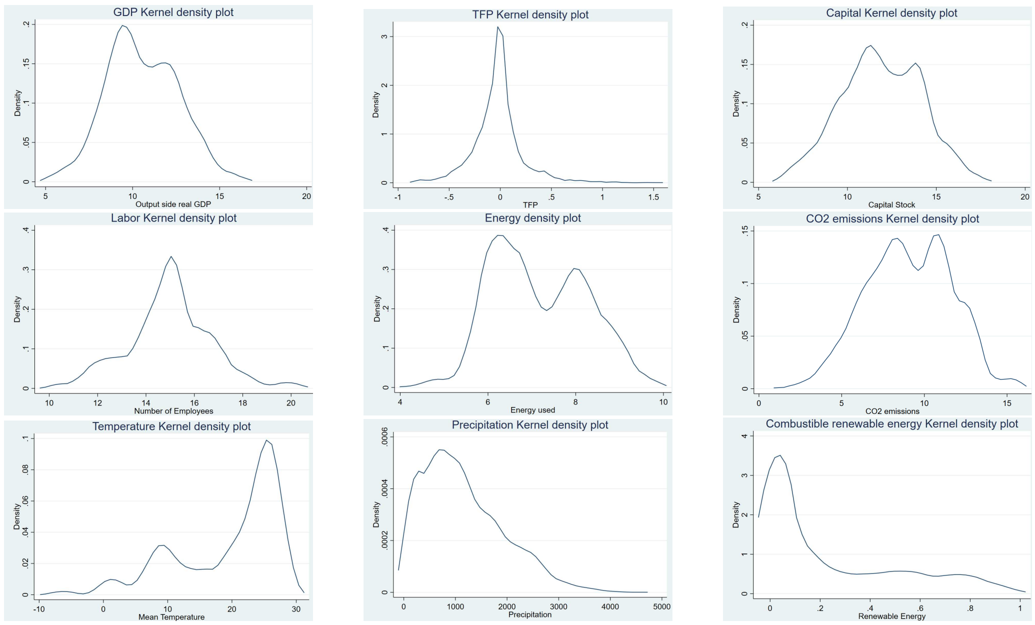

Figure 1: Kernel density plots of regression variables

Table 1: Sample Statistics

Variables	Mean	Standard deviation	Observations	Minimum	Maximum
GDP (in million 2011 US$)	10.581	2.06	5641	5.01	16.54
TFP level at current PPP's	-0.022	0.24	3927	-0.85	1.56
Capital stock	11.921	2.25	5641	6.13	17.73
Labor force	14.991	1.68	5174	10.17	20.46
Energy	7.170	1.04	3993	4.16	9.88
CO_2 emisions	9.076	2.58	5781	1.29	15.76
CO_2 intensity	0.342	0.34	5617	0.5	3.56
Combustible Share of Renewables	0.229	0.27	3967	0	0.97
Clean Alternative Share of Renewables	0.067	0.10	3965	0	0.71
Country Temperature	19.392	7.38	5830	1.05	29.07
Country Precipitation	161.68	6.80	4611	0.10	4162.6

*All variables except for Country Temperature and Country Precipitation are presented here in their logarithmic values. Combustible and Clean Alternative Share of Renewables are shares.

Table 2: OLS and 2SLS estimates

	(1)	(2)	(3)	(4)	(5)
	OLS	2 SLS			
Panel (a)		First stage			
Endogenous Variable:		CO_2	Temp	CO_2	Temp
Temperature		0.016***		0.007***	
		(0.0016)		(0.0014)	
Precipitation		−0.0001***	0.00***	−0.000***	0.001***
		(0.0000)	(0.0001)	(0.0000)	(0.0001)
Renewable		−2.369***		−1.782***	
		(0.0506)		(0.0475)	
CO_2			0.323***		−0.378***
			(0.1150)		(0.1468)
Panel (b)		Second stage			
Dependent Variable:	GDP	GDP	GDP	TFP	TFP
Capital	0.334***	0.488***	0.509***	0.032***	−0.008
	(0.0177)	(0.0170)	(0.0142)	(0.0113)	(0.0078)
Labor	0.126***	0.346***	0.455***	0.055***	0.002
	(0.0207)	(0.0150)	(0.0123)	(0.0118)	(0.0077)
Energy	0.031*	0.202***	0.186***	0.089***	.030***
	(0.0177)	(0.0200)	(0.0222)	(0.0177)	(0.0094)
CO_2 emissions	0.160***	0.148***		−0.093***	
	(0.0144)	(0.0206)		(0.0167)	
Temperature	0.016**		0.162***		−0.017**
	(0.0076)		(0.0142)		(0.0037)
Year fixed effects	Y	Y	Y	Y	Y
Countries fixed effects	Y	N	N	N	N
Regions fixed effects	N	Y	Y	Y	Y
F^{Eff}		962.8	51.4	572.0	91.2
Sample Size	4063	4028	4063	3349	3354

*All models include year fixed effects. Model of column (1) also includes country fixed effects, while the rest include region fixed effects. Column (2) and (4) first stage endogenous variable is CO_2 and column (3) endogenous variable is temperature. Sample period: 1961-2013 for 110 countries. Standard errors are clustered in parentheses. Statistical significance is noted as follows: $***p < 0.01, **p < 0.05, *p < 0.1$

