SPECIAL ISSUE: SUSTAINABLE ECONOMICS AND GREEN FINANCE

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Editorial to the Special Issue: Sustainable Economics and Green Finance

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Are environmental issues relevant at the time of an economic crisis? The current COVID-19 pandemic situation coupled with lockdowns and economic recessions across the world prompt us to reflect upon it. The COP26 UN Climate Change Conference will take place in Glasgow in November 2021 and provide an opportunity for countries, including the United States once again, to engage in discussion on how to best protect the global environmental goods. Around the world governments argue in favour of a green economic recovery that will allow countries to rebound from recession and reset the entire economic systems from fundamental principles. Green finance and climate finance will offer mechanisms and instruments to pursue these objectives. The EU recognises the role of green finance to spearhead sustainable economic growth and actively promotes the incorporation of green finance considerations into its financial policy framework. The UN, World Bank and IMF are all committed to mobilise Climate Finance to finance projects to mitigate Climate Change and its impact on society; notable examples are the World Bank Green Bonds worth over USD 13 billion since 2008. The responses by the private sector (responsible investors) and the public sector (e.g. national green bonds) have also been very promising. Since 1995, the net total assets of US funds incorporating Environmental, Social and Governance Factors has increased more than 400%. Green bonds have reached a record value of USD 257.7bn in 2019 (an increase of 51% from 2018), with the major issuer being the USA, followed by China and several European countries. New clean technologies will also play a crucial role in realising the promises of the sustainability revolution. Opportunities can be raised by hydrogen-fuelled vehicles and carbon storage technologies among others. Government support is paramount in ensuring those technologies become economically feasible. The positive social welfare impact from decarbonisation is beyond doubt, especially when future generations are taken into account. Universities are signing up to the UN Accord on Sustainable Developments Goals to provide education to students and staff on issues of Sustainable Development and its societal values. Trade and students unions are developing their sustainability agenda and business and NGOs their corporate social responsibility strategy. Perhaps as never before, the issue of Sustainability is at the core of all decisions of all stakeholders on the world stage. There are all the premises for the current economic crises to be turned into a once in a generation opportunity to protect our planet. Research has a crucial role in helping to shape our future.

This special issue includes four papers related to the economic effects of climate change and channels through which it can be mitigated (renewable energy, green finance, and carbon trading).

The first paper, "The Macroeconomic Implications of Climate Change on Sub-Saharan Africa: A Case for Sustainable Development" by Aydin Sandalli, addresses the question if climate change has a negative effect on economic growth, and if it affects poorer and hotter regions disproportionately, using a panel for 37 OECD countries and 47 Sub-Saharan African countries between 1970 and 2018. First, it finds that temperature variations have a negative effect on per capita GDP growth. Second, temperature variations disproportionately lower income growth in low-income countries and countries with hotter climate. Third, poorer countries recover more quickly from temperature shocks. This suggests that climate change has a negative economic effect, challenging the view that there is a trade-off between climate change and economic growth.

The second article "Renewable Energy Consumption and its Main Drivers in Latin American and Caribbean Countries: A Robust Analysis between Static and Dynamic Panel Data Models" by Sindy Menéndez-Carbo investigates renewable energy consumption (REC), in 22 Latin American and Caribbean countries, using a panel from 2005 to 2014. It finds that REC is positively related to GDP, and its level in the previous period. First, there is evidence of inertia in REC. If a country has invested in REC, its use is likely to remain at a higher level. Second, REC has the property of a 'luxury good' in that a higher income level makes REC more affordable (society is more prepared to give up consumption to achieve a higher level of the environmental good). These effects are also independent of whether the country has signed up to Kyoto, and can be thought of as a voluntary measure. The article also suggests a future promising research agenda, the role of the Paris 2018 agreement.

The third paper «Practical Vitality of Green Bonds and Economic Benefits» by Ankita Kant, examines the pricing of green bonds, the effect on the share price of the issuer, and the effect on carbon emissions (the latter at country level). First it finds, in a sample of 200 green bonds and 554 conventional, that the coupon is lower for green bonds, implying it is cheaper from the point of view of the issuer. This suggests a company can lower its cost of capital by undertaking 'green projects'. It provides evidence of the idea that socially responsible investors are prepared to accept a lower return when holding 'green' assets. Second it finds, by computing the cumulative abnormal returns (event study) that the stock prices increase in response to the green bond issue, again confirming the idea that investors demand a lower future premium on stocks where firms conduct 'green projects'. Finally, the paper points to the need of further research on whether the prevalence of green bonds in an economy will actually reduce overall carbon emissions.

The final article «The EU ETS and Aviation: Evaluating the Effectiveness of the EU Emission Trading System in Reducing Emissions from Air Travel» by Anne Marit Heiaas investigates the effects of carbon trading. The paper uses a synthetic control model to compare jet fuel consumption under the EU emission trading system (EU ETS) during 2012–2018 to a counter factual without carbon trading. The paper shows that the EU ETS increased jet fuel consumption by 10% relative to the scenario without it. The finding highlights an important insight: since a trading system may increase production efficiency, it is likely the overall production and emissions increases. This is something to bear in mind when designing environmental policies in general.

We hope that this special issue will inspire researchers to pursue further investigation into these crucial questions.

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The Macroeconomic Implications of Climate Change on Sub-Saharan Africa: A Case for Sustainable Development

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"The biggest risk to African growth is climate change."
~ Paul Polman

Abstract

While climate change has harsh universal impacts, it is believed that its negative effects fall disproportionately on hotter, developing regions. This paper examines these claims using a panel datasets for 84 OECD and Sub-Saharan African countries between 1970–2018. I document both the evolution of country-specific temperatures and the long-term economic impact of temperature and precipitation variations on GDP per-capita. Using a panel auto-regressive distributed lag model on the sample mentioned above, I found that temperatures have unanimously increased for all sample-countries and that variations in temperature above historical norms significantly reduced income-growth. No significant relationship was found between precipitation and income growth. When interacting 'poor' and 'hot' country variables, I found that temperature variations disproportionately affected both hotter and poorer Sub-Saharan African countries. In OECD countries, temperatures have increased more quickly relative to their historical norms than Sub-Saharan African countries. Finally, while poorer and developing countries are more adversely affected by temperature variations, they seem to recover more quickly from temperature shocks than sample averages. I explain these results and link them to potential policy implications regarding global sustainable development and greenhouse gas abatement.

Keywords: Sub-Saharan Africa; OECD; climate change; GDP; greenhouse gas abatement; temperature variations

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List of Abbreviations

SSA Sub-Saharan Africa
OECD Organisation for Economic Co-operation and Development
GDP Gross Domestic Product
ARDL Auto-regressive distributed lag
AIC Akaike information criterion
FE Fixed effects

Introduction

Climate change is arguably one of the most complex and daunting global challenges of our time (IPCC, 2007). Science is now unequivocal to the existence of climate change, yet, ascertaining its economic consequences prove far more difficult (Tenkate et al., 2009). The most notable feature of climate change has been unprecedented increases in global average temperatures. Evidence suggests that the global average temperature has increased roughly 1 °C in the last 140-years, with a substantial acceleration in the rate-of-temperature-increase in the last 30-years following a spike in anthropogenic greenhouse gas (GHG) emissions (IPCC, 2014; Kompas, Pham & Che, 2018). Worryingly, without any mitigation policies, forecasts threaten a further 3–5 °C increase in global temperatures by 2100, with potentially drastic consequences on human enterprise (Hertel, Burke & Lobell, 2010; Avecedo et al., 2018).

However, rising temperatures are only part of the problem. Recent years have witnessed surges in extreme weather events, including droughts, floods, heatwaves, and cold snaps. Climate variability can cause severe long-term macroeconomic impacts through changes in precipitation patterns, rising sea-levels, and extreme-weather volatility (World Bank, 2016; United Nations, 2018). Consequently, these climate variations may adversely affect the global economy by reducing agricultural output, slowing investment, and damaging human health with the increased spread of disease and tougher working environments (Stern, 2007; Kahn et al., 2019).

While these distributional changes in weather patterns have harsh universal impacts, it is postulated that the burden of climate change falls disproportionately on hotter, low-income countries (Tol, 2009; Dell, Jones & Olken, 2012; Burke, Hsian & Miguel, 2015a). A particular focus of the literature has been on Sub-Saharan Africa (SSA) due to its unforgiving geographic exposure, dependence on climate-sensitive agricultural sectors and low-income, all weakening its capacity to technologically adapt to climate change (Abidoye & Odusola, 2015). Contemporary literature suggests hotter countries tend to be poorer — reducing their ability to adapt to weather shocks with national income falling 8.5 per cent per-degree Celsius (Dell, Jones, and Olken 2009). Moreover, the economic landscape of SSA makes it particularly vulnerable as economic performance in agriculture, forestry, tourism, energy, and coastal services are all dependent on climate dynamics, exacerbating any impact climate variability has on economic growth (Fankhauser, 1995; Boko et al., 2007). Furthermore, the geographical location of SSA falls on lower latitudes, where nearly 80 per cent of all climate-related damages are concentrated (Mendelsohn, 2008).

The broad consensus among scientists is that climate change is affected by the concentration of GHG's in the atmosphere, with recent anthropogenic contributions widely recognised as the driving factor accelerating climate change (Eboli et al., 2010; IPCC, 2014; Brown et al., 2016). Yet, while SSA contributes some of the smallest proportions of global GHG emissions at less than 5 per cent of the total carbon output, it bears disproportionate adverse effects of climate change (Rehdanz & Maddison, 2003; Mendelsohn et al., 2006; UNDP, 2006; Tol 2009).

What makes matters worse is the continued need for economic growth and development in SSA, given its relatively low GDP per-capita compared to global averages (World Bank, 2020). However, increased energy consumption, accompanied by large-scale rural-urban migration, population increases, agricultural intensification and urbanisation necessary for SSA's economic development, has been adduced as the largest contributor towards GHG-emissions (Martinez-Zarzoso & Maruotti, 2011). With knowledge of the already substantial temperature rises between 1–3 °C in SSA over the past 50-years and the forecasts that further increases in GHG-concentrations will likely increase weather-extremes (Diffenbaugh Ahmed and Hertel, 2009), there is a need to not only understand what the previous impacts of climate change have been on SSA relative to other, developed countries, but also what policies can be put in place by both developed and developing countries to foster global co-operation towards sustainable economic development. By understanding climate variable dynamics, their country-specific heterogeneous impacts on economic growth, and whether these climate variations have regional asymmetry in effects, policymakers can better introduce schemes to abate GHG-emissions.

However, there is a dearth of econometric literature analysing the aggregate and country-specific effects of climate change on SSA. The literature predominantly documents the continental or aggregate effects of climate change on countries' clusters (Burke, Hsiang, & Miguel, 2015a; Avecedo et al., 2018). By doing this, they fail to capture heterogeneous effects of climate variations both within and between countries. Moreover, previous studies tend to focus on the short-term effects of climate change rather than its long-term impacts on growth (Stern, 2007; Cashin et al., 2017). Consequently, they fail to analyse whether climate change has persistent lagged-effects on economic growth, and if so, how long these lagged-effects last. Additionally, much of the literature focuses on cross-sectional approaches (Sachs & Warner, 1997; Nordhaus, 2006); thus, neglecting the potential relationship between countries economic growth and climate change over time. It is particularly problematic as it is subject to endogeneity given the possible feedback-effects and interactions between climate variables and GDP-growth.

Furthermore, methodological issues regarding econometric specifications are pervasive in the literature exploring climate change and economic growth. Most studies adopt the temperature level as a variable, rather than utilising deviation from temperature relative to historical norms (Dell, Jones, & Olken, 2012; Burke, Hsiang, & Miguel, 2015a). As the temperature-level is a trended variable, inclusion as a regressor produces quadratic trends between temperature and log GDP per-capita growth — which can bias estimates (Kahn et al., 2019). While some recent papers tackle some of the issues mentioned above, they either fail to compare SSA to the other countries, important when claiming SSA is worse off than more developed economies (Abidoye & Odusola, 2015), specify arbitrary lag-lengths that fail to recognise the extent of climate variations impact on economic growth and how it fluctuates over multiple lagged-years (Kahn et al., 2019), or use outdated datasets that fail to encapsulate the effects of sharper climate variations seen in the last decade.

Henceforth, this paper looks to fill some of the gaps in the literature. Using a panel auto-regressive distributional lag (ARDL) model, I first measure country-specific annual temperature changes for a set of 84 OECD and SSA countries between 1970–2018. Implementing a panel ARDL model allows for significant heterogeneity between-countries concerning temperature changes over time, permitting better comparisons of country-specific climate variations. Next, I analyse the long-term economic impacts of climate change on log per-capita growth using a panel ARDL model for the 84-country sample over an updated time-horizon between 1970–2018. Lag-lengths are specified using an Akaike information criterion (AIC) to better model the long-run lagged-effects climate change may have on growth over multiple years.

Moreover, using a panel ARDL allows for long-run dynamics and bi-directional feedback effects, better modelling the interactions between climate variables and per-capita growth over-time. This specification also overcomes problems with endogeneity and allows for heterogeneous effects of climate change on per-country economic growth, seldom documented in the literature. The current paper also adopts the use of temperature variations relative to historical norms instead of absolute temperature values, allowing for non-linearity that combats the econometric drawbacks of using trended variables. Ultimately, I conclude by linking results to policy implications for sustainable development.

Literature Review

Given the spur in popularity concerning the climate change debate in recent years, there is a burgeoning attempt to quantify climate change's effects on economic growth. Novel approaches either attempt to document the previous impact climate change has had over the last century (Dell, Jones, & Olken, 2012; Avecedo et al., 2018; Kahn et al., 2019) or forecast future implications of climate change subject to different abatement strategies (Nordhaus & Yang, 1996; Weitzman, 2012; Nordhaus, 2013; Dietz & Stern, 2014; Wade & Jennings, 2016). While both avenues offer useful insights into climate-policy, a greater focus will be given to reviewing the literature regarding the previous effects climate change has had on economic growth rates. Therefore, I can better determine how climate change engenders detriment to growth through its macroeconomic and microeconomic implications and if climate change has asymmetric effects on different regions.

Previous studies focus on how climate change impacts growth through two-dimensions. Firstly, macroeconomic studies subject the adversities of climate change through its influence on agricultural output, crop yields, commodity prices, investment, and institutions (Pindyck, 2011; Dell, Jones, & Olken, 2012; Ignjacevic et al., 2020). Secondly, microeconomic analysis attributes falling growth-rates to an array of factors including physical and cognitive labour productivity, disease, conflict, and political instability (Brückner & Ciccone, 2011; Dell, Jones, & Olken, 2014; Hsiang & Neidell, 2015; Somanathan et al., 2017). I aim to give a brief overview of the literature suggesting climate change has negatively impacted growth, particularly in developing countries. Moreover, I offer possible macroeconomic and microeconomic explanations for these findings based on the literature.

Adverse Temperature Impacts on Developing Countries

While papers are unambiguous to the negative effects of climate change on global economic growth, a nascent trend of articles have evidenced the asymmetric impact climate change has on developing countries. From a panel of 180-economies utilising Jordà's (2005) shock projection impulse-response function, Avecedo et al. (2018) found that annual temperature variations have uneven short-term and long-term macroeconomic effects on low-income countries and countries concentrated in hotter regions. In particular, for the median developing country with an average temperature of 22 °C, each additional 1 °C above this average decreases growth by 0.9 per cent annually, however, for even hotter developing countries with an average temperature of 25 °C, a further 1 °C increase lowers growth by 1.2 per cent annually. Furthermore, the cumulative impacts were noted 7-years after the initial weather shock, with per-capita outputs remaining 1 per cent lower for emerging-economies, and 1.5 per cent lower for low-income economies. These results suggest that developing countries are more adversely affected by temperature variations and that they struggle to recover from long-term adverse temperature shocks.

Seminal contributions have also offered similar results. In a global panel spanning 136-countries between 1950–2003, Dell, Jones and Olken (2012) found that higher temperatures have significant, negative impacts on economic growth, but only in developing countries. The authors find that a 1 °C increase in temperature reduced economic growth for the same year by 1.3 per cent. Moreover, they found that the temperature shock had significant lagged effects that were not reversed after the initial shock subdued. Dell et al. (2012) claim that temperature increases have substantial long-run effects on both the output and growth potential of low-income countries but find no robust evidence for developed economies. Similarly, Bansal and Ochoa (2011) examined the relationship between global temperature changes (contrasting to country-specific changes) and economic growth. They find that a 1 ºC global average temperature increase reduces growth by roughly 0.9 per cent annually, with the most substantial growth reductions in poorer countries located closer to the equator.

These results are corroborated mainly by Burke, Hsiang, and Miguel (2015a). Using a panel dataset of 166-countries between 1960–2010, Burke et al. (2015a) compare the country's economic production with itself over different time-periods, contrasting between when the countries average temperature is hotter and alternatively when cooler. The authors find that economic production peaks at an average annual temperature of 13 °C, with output, strongly declining at higher temperatures, offering these findings an explanation for labour productivity and economic-output differentials between developed and developing countries be hotter.

However, Dell et al. (2012), Burke et al. (2015a), and Bansal and Ochoa's (2011) studies all suffer methodological issues regarding their econometric specification of climate variables. Using trended climate variables such as temperature level instead of temperature variations relative to historical averages, results including temperature-levels as a regressor produce quadratic (or linear for non-logged per-capita growth) trends in log per-capita growth that may bias their estimates. Moreover, Bansal and Ochoa's (2011) study fails to capture climate change's heterogeneous effect. They regress global average temperature shocks instead of country-specific climate shocks and their influence on their economic growth. By neglecting heterogeneity, they assume that all countries, never mind regions within countries, have the same climate variations and react homogeneously, which may not be the case.