Table 3: 2SLS estimates using lags and non-linearity

	(1)	(2)	(3)	(4)
Panel (a)		First stage		
Endogenous Variable:	CO_2	Temp	CO_2	Temp
Temperature	0.002		0.021***	
	(0.0091)		(0.0028)	
Precipitation	−0.000***	0.001***	−0.1***	0.000
	(0.0000)	(0.0001)	(0.0113)	(0.0000)
Renewable	−2.376***		−2.313***	
	(0.0509)		(0.0512)	
CO_2		0.451		0.669***
		(0.4879)		(0.2544)
Temperature lag	0.013			
	(0.0091)			
CO_2 lag		-0.149		
		(0.4856)		
$Temperature^2$			−0.002***	
			(0.0001)	
$Emissions^2$				−0.038***
				(0.0132)
Panel (b)		Second stage		
Dependent Variable:	GDP	GDP	GDP	GDP
Capital	0.487***	0.510***	0.484***	0.285***
	(0.0206)	(0.0118)	(0.0205)	(0.0396)
Labor	0.345***	0.454***	0.356***	0.584***
	(0.0150)	(0.0122)	(0.0149)	(0.1102)
Energy	0.202***	0.189***	0.212***	0.088***
	(0.0200)	(0.022)	(0.0197)	(0.0349)
CO_2 emissions	0.150***		0.145***	
	(0.0206)		(0.0205)	
Temperature		0.161***		−0.397***
		(0.0142)		(0.1266)
Year fixed effects	Y	Y	Y	Y
Countries fixed effects	N	Y	N	Y
Regions fixed effects	Y	N	Y	N
Sample Size	4005	4039	4028	3822
F^{eff}	761.2	33.2	717.0	3.8

*All models include year fixed effects. Sample period: 1961-2013 for 110 countries. Standard errors are clustered in parentheses. Statistical significance is noted as follows: $***p < 0.01, **p < 0.05, *p < 0.1$

Table 4: 2SLS estimates interacting a dummy for country being poor with temperature and CO_2 emissions respectively

	(1)	(2)
Panel (a)	First stage	
Endogenous Variable:	CO_2×poor	Temp×poor
Temp×poor	0.299***	
	(0.0043)	
Precipitation	−0.0003***	0.0006***
	(0.0001)	(0.0000)
Renewable	−0.872***	
	(0.0940)	
CO_2×poor		2.272***
		(0.0698)
Panel (b)	Second stage	
Dependent Variable:	GDP	TFP
Capital	0.559***	0.539***
	(0.0125)	(0.0132)
Labor	0.422***	0.423***
	(0.0126)	(0.0131)
Energy	0.336***	0.301***
	(0.0137)	(0.0143)
CO_2× poor	−0.021***	
	(0.0043)	
Temp× poor		−0.011***
		(0.0018)
Year fixed effects	Y	Y
Regions fixed effects	Y	Y
F^{Eff}	2025	849.7
Sample Size	4028	4063

*All models include year fixed effects and regions fixed effects. Column (1) first stage endogenous variable is CO_2 interacted with a dummy variable for poor countries, while in Column (2) the first stage endogenous variable is temperature interacted with the dummy variable for poor countries. Sample period: 1961-2013 for 110 countries. Standard errors are clustered in parentheses. Statistical significance is noted as follows: $***p < 0.01, **p < 0.05, *p < 0.1$

Table 5: 2SLS estimates using alternative renewable energy sources and CO_2 emissions intensity

	(1)	(2)	(3)	(4)
Panel (a)	First stage			
Dependent Variable:	CO_2		CO_2 intensity	
Temperature	-0.008^{***}	-0.021^{***}	-0.011^{***}	-0.009^{***}
	(0.0022)	(0.0016)	(0.0013)	(0.0012)
Precipitation	-0.001	0.000^{***}	-0.000^{***}	-0.000^{***}
	(0.0001)	(0.0000)	(0.0000)	(0.0000)
Alternative Renewable	-1.796^{***}	-1.935^{***}	-1.08^{***}	-1.057^{***}
	(0.0645)	(0.0604)	(0.0440)	(0.0459)
Panel (b)	Second stage			
Dependent Variable:	GDP	TFP	GDP	TFP
Capital	0.635^{***}	0.045^{***}	0.513^{***}	-0.028^{***}
	(0.0225)	(0.0104)	(0.0115)	(0.0076)
Labor	0.509^{***}	0.076^{***}	0.476^{***}	0.016^{**}
	(0.0211)	(0.0120)	(0.0119)	(0.0079)
Energy	0.420^{***}	0.118^{***}	0.415^{***}	0.065^{***}
	(0.0262)	(0.0154)	(0.0146)	(0.0120)
CO_2 emissions	-0.152^{***}	-0.126^{***}		
	(0.0310)	(0.0153)		
CO_2 intensity			-0.468^{***}	-0.171^{***}
			(0.0436)	(0.0267)
Year fixed effects	Y	Y	Y	Y
Regions fixed effects	Y	Y	Y	Y
F^{Eff}	179.7	336.1	164.4	209.9
Sample Size	4024	3345	4025	3346

*All models include year fixed effects and regions fixed effects. Column (1) and (2) first stage endogenous variable is CO_2, while in Column (3) and (4) first stage endogenous variable is CO_2 intensity. Sample period: 1961-2013 for 110 countries. Standard errors are clustered in parentheses. Statistical significance is noted as follows: $***p < 0.01, **p < 0.05, *p < 0.1$

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