As mentioned above, the literature focuses on larger panels studying climate effects globally. They often fail to capture the diverse impact climate change has on other specific countries or regions, particularly SSA. Therefore, it is important to review literature focused on developing countries and regions to identify any regional disparities between countries. Using annual data for 34-countries in SSA between 1961–2009, Abidoye and Odusola (2015) sought to identify climate change's impact, particularly climate variation, on economic growth. They found a significant, negative impact of climate change on economic growth-rates, deducing that a 1 °C increase in temperature above its average reduces GDP growth in SSA by 0.67 per cent annually. They also conduct sensitivity analysis on the individual impact of climate change per-country, finding that the two larger and more developed economies of Nigeria and South Africa greatly ameliorate the even more severe impacts on poorer African nations. Analogous results are found in country-specific estimates with Ali (2012) who used co-integration analysis on Ethiopia to see that economic growth is significantly reduced following changes in climate variables' magnitude and variability.

Moreover, similar results to those found in SSA were also substantiated in other developing regions. Using a panel of 67 countries comparing developed and developing countries, Rehdanz and Maddison (2005) found that a 1 per cent increase in temperature leads to a 0.4 per cent decrease in global GDP, but with a much more detrimental 23.5 per cent GDP reduction in developing countries. Similarly, when comparing highly vulnerable regions across SSA and South-East Asia, higher temperatures were associated with an increased prevalence in extreme weather patterns such as droughts and flooding, significantly damaging the emerging economies (Mendelsohn et al., 2006). Ahmed, Diffenbaugh, and Hertel (2009) concur with these findings, demonstrating implementation of a novel economic-climate analysis framework on 16-developing countries that climate volatility and temperature changes drastically increased poverty rates, particularly on urban-wage earners in SSA.

Contrarily, not all contemporary literature has found asymmetric impacts on developing countries' climate change effects. Using a panel ARDL model on a set of 174-countries between 1960–2014, Kahn et al. (2019) found that long-run per-capita growth was negatively influenced across all countries following temperature variations from their historical norms, with a 0.01 °C annual temperature deviation above or below historical norms lowering income growth by 0.0543 per cent. Controversially, no significant evidence was found for disproportional, negative impacts of climate variations on hotter or lower-income countries.

There is a large disparity between the absolute growth-reduction estimates between studies ranging from 0.4–23.5 per cent per 1 °C temperature increase. Still, there are some discrepancies between the existence of unequal impacts of climate change amongst developed and developing countries. Additionally, the literature often fails to appropriately capture the lagged impact of climate change on economic growth. Studies either neglect the use of lagged-effects entirely (Abidoye & Odusola, 2015) or use capricious lag-lengths that fail to encapsulate the persistent or variable changes in a countries' response over multiple lagged-years following a climate shock (Kahn et al., 2019).

Precipitation

So far, I have focused predominantly on the literature classifying the effects of temperature variability on economic growth. Yet, much of the literature is focused on factors exacerbated by variations in annual precipitation-rates. Considering the differential effects of temperature and precipitation deviations from historical norms between SSA and non-African countries, Barrios, Bertinelli, and Strobl (2010) focused on increased rainfall's income effects between 1960–1990. They found that increased rainfall is associated with faster income-growth in SSA, but not elsewhere. In fact, they suggest that declining rainfall conditions in SSA can explain 15–40 per cent of the per-capita income disparities between SSA and the rest of the developing world.

Similar results are demonstrated by Miguel, Satyanath, and Sergenti's (2004) analysis of 41 African-countries between 1981–1999. They found that both current and lagged precipitation growth-rates positively predict annual per-capita growth. Moreover, their follow-up study found that the same sample showed similarly positive income effects from current and lagged precipitation increases (as opposed to growth) (Miguel & Satyanath, 2011). Reinforcing this relationship, Bruckner, and Ciccone (2011) found that negative rainfall shocks significantly lowered income-levels in SSA. Studies focused on individual African countries show similar effects, with Ali's (2012) Ethiopian cointegration analysis finding large, adverse effects of changes in rainfall magnitude and variability on income-growth and long-run agricultural output levels.

However, while several studies document the significance of precipitation variations on income growth, an equal number fails to find any significant relationship between the two. Even Miguel and Satyanath's (2011) study found that the association between precipitation variation and income-growth became weak after the year-2000. Moreover, while Dell et al.'s (2012) study mentioned above found that general precipitation has positive influences on agricultural output in developing countries, variations in precipitation-rates have little effect on national growth in both developed and developing countries. These results were also concluded in their earlier study finding that average precipitation levels have no impact on growth between or within sample-countries (Dell, Jones, & Olken, 2009).

Contemporaneous studies also contend with the earlier literature, with both Avecedo et al. (2018) and Kahn et al.'s (2019) large panel datasets obtaining no statistical evidence that persistent precipitation changes above or below historical norms between 1960–2014 have any significant impact on per-capita growth rates. The authors argue that no robust relationship has been found due to potential measurement errors when collating precipitation variables. Auffhammer et al. (2011) suggest that temporal aggregation of precipitation variables bias results, therefore collecting data during a crop's growing season offers a better understanding of the effects of precipitation on economic growth.

Avenues of Impact

So far, I have reviewed literature specific to the impact of climate change variables on income-growth, particularly in SSA and other developing countries. However, I believe it is essential to review the microeconomic and macroeconomic avenues through which climate change may detriment developing economies. However, given the multitude of potential avenues in which climate variables can impact economic growth, the following review will be brief and not exhaustive.

With a clear relationship between agricultural yields and the environment, it is obvious why much of the literature has focused on the effects of climate variations on agricultural productivity. As the climate becomes more extreme, droughts become more frequent and thus, crop-yields fall (Wade & Jennings, 2016). Declining crop-yields increase global food-prices; however, these effects are exacerbated for low-income countries with a higher proportion of income devoted to food-items (Hallegatte et al., 2016; Hallegatte & Rozenberg, 2017). Thus, climate variations are theorised to particularly impact developing countries such as SSA that bare hotter temperatures and depend more on agricultural output (Toi & Yohe, 2007b).

Schlenker and Lobell (2010) used a panel of developing countries to estimate the impact of weather fluctuations on a model of yield-responses. They found that higher temperatures and increased temperature variations largely reduce crop-yields, particularly in SSA. Similar results are found across the developing world, with Guiteras (2009) finding that temperature increases reduce India's agricultural output. Welch et al. (2010) interestingly deduce that increases in minimum temperatures reduce agricultural output, whereas higher maximum temperatures seem to increase agricultural output. While similar results were found in other South-Asian countries (Levine & Yang, 2006), rising temperatures are often more drastic on SSA-yields than other developing countries. Barrios et al. (2008) found that rising temperatures were more severe in SSA, suggesting that had climate variations remained similar across the entire developing world, SSA would only be 32% of their current income-gap deficit with other developing economies.

However, much of the agricultural output climate change nexus is focused on temperature influences on crop yields, rather than precipitation. While studies do exist and suggest that negative rainfall variations and precipitation shocks adversely impact crop-yields, the literature is sparse and usually focused on single-country estimates in South-Asia (Jayachandran, 2006; Yang & Choi, 2007). There is a disconnect between theory and quantitative empirics. While most literature is consistent, linking temperature effects, agricultural yields, and their impact on income growth — it is difficult to say the same for precipitation studies. There is no robust evidence that precipitation effects income-growth, and limited proof that precipitation impacts agricultural output.

Finally, other microeconomic avenues in which climate change may affect developing countries disproportionately include through the spread of disease and health-linkages (Tanser et al., 2003; Deschênes & Greenstone, 2011), conflict and political instability (Burke et al., 2009; Fjelde & von Uexkull, 2012; Harari & La Ferrara, 2013) and labour productivity (Lundgreen et al., 2012). For example, Burke et al. (2015a) found that economic-productivity peaks at an annual temperature of 13 °C, with strong productivity declines at higher temperatures. Moreover, evidence from surveys based on laboratory experiments suggests that heat exposure beyond a certain point significantly reduces performance on cognitive and physical tasks. Seppänen, Fisk, and Faulkner (2003) report that productivity reduces by 2 per cent for every 1 °C temperature increase above 25 °C. In a later paper, they accentuate these claims suggesting that temperatures between 23 ºC and 30 ºC reduce productivity by 9 per cent. Most importantly, Graff, Zivin, and Neidell (2014) extrapolate these claims to hot, developing countries. When classifying sectors as 'heat-exposed' or not, the authors find productivity in 'heat-exposed' industries significantly reduced compared to non-heat-exposed sectors.

Ultimately, there is clearly macroeconomic and microeconomic avenues in which climate change may hinder income growth, particularly for SSA and other developing countries. However, while there is some consistency in results for the effect temperature variation has on economic growth, results are not-robust as clear methodological issues need addressing for much of the literature. For the role of precipitation changes on growth, results are inconclusive and lack clarity in their channels of impact. Finally, given the steep-rise in global GHG emissions in the past decade, the literature needs to be updated to predict better the impact of more recent climate variations on economic growth.

Data

Dataset and variables

The previous predictions that climate change impacts economic growth adversely in SSA are tested using an unbalanced cross-country panel dataset of GDP per-capita and the deviations of temperature and precipitation from their historical norms between 1970 and 2018. Data was gathered for 84-countries in total, including all 37-OECD and 47-SSA countries. Réunion and Western Sahara were omitted from the panel due to data scarcity. I chose SSA as it theorised to have particularly adverse responses to climate change, while also being a region that is agriculturally oriented in output and particularly poor relative to global averages (Hallegatte & Rozenberg, 2017). OECD countries are used as a comparison as they are predominantly focused on more temperate climates with more developed economies, with theorists suggesting that climate change may have a less substantial, or even positive impact on their economic growth (Mendelsohn, Schlesinger, & Williams, 2000; Dell, Jones, & Olken, 2012).

Temperature anomalies for each country were obtained through the Global Historical Climatology Network-Monthly (GHCN-M) and the International Comprehensive Ocean-Atmosphere Data Set provided by the National Oceanic and Atmospheric Administration. The time series, produced by Smith et al. (2008), contains updated monthly average temperature anomalies on a 0.5-degree by 0.5-degree resolution grid with a blended average across land and ocean surfaces. The current study utilises yearly averaged data from January to December between 1970–2018 as other panel variables are less complete across greater temporal scales that may further unbalance the panel. Moreover, this period allows us to clearly interpret climate changes over the last half-century, alongside GHG-emissions' noticeable rise throughout the last 50-years. The panel is rich in its time dimension (T) with $T = 48$ for all cross-sectional (N) observations of $N = 84$ countries.

Temperature anomalies classified in this sample as temperature deviations (degrees Celsius) from historical norms using 1981–2010 as historical averages are used as a reference instead of trended temperature variables. Temperature anomalies better encapsulate both positive and negative influences of deviations above and below historical norms, allowing for nonlinearity in climate variables' impact on labour productivity and growth. It overcomes problems with much of the literature that only analyses trended temperature values, inducing linear trends in per-capita output which may bias growth-equation estimates (Dell, Jones, & Olken, 2012; Burke, Hsiang, & Miguel, 2015a). Thus, the current study analyses temperature changes over time and its relative temperature variability, isolating the effect of temperature fluctuations from time-invariant country-characteristics (Dell, Jones, & Olken, 2014).

A drawback of the dataset is that it does not include climate anomaly data averaged across the country. Simultaneously, it allows for greater spatial accuracy through its 0.5-degree by 0.5-degree resolution grid. Thus, our analysis will only include temperature anomalies using data from coordinates averaged across the country's capital city. It was chosen as it is assumed that a larger GDP-output percentage, with greater GDP per capita, is expected in capital cities relative to other, more rural cities. However, it is important to note that this may underestimate the influence of temperature deviations on more rural, agriculturally focused regions that may not only have different temperature variations than the capital, especially in larger countries but will also underestimate climate changes influence on economies that are more agriculturally focused, like SSA.

Precipitation data is gathered from the Global Historical Climatology Network dataset (GHCN 2), that uses monthly-total rain-gauge-measured precipitation (P, mm) from station data on a 0.5-degree by 0.5-degree resolution grid between 1900–2017 (Matsuura & Willmott, 2018). The current study adopts similar temporal dimensions for precipitation to that of the temperature anomaly with annual data averages between 1970–2017 for the 84 countries. The data is converted into precipitation anomalies, measured by the deviations in yearly precipitation using 1981–2010 as the historical average. However, precipitation data was available as a country-wide average instead of focusing on capital-specific climate variations, allowing us to better assess the precipitation anomalies impact on the entire country. However, encompassing a broader impact of precipitation deviations on country-wide averages neglects regional heterogeneity that may influence regions differently within each country.

All other variables necessary to measure the impact of climate variations on economic growth are obtained through The World Development Indicators (World Bank, 2020). Data for hereafter mentioned variables are obtained for each country between 1970–2018, configuring a rich, unbalanced panel with a maximum of $T = 48$ and an average of $T = 42$ for the $N=84$ countries.

Economic growth is measured through the log real GDP per capita (U.S. 2010 $PPP). We chose GDP per capita instead of the more predominant literature approach implementing GDP-level or growth (Sachs & Warner 1997; Gallup et al., 1999; Nordhaus 2006), firstly, as we can take advantage of the panel data that can better observe variations over time — providing better econometric estimations than cross-sectional approaches (Hsiao et al., 1995), and also as it safeguards against any confounding population effects over-time, as using GDP-level may underestimate per-capita temperature effects if population increases.

For subsequent robustness tests, we also implement controls to ensure that the model is not influenced by omitted variables that may impact per-capita growth. Population growth is added to account for changes in population influencing per-capita GDP. Human capital investment is proxied by life expectancy, infant mortality, and primary school enrolment rates (Mankiw et al., 1992; Abidoye & Odusola, 2015). Furthermore, technological progress and spillover effects are controlled by foreign direct investments (FDI) and secondary school enrolment (Borensztein et al., 1998; Hübler, 2017).

Descriptive Statistics

Table 1 displays summary statistics for all covariates involved in exploring the impact of climate variations on economic growth in the 84-country sample. At first glance, we can deduce that most of the variables are probably customarily distributed, given that the means are similar to the median observations for most variables. However, Table 1 offers early evidence that some of the control variables, namely primary and secondary school enrolment may be not-normally distributed given large disparities between their median and mean values. Regarding the spread of the data, we can see that particularly for the control variables, most covariates are highly varied, especially infant mortality rates, life expectancy at birth and both primary and secondary school enrolment where standard deviations are all above 10. It is important as there is likely a large disparity amongst these variables between the SSA and OECD samples.

For the 84-country dataset, all variables included some observations between 1970–2018 for every country, apart from precipitation anomalies as the GHCN had no observations for Seychelles, subsequently being omitted from model estimates controlling for precipitation anomalies. Apart from primary and secondary school enrollment rates that average only T≈24 and T≈16 years of observations per country, all other variables contain

Table 1
Descriptive Statistics

Variable Name	Definition	Source	Obs.	Mean	Median	Mia.	Max.	Std. Dev.
Main Variables								
LGDC 10	Log GDP per Capita (U.S. 2010 $PPP)	World Bank	3630	3.63	3.66	2.22	5.05	0.77
TempAnom	Temperature deviation from historical norms	GHCN	4116	−0.04	−0.04	−2.25	2.03	0.55
PrecAnom	Precipitation deviation f om historical norms	GHCN	3735	6.25	2.76	−1444.6	1732.1	151.19
Hot	Dummy coded 1 if a country was above the median average temperature of the sample in 2018	World Bank	4116	05	0.5	0	1	0.5
Poor	Dummy coded 1 if a country was below the median GDP per capita ($ 2010) of the sample in 2013	World Bank	4116	05	0.5	0	1	0.5
Control Variables								
POPG	Annual population growth (%)	World Bank	4108	1.75	1.77	−6.77	11.53	1.41
PRIM	Primary school enrollment (net % of population)	World Bank	2054	8133	91.48	10.05	100	2133
SEC	Secondary school enrollment (net % of population)	World Bank	1353	64.77	80.55	0.1	99.91	3138
FDI	Foreign direct investment (net inflows % of GDP)	World Bank	3602	2.95	1.26	−5832	161.82	7.44
LIFE	Life expectancy at birth (years)	World Bank	4106	62.98	62.62	26.17	84.21	12.79
MORT	Infant mortality rates (per l,000 live births)	World Bank	3983	53.57	45.1	1.4	204.4	47.77

T = 47 years of observations per country across the *T = 48* years. Finally, two dummy variables were implemented, coding countries as 1 if the country was either above the median average temperature of the sample (Hot) or if the country was below the median average GDP per capita ($ 2010) of the sample (Poor).

Analysing Table 2 we notice that both temperature and precipitation variables are rich in observations across both regions, with an average *T = 48* years and *T = 45* years of observations respectively per country between 1970–2018. While temperature anomaly data seems normally distributed with identical means and medians (−0.04), precipitation anomalies may be questionable given the mean (6.25) is more than twice the median value (2.76). It is particularly apparent when analysing the data's spread as precipitation has a large standard deviation of 151.17 across the entire sample, with an even greater 178.49 in SSA and a still large 107.7 in OECD countries. It proves that there is variation in precipitation anomalies both between and within regions. This early descriptive analysis is noteworthy as it offers insight into the possible drastic impact precipitation deviations may have on SSA's agriculturally focused sectors (IPCC, 2007).

Interestingly, the mean temperature deviation between 1970–2018 for both SSA and OECD countries are negative at −0.03 and −0.04 degrees lower than the 1981–2010 average, respectively. While surprising at first, it is expected considering the anomaly baseline is taken as an average between 1981–2010 which is likely to be much higher than if 1960–1989 was used as the anomaly reference instead. Thus, one must be tentative when generalising precipitation estimates as it may underestimate the magnitude of temperature increases in both regions. Moreover, we also see that across the sample, the variance in temperature anomalies is greater in OECD than SSA-countries, with greater temperature deviations above (2.03) and below (−2.25) the anomaly average and a larger standard deviation of 0.7 compared to SSA's 0.41.

Table 2
The difference in covariate means for temperature and precipitation anomalies

	Observations	Mean	Median	Minimum	Maximum	Std. Dev.
SSA						
Temperature Anomaly	2303	−0.03	-0.04	−1.37	1.69	0.41
Precipitation Anomaly	1980	11.82	3.52	−1444.63	1732.09	178.49
OECD						
Temperature Anomaly	1813	−0.04	-0.02	−2.25	2.03	0.7
Precipitation Anomaly	1665	−0.68	2.06	−485.05	506.80	107.7
Combined						
Temperature Anomaly	4116	−0.04	−0.04	−2.25	2.03	0.55
Precipitation Anomaly	3735	6.25	2.76	-1444.63	1732.09	151.17

It is interesting to note as the climate literature predominantly focuses on the impact of the temperature changes on growth (Wade & Jennings, 2016) and the vulnerability of developing countries (Dell, Jones, & Olken, 2012), rather than the magnitude of the temperature changes between developed and developing regions.

Although both SSA and OECD countries have seen a consistent increase in temperature across the 48-year period, with anomalies reaching above historical averages in the 21st century, there is a noticeably larger variation and steeper increase in temperature in OECD countries relative to SSA countries.

Analysis of precipitation anomalies is more challenging. As aforementioned, the variation in precipitation anomalies across the entire sample is large, particularly in SSA. Moreover, SSA sports both the largest deviation above (1732.09) and below (−1444.63) the historical precipitation averages compared to the OECD's most extreme precipitation deviations of −485.05 506.8. Further disparities between the samples are noticed when comparing regional precipitation means, with SSA seeing annual mean precipitation of 11.82mm above historical norms. In contrast, OECD countries see average precipitation of 0.68mm below its historical norms.

Unfortunately, Figure 2 offers no tangible trend in precipitation anomalies. Although we can see a considerable variation in precipitation across the years, particularly for SSA, it is difficult to extrapolate a trend regarding whether precipitation increases or decreases over time for either region. However, this preliminary analysis of precipitation anomalies may be interesting, given SSA's larger deviations and its impact on crop-yields in SSA's more agriculturally focused economies (Lobell, Schlenker, & Costa-Roberts, 2011).

Methodology

This paper sets out to elucidate the long-term impact of climate change on economic growth, specifically contrasting the differential impacts climate variations may have between developed (OECD) and developing countries (SSA). Firstly, this section identifies frameworks in previous literature used to model economic growth, while also considering introducing climate variations and their influence on economic growth-models. Finally, it outlines the econometric model adopted, justifying its use relative to past literature downfalls, whilst also considering any possible limitations of the proposed methods.

Growth Model

Following from general growth frameworks delineating how explanatory variables influence economic growth, popularised by Barro (1991)

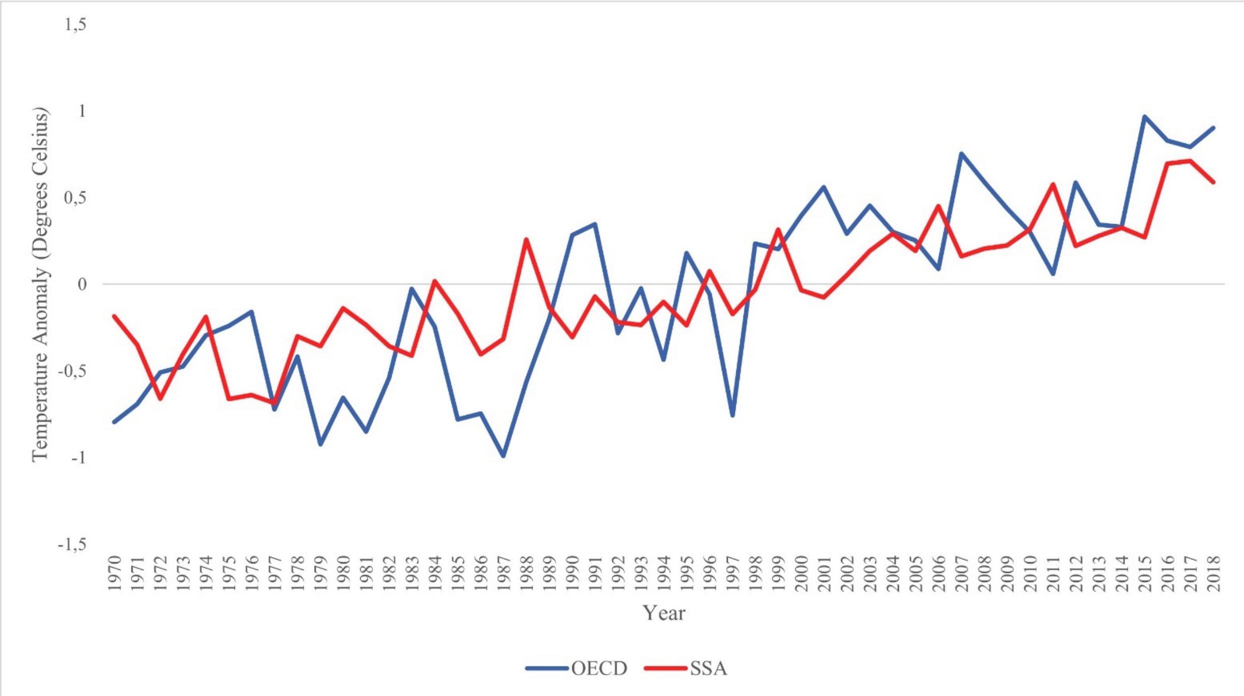

Fig. 1. Average Annual Temperature Deviation from Historical Norms between 1970–2018

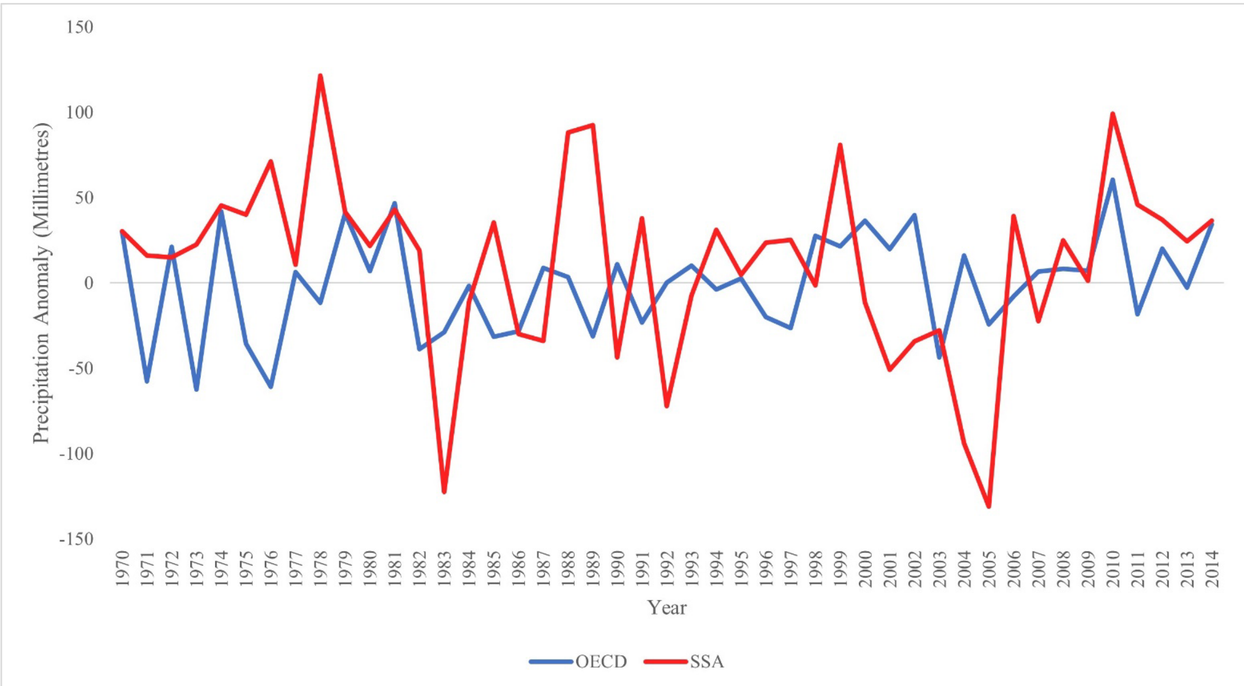

Fig. 2. Average Annual Precipitation Deviation from Historical Norms between 1970–2014

and Sala-i-Martin (1997), and seminal theoretical growth models by Merton (1975), and Binder and Pesaran (1999) developing single economy stochastic growth models, we adopt Kahn et al.'s (2019) approach and expand this literature to a growth process including climate change as an endogenous variable influencing growth in a cross-country model.

I assume that $N = 84$ countries share common technologies but differ in their country-specific climate variations. Consider a set of countries whose aggregate a production function describes production possibilities:

$$Y_{it} = \mathcal{F}\left(\wedge_{it} L_{it}, K_{it}\right),$$

where K_{it} and L_{it} are capital and labour inputs with $\wedge_{it}$ as a scale variable determining labour productivity in an economy for country *i,* at time *t.* I assume that labour productivity, measured by

GDP per capita, is dictated not only by general technological factors but also country-specific climate variables. Climate variables are denoted T_{it} and P_{it} for average temperature and precipitation, respectively. However, I consider that labour productivity is only impacted by climate change when the variables deviate from their historical norms, expressed by $T_{i,t-1}(\eta)$ and $P_{i,t-1}(\eta)$ for temperature and precipitation historical norms where η is the time-scale in the number of years used to calculate historical norms. The assumption is made that technology is neutral over historical norms meaning that technology does not have supplementary effects on labour productivity, given that climate variables do not deviate from historical norms over a given time-horizon. It is intuitive and confirmed in the literature suggesting that hotter countries including Singapore have technologically adapted to harsher climates through air conditioning (Kahn et al., 2019), while opposing effects are found whereby heat-waves are more frequently fatal in colder countries that are less acclimatised to hotter temperatures, reinforcing that different countries adapt to their temperature niche (Heutel et al., 2016).

By accommodating for deviations in climate variables instead of trended temperature variables widespread in the literature (Barrios et al., 2010; Dell, Jones, & Olken, 2012), we can account for any asymmetric effects of climate change on economic growth. Moreover, utilising deviations in climate variables makes it unlikely that the variables have unit roots and counters potential downfalls of linearised climate change trends.

Panel ARDL

The first panel ARDL model will interpret how global temperatures have evolved between 1970–2018 with reference to 1981–2010 historical norms. Allowing for heterogeneous effects between the 84-country sample, country-specific regressions calculating changes in temperature over-time are estimated by:

$$T_{it} = \alpha_i + \beta_{it} + \varepsilon_{it},\ for\ i = 1, 2, \ldots, N = 84,$$

where T_{it} signifies the average temperature of country *i* at time *t,* α_{it} is the country-specific fixed-effect (FE), β_{it} is the individual country's annual average temperature change and ε_{it}, is a serially uncorrelated stochastic shock.

Adopting the above mentioned theoretical growth model, we can estimate the long-term economic impact of climate change on per-capita growth using the panel ARDL model:

$$\Delta y_{it} = \alpha_i + \sum_{\iota=1}^{p} \varphi\iota \Delta y_{i,t-\iota} + \sum_{\iota=1}^{p} \beta'\iota \Delta x_{i,t-\iota}(\eta) + \varepsilon_{it}$$

$$for\ i = 1, 2, \ldots, N = 84, \quad (2)$$

where y_{it} is the log of real GDP per-capita for country *i* in year *t,* α_{it} is the country-specific FE, $x_{i,t}(\eta) = [C_{it} - C_{i,t-1}(\eta)]'$, where $C_{it} = (T_{it}, P_{it})'$ and $C_{i,t-1}(\eta) = [T_{i,t-1}(\eta),\ P_{i,t-1}(\eta)]'$. Here, T_{it} and P_{it} are temperature and precipitation averages, respectively for country *i* at year *t,* whereas $T_{i,t-1}(\eta)$ and $P_{i,t-1}(\eta)$ are temperature and precipitation η=1981–2010 historical norms. Hence, $x_{i,t}(\eta)$ captures the temperature and precipitation anomalies (denoted in vector C) as they calculate the difference between an observed temperature or precipitation for any country *i* in a given year *y,* relative to their respective historical norm averages.

While I could not choose the historical norm time-horizon as the NOAA dataset already predetermined them, fortunately, climate norms in the literature are typically moving averages of a prior 20–30 year-period, large enough to make annual variations in historical norms small, making 1981–2010 a robust historical norm reference (Arguez et al., 2012; Vose et al., 2014; Abidoye & Odusola, 2015; Kahn et al., 2019).

In this paper, an ARDL specification is used to model both the evolution of global temperatures per-country between 1970–2018 and the long-term impact of climate change on growth. Pesaran and Smith (1995), Pesaran and Shin (1999) and Pesaran et al. (2001) prove that traditional ARDL models can be extrapolated for long-run analysis and are valid irrespective of whether underlying variables are *I* (0) or *I* (1). Moreover, it is a robust approach against omitted variable biases and bi-directional feedback effects between per-capita growth and its long-run determinants — making it an appropriate model for this paper. Furthermore, Pesaran et al. (2001) explicate the advantages of the ARDL model against other estimation methods used in the literature such as dynamic panel models (Hsiao & Anderson, 1981), or the use of instrumental variables (Arellano & Bover, 1995) as these methods often produce inconsistent estimates of parameters if coefficients are heterogeneous across countries (Cerqueira et al., 2018). Furthermore, by utilising a panel that offers more variability than cross-sectional approaches, estimates are less susceptible to collinearity among variables, allowing for more accurate estimates of heterogeneous effects among countries.

For ARDL models to be a robust technique and overcome autocorrelation problems, the model's dynamic specification needs to be augmented with sufficient lags, making the regressors weakly exogenous (Chudik et al., 2017). It is intuitive to believe that the impact of climate change on economic growth will have lasting, lagged effects. However, while previous literature assumes an arbitrary lag of p = 4 years to be sufficient (Kahn et al., 2019), this paper adopts the AIC whose premise is to decide which lags offer new 'information' model. I set the maximum lag-order to 5-years and chose the preferred ARDL model based on the lowest AIC value when re-estimating models for robustness tests. A maximum lag-order of 5 was chosen, not only because it is similar to the previous literature chosen lag-lengths, but also because 5-years is an appropriate amount of time to analyse both the lagged-effects of climate change and also notice any potential lagged retaliatory environmental policy-effects or the influence of policies based on new governmental elects as terms usually last 4-years. Moreover, by employing multiple climate lags, one can elucidate whether the effects of climate variations on economic growth are temporary, persistent or vary over-time as countries adapt differently to climate changes.

However, the panel sample contains *N = 84* countries for *T = 48* years, making the cross-sectional dimension larger than the time-dimension. It may be a problem as reporting standard FE estimates for the long-run impacts of climate variations on per-capita growth may be biased from small-T values if any regressors are not strictly exogenous (Chudik et al. 2018). Thus, the lagged dependent variable is included to counter any bias estimates, although one must be circumspect when extrapolating results.

Results

The Evolution of Climate Change

This section explores how global temperatures have evolved between 1970–2018. Equation (1) is employed using a panel ARDL model across $N = 84$ countries to estimate country-specific regressions, allowing for significant heterogeneity between countries concerning temperature anomalies.

Table 3 illustrates how temperatures deviate annually for each of the 84-countries. The entire sample value was estimated by $\beta_t = N^{-1}\sum_{i=1}^{N}\beta_{it}$, with individual countries values estimated by β_{it}. The ARDL estimates demonstrate incontrovertible evidence that between 1970–2018, yearly temperatures have been increasing for all countries relative to 1981–2010 averages. In fact, only 2 countries (2.3 per cent of cases), namely Chile and New Zealand are insignificant, yet still positive with 0.0038 °C and 0.0041 °C increases in their yearly temperatures relative to the historical norms. For the other 82 countries, 7 estimates (8.3 per cent of cases) are significant at the $\alpha = 0.05$ level whereas the other 75 estimates (89.2 per cent of cases) are significant at the $\alpha = 0.01$ level. Estimates vary between Chile's 0.0038 °C and France's 0.0462 °C annual temperature increases. Figure 3's histogram illustrates the frequency of temperature deviations per-country in 0.01 °C intervals. The most common yearly temperature deviations lying between 0.01–0.03 °C increases per-year in which 64 (76.19 per cent of cases) lie.

The average annual temperature increase across the entire sample is 0.023 °C, showing that over the whole 48-year average, countries have increased by roughly 1.104 °C. Unexpectedly, it turns out that annual temperature increases are influenced by larger increases in OECD (0.0326 °C) countries relative to SSA (0.0146 °C) countries. It is surprising given that the literature focuses on temperature deviations adversely impacting growth in developing (SSA) countries more than developed (OECD) countries (Stern, 2006; Dell, Jones, & Olken, 2014). However, while temperatures seem to deviate more in OECD countries, it does not imply that OECD countries are worse affected by these variations.

These estimates are corroborated within the recent literature. Kahn et al.'s (2019) 174-country sample finds that 172 countries (98.9 per cent of the sample) see annual temperature increases, with estimates between −0.0008 °C and 0.019 °C

Table 3
Annual global temperature deviations between 1970–2018

Country	β*it*	Country	β*it*	Country	β*it*
Angola	0.0184***	Gambia	0.0209***	Nigeria	0.0247***
Australia	0.0136***	Germany	0.0255***	Norway	0.019**
Austria	0.0418***	Ghana	0.0266***	Poland	0.0265***
Belgium	0.0222***	Greece	0.0173***	Portgual	0.0316***
Benin	0.0227***	Guinea	0.0211***	Rwanda	0.0141***
Botswana	0.0187***	Guinea-Bissau	0.0209***	Sao Tome and Principe	0.0175***
Burkina Faso	0.0221***	Hungary	0.0418***	Senegal	0.0209***
Burundi	0.0222***	Iceland	0.015***	Seychelles	0.0158***
Cameroon	0.0172***	Ireland	0.0187***	Sierra Leone	0.0211***
Canada	0.0361***	Israel	0.0353***	Slovakia	0.0418***
Cape Verde	0.0191***	Italy	0.0299***	Slovenia	0.0436***
Central African Republic	0.0236***	Japan	0.0194***	Somalia	0.0147***
Chad	0.0259***	Kenya	0.0215***	South Africa	0.0091***
Chile	0.0038	Latvia	0.0167**	South Korea	0.0216***
Colombia	0.0212***	Lesotho	0.0216***	Spain	0.0461***
Comoros	0.0092***	Liberia	0.0211***	Sudan	0.036***
Congo DR	0.0176***	Lithuania	0.0303***	Sweden	0.0163**
Cote d'lvoire	0.0281***	Luxembourg	0.0455***	Switzerland	0.0455***
Czech Republic	0.0255***	Madagascar	0.0158***	Tanzania	0.0216***
Denmark	0.019**	Malawi	0.0208***	Togo	0.0227***
Djibouti	0.0219***	Mali	0.0251***	Turkey	0.0277***
Equatorial Guinea	0.0175***	Mauritania	0.0202***	Uganda	0.0193***
Eritrea	0.0205***	Mauritius	0.0082***	United Kingdom	0.022***
Estonia	0.0167**	Mexico	0.0152***	United States	0.0153**
Eswatini	0.0147***	Mozambique	0.0147***	Zambia	0.0216***
Ethiopia	0.0218***	Namibia	0.0197***	Zimbabwe	0.0182***
Finland	0.0234**	Netherlands	0.0222***	Sample	0.0227***
France	0.0462***	New Zealand	0.0041	OECD	0.0326***
Gabon	0.0175***	Niger	0.0248***	Sub-Sahar an Africa	0.0146***

Note. Significance is highlighted with * for $\alpha < 0.1$, ** for $\alpha < 0.05$ and *** for $\alpha < 0.01$.

across a 1900–2014 time-horizon with greater estimates in temperate climates including Canada and Russia. The entire samples temperature increase of 0.027 ºC is in line with the IPCC's (2013) 0.0175 ºC global annual temperature increase.

Long-term Impacts of Climate Change on Growth

This section estimates the long-term economic impact of climate change variables on the log real GDP per-capita between 1970–2018. Equa-

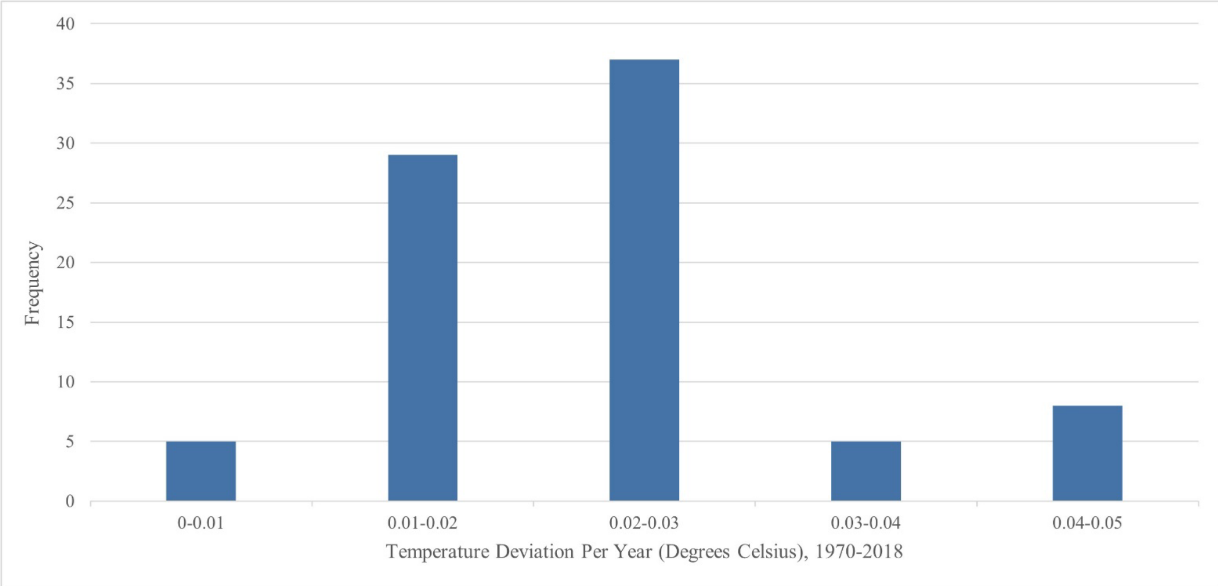

Fig. 3. Histogram depicting temperature deviation frequencies per 0.01-degree interval

tion (2) is employed using a panel ARDL model across $N = 84$ countries, allowing for significant heterogeneous climate effects between countries.

Table 4 provides the summary of 3 panel ARDL regressions including both temperature and precipitation anomaly variables in a baseline model ($ARDL^a$), just temperature anomalies ($ARDL^b$) and just precipitation anomalies ($ARDL^c$), and their influences on the log GDP per-capita. FE estimates are reported, with robust standard errors in brackets. The lagged dependent variables are included to overcome any potential bias with FE models. 'TempAnom' and 'PrecAnom' denote temperature and precipitation anomalies, respectively. As aforementioned, the ARDL lag-orders are chosen based on the AIC, with the lowest values taken as the preferred model.

The baseline model $ARDL^a$ adopts a lag of 1-year for the dependent variable and the precipitation anomaly, with no lags for the temperature anomaly. $ARDL^a$ suggests that neither climate variables significantly impact log GDP per capita. While only slightly insignificant, the temperature anomaly indicates that an increase in temperature as it deviates from historical norms has a marginally positive impact on log GDP per-capita when not lagged. Conversely, while both the lagged and non-lagged precipitation anomaly variables show a negative sign, the coefficients are highly insignificant with estimates recorded beyond 5 significant figures. Finally, the intercept is negative and insignificant with the lagged dependent variable as the only significant variable in the baseline model. Despite this, the overall significance of the $ARDL^a$ is significant at $\alpha = 0.001$ with an F-statistic of 909400.

Since the precipitation anomaly was the most insignificant variable, it was dropped from the model and rerun for $ARDL^b$. In contrast, dropping the precipitation anomaly changes the best AIC order to offer 1-year lags to both the dependent and temperature anomaly variables. $ARDL^b$ provides evidence that long-term economic growth is hindered by temperature variations, suggesting that an annual 0.01 °C increase in temperature above its norm significantly reduces real per-capita GDP by 0.017 per cent after a 1-year lag at the $\alpha = 0.01$ level. $ARDL^b$ also notes that a 0.01 °C annual increase in temperature significantly increases real per-capita GDP by 0.01 per cent in the same year as the temperature deviation at $\alpha = 0.05$ level. However, this non-lagged trend is likely explainable as the temperature deviations have had less time to influence per-capita output for that same-year, especially if temperature deviations were more apparent in later months (i.e., warmer winters). It would mean that temperature anomalies likely influence the following years per capita growth through its impact on agricultural output from lagged temperature effects. Overall, $ARDL^b$ as a model is significant at $\alpha = 0.001$ with an F-statistic of 45650. With the omission of PrecAnom, the intercept is now

Table 4
Long-term impacts of climate change anomalies on economic growth

Covariates	ARDL[a]	ARDL[b]	ARDL[c]
Intercept	−0.0012 (0.0019)	0.05*** (0.01)	−0.0013 (0.0019)
Lag (LGDC 10. 1)	1.002*** (0.001)	0.99*** (0.003)	1.002*** (0.001)
TempAnom	0.001 (0.001)	0.01** (0.004)	–
Lag (Tanom. 1)	–	−0.017*** (0.004)	–
PrecAnom	−0.0000 (0.0000)	–	−0.0000 (0.0000)
Lag (ChangePrecip. 1)	−0.0000 (0.0000)	–	−0.0000 (0.0000)
Observations	3174	3602	3174
F	909400***	45650***	1213000***
R− Squared	0.9991	0.9744	0.9991
Adjusted R−Squared	0.9991	0.9743	0.9991
AIC	−14950.18	−4806.21	−14951.72
AIC Order	1.0.1	1.1	1.1

Notes.
Robust standard errors are in parentheses.
Significance is highlighted with * for $\alpha < 0.1$, ** for $\alpha < 0.05$ and *** for $\alpha < 0.01$.

significant and positive, likely suggesting that $ARDL^b$ is a more econometrically robust model.

To ensure that it was appropriate to remove the precipitation, instead of the temperature anomaly, I rerun the regression instead including 'PrecAnom' and omitting 'TempAnom'. $ARDL^c$ justifies the removal of the precipitation instead of the temperature anomaly given that even without the temperature variable, deviation in precipitation from historical norms remains insignificant in its impact on per-capita GDP growth, regardless of whether the precipitation anomaly is specified with or without a lagged-effect. Additionally, both models that include precipitation anomalies register negative and insignificant intercepts, questioning the model's validity.

Differential Impacts for Poorer and Hotter Countries

So far, we have modelled general climate variables' influence on long-term economic growth. However, we are yet to investigate potential asymmetric impacts of climate change on poorer or hotter economies. Given the literature mentioned above deducing that climate change has uneven, detrimental macroeconomic impacts on poorer and hotter countries (IMF, 2017; Avecedo et al., 2018), I add dummies for 'Poor' and 'Hot' countries and augment the previous models by interacting the dummies with the temperature anomalies. By interacting these dummies with the temperature anomaly variable and including them in supplementary ARDL models, I can more easily determine whether climate change has uneven effects on different regions.

Although $ARDL^b$ was the preferred baseline model, I initially considered whether adding the interaction variables would impact the significance of the precipitation anomaly. Table 5 displays the following ARDL estimations for models, including dummy interaction variables. $ARDL^d$ was estimated, including both climate anomalies and both temperature-dummy interactions. The AIC preferred lagging each variable by 1-year, apart from 'HotTemp', which offered no lagged-effects.

$ARDL^d$ reiterates previous estimations, suggesting that precipitation anomalies offer no significant long-run effects on per-capita GDP growth. Once again, the inclusion of precipitation anomalies makes the models intercept insignificant. Reassuringly, temperature anomalies were robust to the addition of dummy interaction variables, with the lagged 'TempAnom' effect becoming more significant, inferring that an annual 0.01 °C increase in temperature above its norm significantly reduces GDP per-capita by 0.024 per cent after a 1-year lag. However, the non-lagged effect becomes slightly insignificant, sporting a negative sign.

For the interaction terms, $ARDL^d$ suggests that an increase in temperature above the historical norm in hotter countries tends to decrease per-capita growth, although this effect was insignificant. Interestingly, the 'PoorTemp' interaction variable suggests that an annual 0.01 °C increase in temperature above the historical average significantly increases GDP per-capita by 0.01 per cent in the initial year, with a smaller 0.007 per cent increase the following year after the temperature deviation. While this contends against theoretical assumptions and previous literature, the analysis will be saved until a better specified model is chosen.

Given the precipitation anomaly was still largely insignificant, an ARDL model with temperature-dummy interactions was re-estimated, omitting 'PrecAnom'. Following this omission, the AIC now preferred a much richer ARDL model in terms of lagged-effects for each variable. Firstly, $ARDL^e$ offers substantial evidence that temperature deviations from historical norms have significant, negative long-run impacts on income-growth. The model suggests that a 0.01 °C increase in temperature above historical norms, estimates between a 0.011 per cent and 0.022 per cent decrease in per-capita income growth annually up to 4-years after the initial temperature deviation. These ranges are substantiated by the recent literature, although previous estimates are slightly higher between a 0.03 per cent and 0.06 per cent annual decrease in per-capita growth (Abidoye & Odusola, 2015; Kahn et al., 2019). Interestingly, we see that after a lag of 5-years, the effect of a temperature increase becomes slightly positive, increasing per-capita income growth by 0.01 per cent at the $\alpha = 0.05$ level. It suggests that the negative climate influences on growth only last 4-years, which is understandable given that are a long-enough time-period for environmental or governmental policies to take-effect to combat the negative impact of climate change as technologies adapt.

Furthermore, $ARDL^e$ estimates suggest that after a lag of 3-years, an increase in temperature above historical norms in hotter countries seem to have significant, negative, long-term impacts on per-capita growth. Table 5 suggests that an annual 0.01 °C increase in temperature above historical norms for hotter-countries decreases real GDP per-capita by 0.084 per cent after 3-years, 7-times greater than the 3-year lagged impact on the entire samples 0.012 per cent decrease in per-capita incomes. Similar to the entire-sample estimates, although a year earlier, per capita incomes begin to rise again by 0.04 per cent after a 4-year lag. It is interesting as it suggests that hotter countries may adapt quicker than sample averages to climate change's negative influences.

Moreover, $ARDL^e$ estimates elucidate that an increase in temperature above historical norms also has significant, negative impacts on income-growth in poorer countries. For the temperature deviation year, per-capita incomes decrease by 0.041 per cent following a 0.01 °C rise in temperature above historical averages. This more immediate negative temperature effect infers that poorer countries are more susceptible to initial shocks in labour productivity following temperature increases, possibly due to a lack of technologies to combat rises in temperature such as air-conditioning. In antithesis, results suggest that poorer-countries see significant increases in GDP per-capita by 0.043 per cent after 1-year, and 0.11 per cent after 3-year lagged-effects that become insignificant and negative after the fourth year (−0.031 per cent). It is interesting and suggests that 'poorer countries adapt faster than other countries after just 1-year following temperature increases above their historical norms.

Finally, both the intercept and lagged dependent variables are significant, suggesting that the model is better specified. Moreover, the overall model outputs an F-statistic of 8313, significant at the $\alpha = 0.001$ level. Ultimately, I reject the null hypotheses that temperature deviations from historical norms do not have adverse, long-run impacts on growth — particularly in poorer and hotter countries. Finally, an additional model with precipitation interactions between development dummies was also estimated, however, the model was omitted as both precipitation interactions were insignificant and adversely manipulated the $ARDL^e$ results, possibly due to multicollinearity between variables. Thus, we fail to reject the null hypothesis that precipitation deviations impact long-term growth.

Robustness Tests

I have previously shown that the initially preferred $ARDL^b$ model outlining the negative implications of temperature anomalies on per-capita growth is robust to the inclusion of development dummy-interactions with temperature anomalies. In fact, the model was arguably improved to a richer $ARDL^e$ model favouring longer-lags per covariate. However, to further ensure the robustness of $ARDL^e$ The significant impact temperature anomalies have on growth, and I consider two additional robustness controls.

Firstly, it is imperative the variables in $ARDL^e$ maintain their significance when controlling for exogenous variables that may influence real GDP growth per capita. Thus, $ARDL^f$ is estimated with the inclusion of 6-controls, population growth, primary and secondary school enrolment, FDI inflows, life expectancy at birth and infant mortality rates. Reasons for the choice of controls were highlighted above.

AIC prioritises 2-year, and 3-year lags for temperature anomalies and 'HotTemp' interactions while offering no lags for 'PoorTemp' or any control variables. $ARDL^f$ shows that the coefficients signs and significance from $ARDL^e$ They are mostly identical, except a positive and insignificant 'PoorTemp' non-lagged coefficient, and an insignificant second-year lag for temperature anomalies. We see significant, negative impacts of increases in population growth and infant mortality rates on per-capita incomes and significant positive impacts of increases in FDI on income-growth, which are to be expected. However, both school enrolment rates and life expectancy seem to be insignificant.

$ARDL^g$ estimates the same regression but with the omission of life expectancy as it was the most insignificant variable. We see almost

Table 5

ARDL models for the differential impact of climate change on poor and hot countries

Covanates	$ARDL^d$	ARDL−
Intercept	0.001	0.05***
	(0.002)	(0.01)
Lag (LGDC 10. 1)	1.002***	
	(0.001)	(0.003)
Temp A nom	−0.002	0.014**
	(0.001)	(0.005)
Lag (TempAnom. 1)	−0.0024**	−0.022***
	(0.01)	(0.006)
		−0.011*
Lag (TempAnom, 2)	–	(0.006)
		−0.012**
Lag (TempAnom. 3)	–	(0.006)
		−0.017***
Lag (TempAnom 4)	–	(0.006)
Lag (TempAnom 5)		0.01**
	–	
		(0.005)
PrecAnom	−0.0000	
		–
	(0.0000)	
Lag (PrecAnom 1)	−0.0000	
		–
	(0.0000)	
HotTemp	−0.001	0.022
	(0.003)	(0.02)
		−0.01
Lag (HotTemp. 1)	–	(0.02)
		0.002
Lag (HotTemp. 2)	–	(0.02)
Lag (HotTemp. 3)		−0.084***
	–	(0.021)
		0.04**
Lag (HotTemp. 4)	–	
		(0.02)
Poor Temp	0.01***	−0.041**
	(0.003)	(0.02)
Lag (PoorTemp. 1)	0.007***	0.043**
	(0.002)	(0.021)
Lag (PoorTemp. 2)	–	0.034 (0.021)
		0.11***
Lag (PoorTemp. 3)	–	(0.022)
		−0.031
Lag (PoorTemp. 4)	–	(0.02)
Observations	3170	3588
F	462700***	8313***
R−Squared	0.9991	0.9752
Adjusted R−Squared	0.9991	0.9751
AIC	−1500128	−4902.48
AIC Order	1.1.1.0.1	1.5.4.4

Notes.

Robust standard errors are in parentheses.

Significance is highlighted with * for $\alpha < 0.1$, ** for $\alpha < 0.05$ and *** for $\alpha < 0.01$.

Table 6

ARDL robustness tests for controls

Covariates	ARDL[f]	ARDL[g]	ARDL[h]	ARDL[i]
Irtercept	0.033*** (0.012)	0.031*** (0.01)	0.025*** (0.01)	0.12*** (0.02)
Lag (LGDC 10.1)	1.01S*** (0.007)	1.018*** (0.007)	0.99*** (0.001)	0.98*** (0.004)
TempAnom	−0.002 (0.001)	−0.002 (0.001)	−0.001 (0.001)	0.001 (0.004)
Lag (TempAnom. 1)	−0.002* (0.001)	−0.0021* (0.001)	−0.0023** (0.001)	−0.01** (0.004)
Lag (TempAnom. 2)	−0.001 (0.001)	−0.001 (0.001)	−0.001 (0.001)	−0.001 (0.004)
Lag (TempAnom. 3)	–	–	–	−0.001 (0.004)
Lag (TempAnom. 4)	–	–	–	−0.01* (0.003)
HotTemp	0.002 (0.004)	0.002 (0.004)	0.0002 (0.003)	0.004 (0.001)
Lag (HofTemp. 1)	−0.003 (0.003)	−0.003 (0.003)	–	0.01 (0−01)
Lag (HofTemp. 2)	0.001 (0.003)	0.001 (0.003)	–	0.001 (0.01)
Lag (HofTemp. 3)	−0.006** (0.003)	−0.006** (0.003)	–	−0.02* (0.01)
PoorTemp	0.002 (0.003)	0.002 (0.003)	−0.001 (0.003)	−0.07*** (0.01)
Lag (PoorTemp. 1)	–	–	–	0.03** (0.001)
Lag (PoorTemp. 2)	–	–	–	0.04** (0.001)
Lag (PoorTemp. 3)	–	–	–	0.06** (0.001)
POPG	−0.002*** (0.001)	−0.002*** (0.001)	−0.003*** (0.001)	−0.07*** (0.004)
PRIM	0.0000 (0.0000)	0.0000 (0.0000)	0.0000 (0.0000)	–
SEC	0.0000 (0.0000)	0.0000 (0.0000)		
FDI	0.0004*** (0.0001)	0.0004*** (0.0001)	0.0004*** (0.0001)	0.0004** (0.0002)
LIFE	0.0000 (0.0000)		–	–
MORT	−0.002*** (0.001)	−0.002*** (0.001)	−0.005*** (0.000)	−0.007*** (0.000)
Observations	1184	1186	1918	3458
F	142800***	151300***	294900***	13790***
R−Squared	0.9995	0.9995	0.9994	0.9882
Adjuste d R− S quare d	0.9995	0.9995	0.9994	0.9 S 81
AIC	−6473.67	−6476.29	−9S 44.89	−7357.96
AIC Order	1.2.3.0.0.0.0.0.0.0	1.2.3.0.0.0.0.0.0	1.2.0.0.0.0.0.0.	1.4.3.3.0.0.0

Notes.

Robust standard errors are in parentheses.

Significance is highlighted with * for $\alpha < 0.1$, ** for $\alpha < 0.05$ and *** for $\alpha < 0.01$.

identical coefficients and signs with comparison to $ARDL^f$, with continued insignificant relationships between both primary and secondary school enrolment rates and the growth of per-capita incomes. It leads to the removal of secondary school enrolment in $ARDL^h$, and primary school enrolment in $ARDL^i$. The potential reason for the insignificance of the controls is probably that primary and secondary school enrolments only average $T \approx 24$ and $T \approx 16$ years of observations respectively per country, with the lower observation, ranges between 1184–1918 across $ARDL^f$, $ARDL^g$ and $ARDL^h$. With the lack of data for these variables, it may be difficult to extrapolate any meaningful relationships with income-growth over larger time-horizons. Moreover, with sparse coverage in the literature, life-expectancy adds little significance when predicting long-run GDP per-capita growth.

Ultimately, $ARDL^i$ is estimated after omitting the three insignificant controls. Immediately, we notice this AIC specification offers greater potential for analysis given its richer time-lags for all non-control variables. With comparison to $ARDL^e$, the temperature and temperature-dummy interaction variables are lagged 1-less year. Comparing coefficients between $ARDL^e$ and $ARDL^i$, it is noticeable that temperature anomalies remain robust, with 1–4-year lags all maintaining their negative sign, although the second-year and third-year lags become slightly insignificant. As expected, the coefficients are relatively lower when introducing controls suggesting that a 0.01 °C annual increase in temperature above its norm significantly reduces long-run real GDP per-capita by between 0.001 per cent and 0.01 per cent, relative to previously estimated 0.011 per cent and 0.022 per cent income-growth decreases. Despite this, temperature anomalies and their negative long-term impact on growth remain significant and robust when introducing controls.

Regarding the temperature anomaly impacts specific to hotter countries, estimates still indicate that a rise in temperature above historical norms significantly and negatively impacts hotter countries, with a 0.02 per cent fall in annual per-capita GDP after a 3-year lag following a positive 0.01 °C temperature deviation. While the coefficient is slightly smaller than without a control (–0.084), we can deduce that temperature anomaly deviations significantly and negatively impact hotter

Table 7
ARDL robustness tests for alternative temperature anomalies

Covariates	$ARDL^j$	$ARDL^k$
Intercept	0.001 (0.002)	0.05*** (0.01)
Lag (LGDC 10: l)	1.002*** (0.001)	0.99*** (0.003)
TempAnom	−0.0013 (0.001)	0.01** (0.005)
Lag (TempAnom. 1)	−0.002** (0.01)	−0.019*** (0.005)
Lag (TempAnom, 2)	-	−0.011** (0.006)
Lag (TempAnom, 3)	-	−0.01 (0.005)
Lag (TempAnom, 4)	-	−0.015*** (0.005)
PrecAnom	−0.0000 (0.0000)	-
Lag (PrecAnom, 1)	−0.0000 (0.0000)	-
HotTemp	−0.0003 (0.003)	0.026 (0.02)
Lag (HotTemp, 1)	-	−0.01 (0.02)
Lag (HotTemp, 2)	-	−0.004 (0.02)
Lag (HotTemp, 3)	-	−0.06** (0.02)
Lag (HotTemp, 4)	-	0.016 (0.01)
PoorTemp	0.007** (0.003)	−0.045** (0.02)
Lag (PoorTemp, 1)	0.008*** (0.002)	0.03 (0.02)
Lag (PoorTemp, 2)		0.043** (0.02)
Lag (PoorTemp, 3)		0.09*** (0.02)
Observations	3170	3590
F	463200***	9403***
R-Squared	0.9991	0.9752
Adjusted R-Squared	0.9991	0.9751
AIC	−15004.89	−4897.53
AIC Order	1.1.1.0.1	1.4.43

Notes.
Robust standard errors are in parentheses.
Significance is highlighted with * for $\alpha < 0.1$, ** for $\alpha < 0.05$ and *** for $\alpha < 0.01$.

countries — remaining robust to controls. Finally, it is evident that temperature deviations remain robust in their effects on poorer countries, suggesting an immediate 0.07 per cent decrease in per-capita growth when temperatures increase by 0.01 °C above historical norms. Similar to the $ARDL^{e}$ specification, it seems that poorer countries adapt quicker than others to temperature deviations with positive per-capita growth levels when lagged-effects are considered, with estimates between a significant 0.03–0.06 per cent increase for 1–3-year lags. Moreover, I find that population-growth and infant mortality rates have significant negative, and FDI inflows have significant positive effects on long-term GDP per-capita growth-rates. For all 4 robustness test iterations with controls, models are highly significant with F-statistics ranging between 13790–294900, all significant at the $\alpha = 0.001$ level. Ultimately, apart from slightly diluted impacts on growth when controls are introduced which is expected, the temperature anomalies and their development dummy-interactions remain significantly robust to the introduction of control variables.

Secondly, a critical argument against this paper may be in its use of temperature anomalies in capitals, potentially undervaluing the negative or heterogeneous impact of temperature deviations in more rural, agriculturally focused areas of the country. Therefore, I run a robustness test instead using temperature anomalies averaged across the capital and across 4-extreme coordinates at the most north-south-east and westerly cities to better encapsulate how temperature deviates across the country.

$ARDL^{j}$ includes the newly averaged temperature anomaly, the new anomalies interactions between both development-dummies, and the reintroduction of the precipitation anomaly. Precipitation was reintroduced to gauge whether estimates change when coupled with a different temperature anomaly estimate. Results from $ARDL^{j}$ are almost identical with results of the $ARDL^{d}$. Most importantly, specification suggests that the precipitation anomaly has no significant impact on long-run per-capita growth-rates. Moreover, all coefficient signs and significance levels remain the same across both ARDL specifications, apart from minuscule changes to the coefficients' values by no more than 0.01 decimal places.

Henceforth, our final ARDL model is specified with the omission of precipitation anomalies. Comparable to $ARDL^{e}$, the exclusion of precipitation anomalies improves the lag-lengths per variable with AIC specifying lags of 4-years for temperature anomalies and 'HotTemp' interactions and lags of 3-years for 'PoorTemp' interactions. Table 7 illustrates that temperature anomalies and their interactions with development-dummies remain robust to more aggregate temperature anomalies measurements. Estimates predict that a 0.01 °C increase in temperature deviations above historical norms have significant, negative, long-term influences on real GDP per capita growth by between 0.01 per cent and 0.019 per cent over a 1–4 year lagged period. These estimates are very similar to the capital adjusted temperature anomalies with decreases ranging between 0.011 per cent and 0.022 per cent. Furthermore, the impacts of temperature deviations on hotter countries remain negative and insignificant across 1-year and 2-year lags and become negative and significant, with a 0.06 per cent annual GDP per-capita decrease after three lagged-years. Thus, proving that temperature increases have more adverse impacts on hotter countries and that these findings are robust against aggregate temperature anomaly estimates. Finally, I also find robust results for poorer economies, with an annual 0.01 °C increase in temperature above historical norms having a significant and immediate negative impact on income-growth of 0.045 per cent for poorer countries. This changes to significant increases in real per-capita growth after a lag of 2-years (0.043 per cent) and 3-years (0.09 per cent). Ultimately, these tests demonstrate that the use of temperature deviations in capital cities offer robust estimates of the aggregate country impacts of temperature changes on long-term real GDP per-capita growth.

Discussion

The present study aims were two-fold; i) identify how country-specific temperatures have varied over the last 48-years relative to their historical averages, and ii) investigate whether deviations in climate variables have a significant impact on economic growth, particularly in hotter, developing countries. Firstly, I documented the evolution of country-specific temperatures between 1970–2018 in a sample of 84 OECD and SSA countries. Secondly, this paper explored the long-term economic impact of climate anomalies on the log real GDP per-capita between 1970–2018 across the same sample. Both research questions implemented a panel ARDL model for their respective quantitative analysis. This paper found that i) temperatures across all countries have consistently increased relative to their historical norms, with 82/84 countries finding significant evidence of annual temperature increases across the 48-year panel. Temperatures were found to increase more dramatically in OECD relative to SSA countries. Secondly, the current paper found ii) robust evidence that deviations of temperatures, particularly increases in temperature relative to historical norms, had significant and negative impacts on long-term per-capita growth. The results also found evidence that temperature deviations disproportionately and negatively affected poorer and hotter countries. However, precipitation variations had no significant effect on long-run income growth.

Long-term Temperature Trends

Relative to 1981–2010 historical norms, the average per-country temperature increase was 0.027 °C annually. Worryingly, temperatures considerably increased for every sample country, with only two countries, namely Chile and New Zealand, being slightly insignificant. Thus, 97.6 per cent of the sample saw significant increases in their relative temperature in the last 48-years, with estimates ranging between Chile's 0.0038 °C to France's 0.0462 °C annual temperature increase. Surprisingly, I found that yearly temperatures increase considerably in OECD (0.0326) countries relative to SSA (0.0146) countries.

My analysis has contributed to the literature in multiple ways. Firstly, it has added to the very sparse literature regarding country-specific temperature increases. Most studies focus on global temperature trends over recent decades rather than country-specific variations (IPCC, 2013; Avecedo et al., 2018). By allowing for country-specific temperature changes, we can better determine climate change heterogeneity between countries. It is useful to economists for multiple reasons as it will enable them to not only analyse which countries have seen specific temperature changes over a given period; allow econometricians to apply this data to determine which countries or regions have been impacted disproportionately in economic-growth models; interpret how different demographics respond to climate change, and finally, allow economists to determine policies to combat regional-specific climate changes from evidence-based policy considerations.

Moreover, by using temperature deviations instead of absolute temperature values, I not only overcome methodology mentioned above issues found when using trended variables, but I also clarify how temperatures have changed over-time relative to historical norms instead of showing the trend of the data. Doing so signifies a potential causal influencer that may be driving temperatures away from historical averages instead of showing that temperature may just be trended in a specific direction. Finally, by analysing updated datasets, I can interpret any potential temperature variations following noticeable rises in GHG emissions in the last decade, ultimately, better informing environmental-policy decisions.

However, it is important to note potential pitfalls of using historical norms as a reference anomaly when calculating increases in average annual temperatures. By utilising temperature variations, my results may have even underestimated the true (absolute) increase in the entire sample's yearly temperatures. It is because I have estimated how temperatures have deviated relative to large 1981–2010 averages. If the data used earlier years as the historical average reference norms or used absolute annual temperature values, results may have shown even further country-specific temperature increases. It is crucial as the literature should not underestimate the impact climate change has on the global economy. Henceforth, my estimates must be extrapolated tentatively, not only as they fail to capture within-country temperature variations that may differ significantly from the country-averages, but also because generalising estimates across longer time-horizons will infer indefinite temperature increases even when policies could be put in place to limit future climate change.

Long-term Impacts of Climate Change on Growth

This paper's central focus was to analyse the long-term impact of climate anomalies on real GDP per-capita between 1970–2018. Results were robust, suggesting that temperature deviations, particularly increase above historical norms, have significant negative impacts on long-term per-capita growth. More worryingly, the fall in per-capita incomes was persistent across 4-lagged years after the initial temperature shock, suggesting that climate change has lasting, long-term impacts on income-growth. Estimates range between a 0.011 per cent and 0.022 per cent annual decline in per-capita incomes following a 0.01 °C temperature increase. These estimates are mostly similar to the literature 0.03 per cent and 0.06 per cent yearly decreases in per-capita growth (Abidoye & Odusola, 2015; Kahn et al., 2019).

There are two additional takeaways from the temperature anomaly estimates; firstly, the non-lagged estimates show a significant positive coefficient on the temperature shock year. This likely suggests that temperature change has less of an effect on labour productivity as opposed to agricultural output considering labour productivity would likely reduce output the year of the temperature shock, whereas agricultural output will be predominantly impacted in lagged years (Seppänen, Fisk, & Faulkner, 2003; Schlenker & Lobell, 2010). Secondly, after the 5-year lag, coefficients became positive. It suggests that the negative influences of temperature variations on income-growth are neutralised 5-years after the shock. It is intuitive given 5-years is a long-enough time-period for environmental policies or governmental changes to take-effect to combat the impact of temperature increases as technologies and policies adapt.

Furthermore, I find that both hotter and poorer economies are significantly and disproportionally impacted by increases in temperatures relative to historical averages. Yet, results differ between the two development-variables. The significant effect for hotter countries is only disproportional after a 3-year lag. The literature can explain it as hotter, agriculturally focused on increasing temperatures over multiple-lags significantly hinder developing countries due to their agricultural dependence (Barrios et al., 2008; Avecedo et al., 2018). Alternatively, poorer-countries see more immediate declines in income-growth — the same year as the temperature shock. It infers that in poor-economies labour productivity may be instantaneously impacted by increases in temperature, which is intuitively based on their lower technological investment than advanced economies adopting more pervasive technologies such as air conditioning (Kahn et al., 2019).

However, estimates contradict some previous literature given that hotter and poorer countries adapt quicker than sample estimates after just 4-year and 1-year lags, respectively. Past papers not only theorise that poorer, hotter countries have a weaker capacity to adapt to climate changes given their lack of resources and weaker institutions (Adger, 2006; Toi, 2008b, Tol, 2009) but also empirically support this suggestion, finding that low-income countries have persistent and lasting negative responses even after 7-lagged years (Dell et al., 2012; Avecedo et al., 2018). Nevertheless, the present results can be explained by Heutel et al. (2016), suggesting that countries with hotter climates better adapt to their temperature niche. It would not only explain why both hotter and poorer countries in the sample have shorter-negative periods of income growth relative to the sample but also corroborates our results that OECD countries have seen greater temperature increases than SSA countries, potentially inferring that even developed economies are struggling to adapt to temperature deviations over-time. An alternative explanation could be that given the increased awareness of climate change and pressures on global-policy to abate GHG emissions, novel policies may be effective at enabling developing countries to better adapt to the difficulties of climate change (IPCC, 2007; Kompas, Pham & Che, 2018).

Nevertheless, this finding is particularly important due to its policy implications. In fact, results suggest that poorer countries react more effectively to temperature deviations than hotter economies. Although interesting given that poorer countries are also typically hotter, findings would infer that policy needs to be particularly focused on the potential temperature-effects on hotter climates as they are more vulnerable to persistent, long-run declines in income-growth following temperature deviations. Moreover, results would also suggest that greater-investment is needed in poorer-countries as they are particularly susceptible to temperature deviations impacting their labour-productivity.

Finally, precipitation anomalies are ubiquitously insignificant in their impact on long-term income growth across all estimations and robustness tests. While inconclusive, this result is substantiated by recent literature all finding no significant impact of precipitation on income-growth (Auffhammer et al., 2011; Avecedo et al., 2018; Kahn et al., 2019). Thus, this paper suggests that temperature variations are more impactful than precipitation variations when understanding climate change's influence on economic growth and development.

This study ultimately adds to the literature through multiple avenues. Firstly, it adopts a robust ARDL model to better study the long-term, heterogeneous impact climate variations have on economic growth between developed (OECD) and developing (SSA) countries. Moreover, by adopting temperature anomalies, I overcome the literature mentioned above difficulties when implementing trended variables. Thirdly, I formulate a robust estimation method based on seminal economic growth-models to substantiate claims made in previous literature that temperature variations negatively impact hotter, developing countries and those precipitation anomalies are inconclusive in their impacts on growth. Finally, I implement the AIC specification method to understand better the differential lagged effects of climate variables in specific regions to better inform policy decision-making.

However, it is also important to mention this paper's limitations that may be useful to consider when expanding future research opportunities. Firstly, while the AIC method was useful in suggesting appropriate lag-intervals to form a more econometrically-robust model, it frequently failed in its task to identify the reactions of specific variables over-multiple lags by regularly understating the number of lags offered to each variable. By doing this, it was difficult to compare how coefficients of lag-lengths change not only when comparing two variables in a model, but also when comparing the same variable between different models as lags often changed between robustness tests. Secondly, to further the model's validity, it would be useful to compare how estimates differ when referencing anomalies using different historical averages because the current results may have underestimated the magnitude of temperature effects on economic growth. Finally, even though using estimates of temperature anomalies at the capital passed robustness tests when comparing to estimates using more aggregate temperature averages across the country, the study still failed to show the true negative extent temperature deviations may have on agriculture assuming that the capital is more services intensive and more rural cities are more agriculturally intensive. Therefore, future studies should either find more inclusive estimates averaged across the entire country or focus on regional temperature variations and their heterogeneous impact on specific areas or countries in SSA to overcome these downfalls.

Policy Implications

The previous results have suggested that temperatures have been rising significantly relative to their historical averages. These temperatures have had significant global impacts, particularly for hotter and developing countries. Next, results must be used as an evidence-base to extract important policy implications. Adaptation to climate change is regarded as a significant future issue, requiring a global effort to contain GHG-emissions consistent with a manageable increase in temperatures to limit any potential long-term impacts of climate change (IMF, 2015; Stern, 2015; Farid et al., 2016). These adaptation-policies are even more significant for developing economies that will face increasing strain on domestic budgets as governments are forced to channel resources away from growth and productivity-enhancing projects, towards countering the costs of damage from extreme temperature variability and reconstruction efforts (Hallegatte, Dumas, & Hourcade, 2010; Wade & Jennings, 2016).

While multiple domestic policies including carbon taxation (Metcalf & Notes, 2008; Covington & Thamotheram, 2015) and investment into sustainable energy (Wade & Jennings, 2016) have been suggested to limit anthropogenic GHG-emissions that significantly influence climate change, more global policies such as international environmental agreements should also be proposed given the disproportionate impact developed-country emissions have had on the developing world (Schelling, 2000). The United Nations Framework Convention on Climate Change established the Paris Agreement (2015) obliging both developed and developing countries to reduce emissions in high-emission industries to reduce emissions. Recent estimates suggest a decline in developed emissions following more stringent mitigation policies (Kim, 2019). Regardless of which policies are adopted, GHG-emissions' abatement must be a worldwide-effort that fosters sustainable development to reduce climate change's detrimental impact on the global economy.

Conclusions

This paper aimed to analyse the variability in global temperatures over the last half-century and estimate the asymmetric impact on developing countries. Utilising innovative ARDL models for an 84-country sample of OECD and SSA countries between 1970–2018, I found that temperatures have unanimously increased for all sample-countries and that variations in temperature above historical norms significantly reduced income-growth across the entire sample. Most importantly, I found that temperature variations disproportionately affected hotter, poorer SSA countries. However, the study also found some original results. Firstly, OECD countries' temperatures have increased more quickly relative to their historical norms than SSA-countries. Secondly, while poorer and developing countries are more adversely affected by temperature variations, they seem to recover more rapidly from temperature shocks than sample averages. Concurring with the literature, I found no evidence that precipitation impacts long-run income-growth.

This study offers multiple additions to the literature. Using ARDL models, this paper better encapsulates both regional and country-specific heterogeneity between effects while also implementing an updated dataset. Moreover, utilising temperature anomalies and AIC specifications overcame previous papers' methodological downfalls. However, caution should be taken when extrapolating results as using temperature anomalies with larger historical norm averages may have significantly underestimated the impact of climate change. Further studies should consider the suitability of AIC, making a comparison between models difficult and inconsistent. Future research could also build on this paper's foundations by potentially looking at the impact of regional-specific climate shocks on SSA, given the dataset's great spatial-dimensions.

This topic is interesting and incredibly important, given its paradoxically disproportionate effect on developing countries and its potentially devastating unmitigated effects on the entire globe. While the analysis emphasised the impact of climate change on SSA, it also highlights that all countries feel the negative effects of unmitigated temperature increases. Going forward, all nations must consider the detrimental impact of climate change when creating policies towards their future development. With a global effort, combatting climate change may be the fundamental driver that fosters worldwide sustainable development.

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Макроэкономические последствия изменения климата для стран Африки к югу от Сахары: аргументы в пользу устойчивого развития

Айдын Сандалли

Аннотация. Несмотря на то, что изменение климата имеет серьезные глобальные последствия, считается, что они непропорционально сильно проявляются в развивающихся регионах с жарким климатом. В данной статье эти утверждения исследуются с использованием панельных данных для 84 стран ОЭСР и стран Африки к югу от Сахары в период с 1970 по 2018 г. В работе анализируется эволюция температур в конкретных странах, а также долгосрочное экономическое влияние колебаний температуры и осадков на ВВП на душу населения. Используя панельную модель авторегрессивного распределенного запаздывания, автор констатирует: поскольку отклонения температуры выше исторических норм произошли одновременно во всех исследуемых странах, то одномоментно и значительно здесь снизился и рост доходов. Никакой существенной связи между выпадением осадков и ростом доходов не обнаружено. При взаимодействии «бедных» и «жарких» стран автор обнаружил, что колебания температуры непропорционально сильно влияют как на более жаркие, так и на более бедные страны Африки к югу от Сахары. Температуры в странах ОЭСР росли быстрее по сравнению с их историческими нормами, чем в странах Африки к югу от Сахары. И хотя более бедные и развивающиеся страны больше страдают от колебаний температуры, они, похоже, быстрее восстанавливаются после температурных шоков, чем страны среднего уровня. Автор объясняет эти результаты и связывает их с потенциальными последствиями для политики в отношении глобального устойчивого развития и борьбы с выбросами парниковых газов.

Ключевые слова: Африка к югу от Сахары; изменение климата; ВВП на душу населения; снижение выбросов парниковых газов; колебания температуры

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Renewable Energy Consumption and its Main Drivers in Latin American and Caribbean Countries: A Robust Analysis Between Static and Dynamic Panel Data Models

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Abstract

This study examines the potential drivers of renewable energy consumption for 22 Latin American and Caribbean countries during 2005–2014. I use the sys-GMM method to deal with the presence of endogeneity, country-specific components and serial correlation within observations. Results confirm the dynamic behaviour of green energy consumption. Moreover, GDP per capita and CO_2 emissions per capita are the determinants of this clean energy source. The positive effect of per capita GDP implies that a non-depleting alternative source has been used to satisfy an increasing energy demand, which was experienced due to the acceleration of economic growth in the region. On the other hand, the negative effect of per capita CO_2 emissions reflects the weight that fossil fuels have in the energy mix. Because of some of the analysed countries' oil-producer nature, oil prices rise is not enough for a switch response.

Keywords: Renewable energy; Latin American and Caribbean countries; CO_2 emissions; panel data models

JEL Classification: C33, O13, O54, Q20, Q43, Q53, Q58

Introduction

Before 1973–1974, energy consumption rose at increasing rates in industrialised countries. After that, this factor's consumption growth evolved into moderate levels in virtue of the shock in real oil prices and the gradual decrease of global capitalist economies' economic growth rate. This phenomenon developed an interest in academia to start studying energy effects. First contributions are attributed to Hudson and Jogerson (1974) and Berndt and Wood (1975), who found that energy, as a production factor, substitutes labour while complements capital. Nevertheless, other scholars manifest that energy substitutes capital in the long-run (Griffin & Gregory, 1976). These debatable results gave foundation about the study of energy's performance in the economy. However, research has been more appealed to find causal relationships between energy and growth to comprehend whether energy conservation policies could affect economic levels. Following Kraft and Kraft (1978) seminal contribution, the debate about growth, conservation, neutrality, and feedback hypothesis emerged. Energy economics' research was guided toward that issue until in the last few decades, with the evidence of the hole in the ozone layer, climate change, global warming and the contribution of human activities in the generation of greenhouse gases (GHG), scholars developed an interest in renewable energy topics.

Since energy plays a fundamental role in economic development, and likewise, it has detrimental contributions to the environment through dirty emissions, adopting clean energy sources is indispensable. This decision can draw a path to sustainability in the following aspects: 1) Combating GHG emissions, 2) Giving support to the no-depletion of natural resources such as oil, natural gas and coal, 3) Lessening the impact of oil price volatility, 4) Offsetting the foreign exchange proportion due to oil imports, 5) Improving the living conditions of rural areas and job creations (Cardoso & Fuinhas, 2011; Ackah & Kizys, 2015). Therefore, understanding which factors drive renewable energy deployment is substantial. Empirical research has contributed to explaining the influence of economic growth, carbon dioxide (CO_2) emissions and oil prices, mainly. Most of the literature has focused on developed and industrialised countries. There are few studies about the determinants of green energy consumption in Latin America and the Caribbean (LAC) countries. To my knowledge, there is no research exploring this topic in the whole region.

Inspecting LAC context is appealing. Its environment could convince that renewable sources' share would exceed non-renewable ones. Nevertheless, its important role as oil producer makes this fuel as the main source of total primary energy supply (46 per cent), followed by natural gas (25.8 per cent), coal (6.9 per cent) and hydro-energy (6.2 per cent); other sources accounts for 15.1 per cent (CEPAL, 2019). Oil principal use is from transport and industrial sector, while its participation in power generation has been replaced by natural gas. By sub-region, energy mix differs in weight but, overall, oil predominates.

On the other hand, hydropower is highly employed in electricity. During the last decades, power generation has increased its contribution to the total final energy consumption (IRENA, 2016a). Its historical dependency on hydropower to produce electricity and the lower use of coal on it, which is the main fuel generator of CO_2 gases, set up LAC as the lowest fossil fuel-based global carbon emitter (IDB, 2000). However, hydropower generation has diminished in the response of droughts and natural gas expansion, positioning the latter as second in the power mix.

Transport and industry are the sectors with higher total final energy consumption (TFEC): 39 per cent and 35 per cent, respectively. Since 80 per cent of its population lives in cities, road transport demand has risen at increasing rates (IRENA, 2016a). As a result, dirty emissions continue growing since vehicles are mainly feeding by oil or natural gas. Furthermore, industries are significant for the region: During 2016, its contribution to GDP represented 32 per cent (IRENA, 2016a). From this sector, extractive industries are transcendent in LAC. The region is home to about 20 per cent of the proven world's oil reserves, with Venezuela and Brazil as the main endowed countries (IRENA, 2016a). If non-renewable sources remain to have a high share in TFEC structure, CO_2 emissions will continue growing. Dismayed by the environmental problems these would carry out, policymakers have intensified the implementation of low-carbon measures to promote renewable energy use since 2004. Hence, this question arises: Do CO_2 emissions trigger the consumption of renewable energy significantly?

Energy plays a vital role in the development of the region. Since the 2000s, its demand in LAC has risen at increasing rates due to rapid economic growth and increased population. Some countries have not been able to cover those requirements, challenging fossil fuels and power generation. Therefore, the necessity of diversifying traditional energy sources with renewables has heightened. Hence the following question arises: Does economic growth drive renewable energy consumption significantly in LAC?

Another point that may benefit renewables expansion is related to fossil fuel prices volatility. For instance, Central America has adopted renewable energy sources to deal with oil prices shocks. It conducts to question: Do fossil fuel prices determine renewable energy demand significantly in LAC?

Regarding green energy consumption, it excelled the global average in 2013, reaching participation of 27 per cent (IRENA, 2016a). Its favourable amounts have been due to the share of hydro-energy. However, it has been declining as mentioned. Expectations about other renewable energy sources are mainly related to resources endowments that some countries have — for instance, wind in Brazil, Argentina and Mexico, and biomass in Brazil. Regarding the first renewable case, its technology has been expected to be costly. However, costs have fallen due to auctions. This regulatory instrument has translated reductions in renewable prices in some countries, motivating to question: Do auctions significantly impact clean energy adoption, enhancing its consumption? It is worth mentioning that some studies (Vergara et al., 2013) suggest that green technology costs can be competitive with fossil fuels ones. However, others argue that renewable costs are more effective than non-renewable ones in the long run (Lazard, 2017).

Unquestionably, this energy's deployment is related mainly to policies to attract private investment since capital-intensive. LAC countries exposed to higher investment levels reveal liberalisation characteristics (i.e., Brazil, Chile, Costa Rica, Uruguay). Being opened allows the country to take advantage of technological transfer. Since technologies are transferrable, countries can acquire the *know-how* to innovate after that (Pueyo & Linares, 2012). Moreover, trade openness may represent benefits in energy supply/consumption due to the possibility of interconnection between countries. Therefore, this brings us to ask: Does trade openness generate a significant effect on LAC's renewable energy consumption?

Previous and other queries will be responded in this application, which aims to determine the factors that have significantly impacted the consumption of clean energy in LAC countries during the period 2005–2014. I execute a robust analysis between static and dynamic panels models to achieve this. The remainder of this study follows this structure: Section 2 reviews theoretical and empirical literature about energy consumption and renewable energy consumption, and announces my contribution to the literature; Section 3 exposes data and variables employed in the empirical model, discusses their respective hypothesis, and comments about the methodology; Section 4 evaluates results; Section 5 concludes, suggests about policies which might be implemented to stimulate green energy consumption, discloses about limitations, and ends recommending future works.

Literature Review

Theoretical Framework

It is fundamental to address the literature about conventional energy and its consumption to comprehend which factors may be related to renewable energy consumption.

Energy and production factors.

The relationship between economic growth and energy consumption has been covered widely. In the beginning, the aim was to discover whether there is substitutability or complementarity between the factors of production and energy. Initially, Hudson and Jogerson (1974) and Berndt and Wood (1975) led the research on this topic, finding that energy has a substitute effect on labour and a complementary effect on capital.

Because of methodological aspects, these results were questioned by Griffin and Gregory (1976). Assuming a twice-differentiable aggregate production function with capital (K), labour (L), energy (E) and materials (M) as inputs, and weakly separability condition [(K, L, E), M] due to unavailable information about material prices, scholars find short-run substitutability between energy, labour, and material, and complementarity between energy and capital. Yet in the long run, energy and capital substitution effects emerge.

Griffin and Gregory (G-G hereafter) justification relies on "(...) *in the long run, the use of new equipment to achieve higher thermal efficiencies in an industry may represent substantial capital costs*" (p. 846). Judging the previous argument as misleading due to the omission of material inputs in the model, Berndt and Wood (1979) reconfirm the complementarity between capital and energy. They show that they have not controlled for the material explains biased conclusions from G-G since results indicate "*gross substitution elasticities instead of net elasticities*" (p. 349).

Previous investigations gave insight into the role of energy. However, the focus in energy economics literature has been causal relationships between energy consumption and economic growth. Since profound implications could be derived from the direction of the relationship between energy consumption and economic growth, it has originated interest in the literature to be documented theoretically and empirically. If a predicted causal effect from energy consumption to economic growth is corroborated, any repercussion in energy could generate social welfare issues. The previous assumption results from the *growth hypothesis*, and it continues being the reason for several debates in energy economics.

The growth, conservation, neutrality and feedback hypothesis.

Since the late 70s, scholars have explored the relationship between energy consumption and the level of economic activity. Kraft and Kraft (1978) realised a seminal study about this concern. Having inspected the US context for the post-war period 1947–1974 and applying Sims' causality test (1972), they conclude about unidirectional causality from the gross national product (GNP) to gross energy consumption (GEI), and not from GEI to GNP. That means, an economic activity might influence on energy consumption, but not vice-versa. Evidencing a *conservation hypothesis*, authors argue that energy conservation policies may not endanger the country's economic activity since the economy is not energy-dependent. Upon the Granger-causality framework, the *conservation hypothesis* is evidenced when real GDP increases cause increases in energy consumption (Payne, 2010). Hence, any adverse shock on GDP may negatively impact energy consumption.

Given Kraft and Kraft (1978) judgement, other scholars were interested in evaluating previous conclusions. Akarca and Long (1980) question the period employed by Kraft and Kraft (K-K hereafter) since it does not include meaningful events, as the two World Wars, which may impact US economic condition. Moreover, Akarca and Long (1980) argue that during 1973–1974 there was an acceleration in energy prices because of the oil embargo. Changing by two years the data used by K-K, researchers conclude no causal relationship between GNP and GEI. With this, another scenario results: the *neutrality hypothesis*. In this scheme, energy consumption would not generate significant economic growth impacts since this factor is a small component of real GDP (Payne, 2010). Hence, expansive or conservative energy policies do not produce repercussions in economic growth since they do not influence each other (Ozturk, 2010). The *neutrality hypothesis* holds when no-causal relationships between real GDP and energy consumption is evidenced.

Two opposite findings open the debate about whether economic level influences energy consumption, or in fact, there is no short-run association. To contribute to that, Yu and Hwang (1984) review the causality from GNP to GEI, using US updated data for the same K-K analysis period. Although both variables are highly correlated, causality tests produce evidence of no-causal linkage within the US context. Likewise, Yu and Choi (1985) support the *neutrality hypothesis* in the US. However, other countries analysed evidence causal linkage: from GNP to total energy consumption in South Korea, and from total energy consumption to GNP in the Philippines. The literature references this latter causality as the *growth hypothesis*.

Regarding growth hypothesis, energy consumption has a key role in economic growth directly, and indirectly as a complement of production factors (Ozturk, 2010; Payne, 2010). Hence, energy deficiencies may affect economic growth, while improvements may enhance it. Testing for the *growth hypothesis* is fundamental because policymakers need to know whether a specific policy will threaten the economy. Upon the Granger-causality framework, the *growth hypothesis* is evidenced when energy consumption increases cause increases in real GDP. Thus, if energy consumption Granger-causes economic growth, stringent policies which seek to protect the environment might discourage the economic level, another theorem, the feedback hypothesis, indicates that energy consumption and economic growth influence each other and might perform as complements. (Payne, 2010).

A final re-examination about the causal relationship between GNP and energy consumption in the US was done by Abosedra and Baghestani (1989). They reconfirm unidirectional causality from GNP to GEI, rejecting observations from Akarca and Long (1980), Yu and Hwang (1984), Yu and Choi (1985). Authors work with the same period used by previous scholars. According to Abosedra and Baghestani (1989), their conclusions are mistaken due to a possible methodological error.

Some research continued extending (Erol and Yu, 1989; Yu et al., 1988). Nevertheless, the literature has not attained a consensus. One explanation about the discrepancy of the results lay on the econometric techniques. Most of the estimations were conducted applying OLS, making inferences without contemplating the data's time series properties (Huang et al., 2008). Therefore, spurious regressions could prevail, producing misleading results (Granger and Newbold, 1974). The empirical literature has reinforced the hypothesis test of relationships between energy consumption and economic growth with the improvement of statistical methods in time series and panel data.

Empirical Literature

Energy consumption.

Although advanced econometric tools have improved results, it does not evidence consensus about the causality direction. The economic development within countries can explain the remained divergence in conclusions, energy consumption (EC hereafter) patterns, periods analysed, model specifications, methodologies and omitted variables problems (Payne, 2010; Apergis & Tang, 2013).

For instance, Chontanawat et al. (2008) continued working with bivariate models, employing the Johansen-Juselius technique to study 100 countries during 1976–2000. They find long-run causality from energy to per capita GDP for most OECD-developed countries compared to non-OECD-developing countries. Hence, energy-conservation policies may affect more OECD-developed countries growth than non-OECD-developing countries growth. Similarly, Soytas and Sari (2003) use Johansen-Juselius to study the relationship between EC and GDP per capita in G7 countries and top 10 emerging markets (excluding China), during 1950–1992. Unlike Chontanawat et al. (2008), their results confirm long-run unidirectional causality from EC to GDP per capita for Turkey and France. Additionally, they identify long-run unidirectional causality from per capita GDP to EC for Italy and Korea; and long-run bidirectional causality for Argentina.

To lessen omitted variable bias issues, scholars started working with trivariate models. Salim et al. (2008) cover six non-OECD Asian countries to evaluate the dynamics between EC, GDP and a proxy of energy prices. From their results, Bangladesh does not evidence any causal linkage while Malaysia exhibits long-run bidirectional causality between GDP and EC; India and Pakistan have long-run causality from EC to GDP while Thailand from GDP to EC. Controlling for the same factors, Asafu-Adjaye (2000) finds long-run causality from EC to GDP per capita in India and Philippines; no long-run effect on EC in Indonesia; long-run bi-directional causality between EC and GDP per capita in Thailand. On the other hand, Mishra et al. (2009) control urbanisation since EC may increase due to connections to the grid. Taking the Pacific Island countries as an economic framework and using dynamic ordinary least square (DOLS) estimator, scholars show that per capita GDP and urbanisation have positively influenced EC for the whole panel. I predisposed empirical literature to apply time series approach to examine relations between EC and GDP per capita. However, most studies work with samples size around thirty, which has low statistical testing power (Huang et al., 2008). Hence, inconsistency could be contemplated, and with that, the disparity in conclusions. For that reason, recently, scholars have proposed implementing alternative techniques such as dynamic panel data. Moreover, they have contemplated financial variables as potential determinants of EC.

Sadorsky (2011) and Çoban and Topcu (2013) indicate that EC could be fostered by financing factors through credits, for example. In Sadorsky's model, financial development is discriminated between banking and stock market variables. He uses four banking and three stock markets regressors to capture their partial effect on the predicted variable. Contrarily, Çoban and Topcu (2013) apply the Principle Component Analysis to detect banking and stock markets' aggregate effects. Sadorsky (2011) finds that EC is strongly determined by its previous level, and — unexpectedly — that GDP per capita does not influence it.

Regarding banking covariates, liquid liabilities, financial system deposits, and deposit money bank assets impact EC. However, the stock market turnover ratio is the unique stock regressor which enhances EC in his sample of nine Central and Eastern European countries. On the other hand, Çoban and Topcu (2013) do not achieve significant effects from financial indicators when they analyse the model for EU countries as a whole. Significance from banking and stock markets regressors are acquired when authors divide the model into old and new EU members. For old members, lagged-energy consumption, GDP per capita and both financial indicators evidence positive causal effect on EC. For new members, banking and stock markets variables do not present significant impacts. Hence they estimate non-linear relationships. This latter confirms that the stock index is not a driver for EC in EU countries.

Renewable energy consumption and its drivers.

The empirical literature has explored EC extensively since the 70s. Nevertheless, the determinants of renewable energy have been studied narrowly. The causal analysis for renewable energy consumption (REC hereafter) has intensified during the last decades due to the global warming problem's awareness. According to "Mitigation of Climate Change" Report (IPCC, 2007), "*the energy* *supply sector is the responsible for the largest growth of GHG emissions, with increments of 145% between 1970–2004"*. Stern (2006) states that adopting clean energy technologies is necessary to counterbalance GHG emissions effects. Otherwise, there would be repercussions in economic growth. These judgements guided researches to green energy consumption evaluations.

The literature started testing causal relationships between REC and economic growth using bivariate/trivariate models. Sadorsky (2009a) gives one of the leading contributions. Working with G7 countries, researcher finds mostly similar estimators applying fully-modified ordinary least square (FMOLS) and DOLS. Specifically, rising 1 per cent GDP per capita generates increments about 8.44 per cent and 7.25 per cent in REC according to FMOLS and DOLS, respectively. Moreover, CO_2 emissions per capita evidence similar significant elasticities among techniques. However, the effect of oil price is small-negative but significant in DOLS while insignificant in FMOLS. From the error correction model (ECM), his main conclusion is that the time to return to the equilibrium can diverge considerably among countries. In another study, Sadorsky (2009b) predicts the relationship between REC and GDP per capita, in eighteen economies (some LAC countries such as Argentina, Brazil, Chile, Colombia, Mexico, Peru, are considered). For countries with available information about electricity prices, he also analyses its long-run association with REC. Likewise, GDP per capita is a highly important predictor. Therefore, modest adjustments on it might generate substantial impacts on REC. Furthermore, ECM estimations expose that GDP per capita responds to adjustments back to the equilibrium level, while electricity prices do not.

Because of cross-sectional dependence and structural breaks, Salim and Rafiq (2012) apply Westerlund cointegration technique to identify a long-run relationship between the same variables examined by Sadorsky (2009a). According to FMOLS and DOLS results, income elasticities, in the long run, are 1.23 per cent and 0.20 per cent, respectively, and carbon-dioxide elasticities are 0.03 per cent and 0.13 per cent, respectively. Unlike other studies, authors apply ARDL technique individually to examine short-run causality for Brazil, China, India, Indonesia, Philippines, and Turkey. They conclude that CO_2 emissions per capita are a determinant of REC in almost all countries, excepting for Philippines and Turkey. However, in these countries, income is the principal long-run determinant of REC. Regarding oil prices, it does not evidence significant influence in any examination.

Studying six Central American countries, Apergis and Payne (2011) analyse REC, GDP, gross fixed capital formation and labour, identifying positive long-run relationships between the variables.[1] Authors also find short-run and long-run bidirectional causality between REC and GDP. Similarly, in another study of eleven South American economies, Apergis and Payne (2015) reveal bidirectional causality between REC and GDP per capita in the short and long run. Additionally, they detect a positive long-run relationship between GDP per capita, CO_2 emissions per capita, oil prices and REC.

Besides standard factors such as CO_2 emissions per capita and fossil fuel prices, scholars start evaluating other possible predictors. Moreover, the literature considers additional econometric techniques. For instance, Marques et al. (2010) employ fixed effects with vector decompositions methodology to avoid drops of country-specific components such as geographic dimension. This variable is relatively time-invariant since its size does not change drastically year by year. Besides, it is expected to impact the use of renewable energy according to the country's production potential. That means the geographically extensive the country is, the more production potential and use of renewables.

Additionally, they control for energy import dependency. Estimating three models (all countries, non-EU members and EU members), their main finding is that CO_2 emissions per capita have significant negative impacts on renewable energy usage, in all outputs. Moreover, energy import dependency presents a direct effect in almost all the models; GDP impacts positively in EU members, but negatively in the non-members; oil prices encourage the consumption of non-renewables for EU members instead of driving the use of renewable energy while in non-EU members it has a non-significant impact. Finally, natural gas prices positively affect renewable energy usage in all countries.

[1] Gross capital formation is applied as proxy of capital stock.

One of the limitations to exploit clean energy sources is technology costs during the initial stage. However, costs have been diminished with the support of some regulatory instruments such as feed-in-tariff and auctions, or by financial aid from governments in the R&D phase. According to Johnstone et al. (2010), public policies enhance renewable energy innovations. Moreover, technology improvements may close the cost gap between renewable and non-renewable, making it feasible to develop clean energy sources. Because of this, Popp et al. (2011) examine the impact of the innovative process through feasible generalised least squares technique. Using the OECD patent database as a measure of the technological frontier to evaluate its influence on renewable energy investment and control other non-standard factors such as feed-in-tariff, renewable energy certificates and Kyoto ratification, authors find that innovations have a positive but small effect. Indeed, Kyoto commitment evidences a larger impact on renewable investment in 26 OECD countries during 1990–2004.

Furthermore, researchers have applied econometric techniques dealing with endogeneity produced by variables which were not strictly exogenous. Since it has been evidenced empirically that current EC levels are influenced by its past levels (Sadorsky, 2011; Nayan et al., 2013), literature has assessed renewable drivers upon a dynamic approach. For instance, Cardoso and Fuinhas (2011) control several factors that potentially determine renewable energy contribution in 24 European countries. Besides the usual variables, energy consumption, nuclear power share to electricity generation, and energy import dependency are controlled. They estimate three dynamic models (diff-GMM, sys-GMM and least squares dummy variable corrected), with outputs not differing substantially by estimation. Results from these variables are: 1) renewable energy use from previous period determines the current one, 2) increases in energy consumption forces to exploit alternative energy sources to satisfy energy needs, 3) nuclear power as inputs of energy production lessen the development of renewable energy because of lobbying effect, and 4) high energy imports reduce renewables commitments since countries have lower resources available to develop clean sources. Moreover, GDP, fossil prices and CO_2 emissions per capita evidence unexpected results: the formers present non-significant effects on the predicted variable while the latter negatively impact renewable energy contribution.

Omri and Nguyen (2014) continue studying the standard determinants of REC but incorporating trade openness as control variable since it can drive REC through income improvements. As part of robustness analysis, they segregate their sample between high-income, middle-income and low-income groups. Their model is estimated in growth form due to the non-stationarity of their data. Sys-GMM results suggest that CO_2 emissions per capita are the main driver of REC, being positive significant in four models (global panel and the three income level panels). Moreover, current REC is influenced by its previous value. Other predictors vary according to the model. For example, oil price presents significant negative effects in middle-income and global panel. Simultaneously, per capita GDP and trade openness are positive in the high and middle-income panel, and low-income and global panels, respectively. In another study, Omri et al. (2015) contrast the estimations between static and dynamic panels, showing that the former approach is not suitable due to autocorrelation in residuals. Likewise, their model is estimated in growth form. Under dynamic panel data methodology, they discriminate between diff-GMM and sys-GMM. The lagged-variable confirms a persistent effect in REC.

Unlike their previous paper, oil prices do not evidence a relevant effect in most panels. Trade is only significant in low- and middle-income and the global panel. CO_2 emissions per capita and GDP per capita are the main drivers, presenting significant positive effects in their four models. Akar (2016) apply sys-GMM to explore the determinants of REC in the Balkans. Unexpectedly, the author finds that per capita GDP has a negative highly significant impact on REC, which suggests that Balkans development does not lead to the higher costs of technology that require the adoption of clean energy. Trade openness and natural gas prices influence positively on REC. Moreover, the dynamic effect of REC is corroborated.

Elements that boost economic growth may contribute to the deployment of green energy. For instance, capital stock and labour force are input factors that might affect the predicted variable through GDP.[2] Therefore, controlling for them is rational, as Ackah and Kizys (2015) have done. Seeking to determine the causal effect on REC in African countries, they also include human capital and energy depletion as predictors. More educated people are more aware of environmental issues, and energy deficits would seek alternative sources, respectively. Their results from contrasting between random effect and sys-GMM do not diverge: the main drivers for REC are per capita carbon-dioxide emissions and energy depletion. An excellent outcome is produced by capital since its effect changes from positive to negative when this variable is regressed jointly with the other regressors. A plausible explanation is that other determinants lessen its impact. Furthermore, dynamic regressor is significant in the model.

From the previous causal studies performed on this topic (Berk et al., 2018), two novelties have to be recognised. Firstly, the inclusion of FDI inward stock regressor in the model. Controlling for this indicator is reasonable given that FDI may prompt the predicted variable through allowances on financial capital, which might support investments in renewables. Secondly, the convergence speed analysis of renewables has not been considered in previous REC literature. Authors contrast between unconditional and conditional convergence examination. That means, regressing the lagged variable on the predicted variable (unconditional), and regressing the predicted variable against the lagged and control variables (conditional). Having control for all predictors (FDI inward stock, CO_2 emissions per GDP in the previous period, electricity prices) authors find that the magnitude of the lagged-value coefficient is reduced, which means a fast convergence of renewables share in primary energy consumption in European countries. Although not all the control variables are significant jointly, the result lays on the strength that additional regressors produce on the sys-GMM instrument set (Hoeffler, 2002).

Contribution to the Literature

The empirical literature has advanced gradually applying different tools to determine which factors influence on REC. It has evolved from panel cointegration techniques to static panel data, and ultimately dynamic panel data. Nevertheless, there are still some improvements that must be done upon the latter approach. Most of the studies conclude the validity of their results after testing for no-autocorrelation and over-identifying restrictions.

However, information about the number of instruments, and the instrument variables selected with their respective number of lags, are not usually reported. Some researchers present their choices between static panels and dynamic panels, but a minority exhibits their discrimination between one or two-step estimation, or among diff-GMM and sys-GMM. According to Roodman (2006), these details must be shown to reduce false-positive results. Therefore, my main contribution to this application is to perform a robust analysis, following previous advice.

Moreover, the tendency to determine causal relationships/effects on REC is distinguished: explore usual factors (GDP, CO_2, oil prices); segregate between high, middle, low-income countries; work with European, OECD or industrialised countries as the framework. In this study, I also contemplate to contribute with these aspects: 1) Using LAC countries as economic context, and 2) controlling for additional factors which have not been examined widely in previous literature.

Data and Variables, and Methodology

Data and Variables

Data description.

In this study, a balanced panel of 22 LAC countries is used. It contains information about renewable energy consumption, real GDP per capita, real oil price, real natural gas price, CO_2 emissions per capita, trade openness, real gross capital formation (GCF) per capita, auctions adoption, and Kyoto commitment.[3]

Real oil and natural gas prices were constructed deflating the West Texas Intermediate (WTI) and Henry Hub spot price by US consumer price in-

[2] Scholars use gross capital formation as proxy of capital stock.

[3] The available free data of renewable energy consumption of LAC countries express this variable in percentage terms. Literature (Carley, 2009; Marques et al., 2010; Akar, 2016) has worked with the dependent variable in that unit of measurement. GDP and GCF are measured in constant 2010 USD. GCF is a flow variable; it does not represent capital stock (Lee et al., 2008). Following Akar (2016), trade openness sums up total exports and imports, measured as share of GDP.

dex (2010 = 100).[4] WTI prices are used since the framework of this study is LAC countries. Besides, it has been employed extensively in previous research to represent world crude prices. Since all the economic variables are measured in dollar USD, the country's conversion to specific oil and natural gas prices is not compulsory. Furthermore, GCF is converted to per capita terms dividing it by the respective population.

The dataset, which covers the period 2005–2014, was set up with information acquired mainly from World Bank Development Indicators (WDI), except for oil and natural gas prices, auctions and Kyoto, whose statistics were collected from Bloomberg terminal, IEA/IRENA Joint Policies and Measures database, and United Nations Treaty Collection website, respectively.[5]

The sample contains the following LAC countries (Table 1): Argentina, Bahamas, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Mexico, Nicaragua, Panama, Paraguay, Peru, Uruguay and Venezuela. Because of lack of data, Barbados, Grenada, Guyana, Jamaica, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago were omitted from the analysis.

Table 2 displays the descriptive statistics of the variables across countries over time. Regarding the share of REC, the sample average is 33 per cent roughly. Its dispersion is by 20 per cent around the mean, varying from consumption levels from 0.84 to 83.16 per cent. About GDP per capita, it indicates an average of 7,088.23 USD. The economic performance heterogeneity is reflected in the region, varying from 665.63 USD to 31,632.45 USD. Another indicator that evidences a meaningful distance between the highest and lowest value is GCF, ranging from a minimum amount of 168.27 USD to a maximum of 11,679.63 USD, with a deviation from the mean of 2,026.82 USD on average. As reported by emissions, LAC countries show an average of 2.34 metric tons per capita over time, without vast disparity across countries. Due to the global recession, the fall in oil price is documented in the dataset, being the minimum value (45.17 USD per barrel).

Table 1
*Classification of countries**

Sub-Region	No. Countries	Countries
Central America	8	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
Caribbean	4	Bahamas, Cuba, Dominican Republic, Haiti
South America	10	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Peru, Paraguay, Uruguay, Venezuela

* Although Mexico belongs to North America geographically, some states are located in Central America region.

Moreover, real natural gas does not deviate substantially from their mean, with approximately 3 USD. About trade openness ratio, it seems that some areas of the region have been more integrated into the world economy than others. Overall, it suggests that LAC countries have been exposed to international trade. Ultimately, auctions' policy variable shows that it was not widely implemented in LAC (29 per cent on average). In comparison, the commitment to environmental performances has been ratified by 81 per cent of the sample.

Intending to inform which LAC countries lead some analysis factors during 2005–2014, Table 3.3 exhibits a ranking according to the average of each variable by country. Bahamas shows high levels of per capita GDP, CO_2 emissions and GCF.

However, it presents the lowest demand for REC over the period.[6] These results may suggest a limited relationship with REC. Paradoxically, Haiti and Paraguay, which were the countries with higher REC are listed as the lowest CO_2 emitters, anticipating an indirect relationship between these factors. Regarding trade openness, it does not hint about its relation with REC.

[4] CPI data was acquired from WDI.

[5] Initially, the time of analysis was decided from 2000 to 2016. However, the time horizon was narrowed due to the unavailability of data for all the countries.

[6] Venezuela ranked as the second highest GDP per capita in the region is due to the period of analysis, which is before its economy contraction. This country intensified its economic crisis with the fall in oil prices during 2014 (OPEC, 2019).

Table 2
Summary statistics

Variables	Mean	Std. Dev.	Min.	Max.
Renewable energy consumption (% total final energy consumption)	32.875	20.059	0.844	83.161
GDP per capita (constant 2010 USD)	7,088.228	6,163.889	665.627	31,632.450
CO2 emissions (metric tons per capita)	2.336	1.582	0.213	7.427
Real oil price (USD per barrel)	77.654	18.663	45.170	100.939
Real natural gas price (USD per million BTU)	5.568	2.846	2.661	12.533
Real gross capital formation per capita (constant 2010 USD)	1,782.666	2,026.821	168.267	11,679.630
Trade openness (% GDP)	70.726	29.960	22.106	166.699
Auction (dichotomous)	0.286	0.450	0	1
Kyoto (dichotomous)	0.814	0.390	0	1
No. Observations	220	220	220	220

Source: WDI, Bloomberg terminal, IEA/IRENA Joint Policies and Measures database, United Nations Treaty Collection website.

Variables and hypothesis.

This study's variables are included due to economic theory, previous literature, and data availability.

Renewable energy consumption (REC): Historically, LAC has utilised considerable amounts of hydropower to produce electricity. Nevertheless, its share has diminished over time, while fossil fuel share has increased, and emissions levels have increased. Furthermore, energy consumption has expanded during the last decades due to population growth and the development of its economy, exceeding even the quantities demanded from OECD countries (IDB, 2000). These facts develop a concern about the relevance of promoting regenerative energy sources. This variable is regressed against a vector of explanatory/control variables to determine which factors may influence renewable consumption. In this study, REC is measured as the percentage of total final energy consumption.

Continuous consumption of renewable energy (REC_{t-1}): As suggested by Cardoso and Fuinhas (2011), the use of renewable energy is a continuous process since it depends on meaningful investments done to supply it. Moreover, the production of energy would require a stable level of demand. Hence, I expect that REC_{t-1} has a positive and significant impact on the dependent variable. The hypothesis to be tested is:

H_1 – *Renewable energy consumption is positive affected by its previous value*

GDP per capita (Y): GDP is commonly implemented in this literature since it keeps the relationship with energy consumption, is a proxy of income and a growth measurement. Scholars have found that increases in per capita GDP positively affect the consumption of clean energy since countries have more resources to afford the higher technology or regulatory costs (Sadorsky, 2009b; Apergis & Payne, 2011). Furthermore, economic growth implies more demand for energy, leading to the use of renewable sources to satisfy it. For that reason, I expect a significant positive relationship between per capita GDP and the dependent variable. The hypothesis to be tested is:

H_2 – *GDP has a positive significant effect on renewable energy consumption.*

It is worth mentioning that this regressor is not strictly exogenous because of the following reasons: Literature has proved that GDP determines renewable energy consumption (i.e. Omri et al., 2015; Akar, 2016). Likewise, literature has evidenced that renewable energy consumption drives economic growth (i.e. Inglesi-Lotz, 2016; Amri, 2017).

Carbon-dioxide emissions per capita (CO_2): During the process of energy production, fossil fuels are burned, emitting toxic gases to the environment like CO_2, which is the main responsible for

Table 3
Ranking of countries according to indicators, period 2005–2014

Country	REC	Country	GDP	Country	TO	Country	CO2	Country	GCF
Haiti	78.402	Bahamas	29,517.94	Panama	145.438	Venezuela	6.210	Bahamas	9,832.539
Paraguay	65.216	Venezuela	14,083.45	Belize	122.305	Bahamas	5.282	Venezuela	3,230.321
Guatemala	61.545	Chile	12,939.34	Honduras	121.947	Argentina	4.499	Panama	3,146.191
Nicaragua	52.318	Uruguay	11,546.97	Nicaragua	98.082	Chile	4.343	Chile	2,971.688
Honduras	51.298	Argentina	10,046.00	Bahamas	84.575	Mexico	4.141	Uruguay	2,315.518
Uruguay	46.032	Mexico	9,494.83	Bolivia	77.917	Cuba	2.826	Brazil	2,253.547
Brazil	45.743	Panama	8,243.70	Costa Rica	76.240	Ecuador	2.415	Mexico	2,123.628
Costa Rica	40.992	Costa Rica	8,085.31	Paraguay	75.752	Panama	2.378	Argentina	1,716.798
El Salvador	33.910	Colombia	6,392.25	El Salvador	75.655	Uruguay	2.134	Costa Rica	1,567.036
Belize	33.422	Cuba	5,583.82	Chile	70.804	Brazil	2.126	Colombia	1,371.858
Chile	30.102	Dom. Rep.	5,417.49	Haiti	65.227	Dom. Rep.	2.115	Dom. Rep.	1,339.856
Peru	29.334	Peru	4,964.75	Guatemala	62.434	Costa Rica	1.698	Ecuador	1,309.569
Colombia	27.615	Ecuador	4,755.33	Mexico	60.772	Peru	1.660	Peru	1,105.523
Panama	23.702	Belize	4,415.92	Ecuador	60.242	Colombia	1.603	Belize	896.985
Bolivia	20.080	Bolivia	4,339.11	Dom. Rep.	58.559	Bolivia	1.580	Paraguay	887.660
Cuba	18.436	Paraguay	4,193.83	Uruguay	55.747	Belize	1.572	Cuba	609.209
Dom. Rep.	17.826	El Salvador	3,025.50	Venezuela	53.339	El Salvador	1.066	El Salvador	585.255
Venezuela	13.646	Guatemala	2,840.76	Peru	51.825	Honduras	1.040	Honduras	509.290
Ecuador	12.978	Brazil	1,959.87	Cuba	40.906	Guatemala	0.887	Guatemala	468.511
Mexico	9.491	Honduras	1,910.72	Colombia	37.707	Nicaragua	0.803	Nicaragua	454.411
Argentina	9.427	Nicaragua	1,557.75	Argentina	35.483	Paraguay	0.772	Bolivia	340.650
Bahamas	1.735	Haiti	703.17	Brazil	25.008	Haiti	0.233	Haiti	182.610

REC = renewable energy consumption; TO = trade openness; GCF = gross capital formation. *Source:* WDI.

global warming. Because of the apprehension about climate change, and the necessity to diminish pollution and contribute to sustainable development, countries could be triggered to adopt pro-environmental actions such as promoting clean energies. From empirical studies, it has been found that CO_2 emissions per capita drives green energy consumption (i.e. Sadorsky, 2009a; Salim & Rafiq, 2012; Omri & Nguyen, 2014). Nevertheless, Marques et al. (2010) and Cardoso and Fuinhas (2011) have found negative impacts, concluding that higher emissions levels lessen its use. However, I expect a positive effect from this explanatory variable. The hypothesis to be tested is:

H_3 – CO_2 *has a possitive significant effect on renewable energy consumption*.

Moreover, the empirical literature has evidenced that renewable energy affects significantly carbon-dioxide emissions (i.e. Shafiei & Salim, 2014). Therefore, CO_2 is judged to produce endogeneity in the model.

Oil price (ROP), Natural gas price (RGP): Oil and natural gas are categorised by IEA such as non-renewables because they arise from the buried remains of plants and animals. Renewable sources are considered substitutes of non-renewables in the production of energy. Furthermore, prices of energy produced by fossil fuels are lower than the price of renewable energy because the formers do not internalise social damage. It would be expected that increments in fossil fuel prices could influence to reduce their use and promote renewable energy demand, ceteris paribus. However, a consensus has not been evidenced since some literature confirms a significant positive influence of oil prices (i.e. Apergis & Payne, 2015) while others state negative or non-significant effect (i.e. Sadorsky, 2009a; Omri & Nguyen, 2014). The two respective hypothesise to be tested are:

H_4 – ROP *has a possitive significant effect on renewable energy consumption.*

H_5 – RGP *has a possitive significant effect on renewable energy consumption*.

Since quantities and prices emerge from the equilibrium of demand and supply, outcomes arise from the dynamic market process. Changes in fossil fuel prices generate changes in renewable energy consumption. Changes in the demand for renewable energy could contribute to adjustments in fossil fuels' price due to future demand expectations. Hence both covariates are judged to produce endogeneity.

Trade openness (TO): Renewable energy technologies are transferrable across countries (IRENA, 2016b). Being exposed to international trade allows the country to the possibility of technological transfer, which may represent improvements in renewable energy deployment. Furthermore, foments in economic growth due to being opened could represent opportunities to attract more foreign investment (FDI) and develop renewable energy sources. Therefore, I expect a positive impact on the dependent variable. Indeed, there is confirmation about its positive influence on green energy consumption (i.e. Omri et al., 2015). The hypothesis to be tested is:

$H_6 -$ TO *has a possitive significant effect on renewable energy consumption.*

This regressor could be a source of endogeneity because of the omission of a variable correlated with TO and determines clean energy use, for instance, energy conservation policies. This factor could affect trade openness in two ways: 1) by export side: conventional energy is required during the process of production and transportation of goods, hence promoting the reduction of energy modifies operative mechanisms which could shrink exportable amounts, 2) by import side if foreign commodities are energy-intensive (Sadorsky, 2012). Further, energy conservation policies could impact the dependent variable. Given that conventional energy consumption is lowered, they induce the adoption of alternative sources to satisfy the increasing energy demand.

Investment in capital per capita (GCF): This explanatory variable may trigger the adoption of renewable energy consumption since it could positively affect the production capacity of this energy source. Ackah and Kizys (2015) have found that increases in gross capital formation promote clean energy consumption when this variable is regressed individually on renewable energy consumption. When renewable energy consumption is regressed against the gross capital formation and other covariates, the effect is negative. Nevertheless, I anticipate a positive effect on the predicted variable. The hypothesis to be tested is:

$H_7 -$ GCF *has a possitive significant effect on renewable energy consumption.*

Capital investment might keep relation with renewable energy consumption growth or expectations about its future demand. Given that investors need confidence before investing, they may evaluate demand's evolution to seek whether consumption levels justify the respective higher risks and costs. Hence it would not be expected that consumption affects investment during the same year. Therefore, I assume that GCF does not produce endogeneity in the model.

Furthermore, *auctions* and *kyoto* variables are considered as part of robustness. As reported by IRENA (2015), auctions are the most applied regulatory instrument in LAC to promote renewable energy.[7] Its implementation has created economic benefits like price competitiveness, local employment and industry development, and technologies. Moreover, the study exposes that Latin America is a pioneer and innovator in the design of auctions. Hence, this variable is included in the robustness process to explore whether it significantly impacts renewable energy consumption. It is treated as a dichotomous variable, taking the value of one when the policy was established. The hypothesis to be tested is:

$H_8 -$ *auctions have a possitive significant effect on renewable energy consumption.*

According to Johnstone et al. (2010), policies that induce innovations for developing renewable technology are enforced in some OECD countries because of Kyoto Protocol commitment. Moreover, Popp et al. (2011) find that renewable energy has risen after signing the Kyoto Protocol. OECD countries that invest more in technology are due to their commitment. Therefore, I consider Kyoto commitment as a part of the robustness exercise to verify its partial effect on renewable energy consumption. This regressor is a dummy variable, which takes the value of one when the country has ratified, accepted, acceded or approved the protocol. It is remarkable to comment that the first stage finished in 2012, however, some countries like Honduras, Mexico and Peru accepted in 2014 the Doha Amendment.

[7] The process of auctions is the following: project developers present a bid withelectricity price per unit. Governments take a decision upon some criterias such as prices, environmental requirements, technologies implemented. The winner signs a contract to be the renewable generator over a time period (IRENA, 2015, p. 12).

Therefore, these countries take the value of one in 2014. The hypothesis to be tested is:

H_9 – kyoto has a possitive significant effect on renewable energy consumption.

Methodology

In this study, static and dynamic approaches are employed to produce a robust comparison and verify their estimations' accuracy. Since dynamic panel models expunge the bias generated from the association between the lagged-dependent variable and the error and also deals with regressors which are not strictly exogenous, therefore, some authors implemented them recently to examine the determinants of renewable energy consumption (i.e. Omri et al., 2015; Cardoso & Fuinhas, 2011).

Static panel model.

Based on previous literature (Omri et al., 2015; Ackah & Kizys, 2015; Akar, 2016), Equation 1 is expressed as a function of the following variables:

$$REC = f\left(Y, CO_2, ROP, RGP, GCF, TO\right) \quad (1)$$

where REC indicates the consumption of renewable energy, Y GDP per capita, CO_2 carbon-dioxide emissions per capita, ROP real oil price, RGP real natural gas price, GCF gross capital formation per capita are measures of capital investment and TO trade openness.

Equation 1 is written in panel form as follows:[8]

$$\begin{aligned} \log REC_{it} &= \alpha + \beta_{i1}\log Y_{it} + \\ &+\beta_{i2}\log CO_{2_{it}} + \beta_{i3}\log ROP_{it} + \\ &+\beta_{i4}\log RGP_{it} + \beta_{i5}\log GCF_{it} + \\ &+\beta_{i6}\log TO_{it} + \mu_i + \varepsilon_{it}, \end{aligned} \quad (2)$$

where $i = 1,\ldots,N$ denotes the country, and $t = 1,\ldots,T$ the periods, μ_i captures country-specific non-observable effects, and ε_{it} represents the disturbance.

Variables in Equation 2 are converted in logarithm form since that helps deal with any issue arisen from the data's dynamic properties (Bhattacharya et al., 2016). Following Marques et al. (2010), a normality test for REC_{it}. It is measured in percentage terms and executed, indicating a skewed distribution (Appendix). Hence, it is recommendable to transform the regressor in logarithm to avoid biased and inconsistent results (Cameron & Triverdi, 2009).

To estimate Equation 2, I employ static panel data techniques. The country-specific non-observable effects μ_i could be fixed or random. If μ_i is assumed to be fixed, the correlation between this factor and regressors are presumed. It will generate biased results due to omitted variable issues. However, it is possible to obtain consistent estimators applying fixed effects (FE) model. FE disposes of those risks, operating such as transformation to dropping the regression's noisy component. If μ_i is assumed to be random, zero correlation between this factor and regressors are presumed. Under this approach, estimating Equation 2 by FE produces inconsistent results. The suitable is to apply random effects (RE) technique.

Although the model's feature could decide whether performing FE or RE, scholars generally apply both methods and select one of them after conducting a formal examination. Hausman (1978) developed a test to seek whether the coefficients of the time-varying variables evidence statistically significant differences. If the assumption sustained by RE about no correlation between the country-specific components and the regressors fails, this estimator will be inconsistent. FE is not affected because it does not rely on the previous assumption. A rejection of the null hypothesis states that both estimators are consistent, and being in favour of the alternative will be the conclusion, suggesting that FE is more suitable.

Dynamic panel model.

Nayan et al. (2013) explained that the current energy consumption level tends to follow the pattern of consumption from the previous period. Since the production process would require a continuous demand level, it could be expected an interdependence of renewable energy consumption. It implies a dynamic feature in the model. To represent it, Equation 2 is rewritten in the following form:

$$\begin{aligned} \log REC_{it} &= \alpha + \beta_i \log REC_{it-1} + \beta_{i1}\log Y_{it} + \\ &+\beta_{i2}\log CO_{2_{it}} + \beta_{i3}\log ROP_{it} + \\ &+\beta_{i4}\log RGP_{it} + \beta_{i5}\log GCF_{it} + \\ &+\beta_{i6}\log TO_{it} + \mu_i + \varepsilon_{it}, \end{aligned} \quad (3)$$

[8] Auctions adoption and Kyoto commitment are considered as part of robustness analysis.

where REC_{it-1} provides the impact of the one-period lagged value of renewable consumption in the model. The existence of the lagged-dependent variable displays the dynamic structure of the system. To estimate Equation 3 under a dynamic framework, the first step is to remove μ_i by first-differencing procedure:

$$\Delta y_{it} = \delta \Delta y_{i,t-1} + \Delta x'_{it}\,\beta + \Delta v_{it}; \qquad (4)$$

where $\Delta v_{it} = \left(\varepsilon_i - \varepsilon_{i,t-1}\right)$; y_{it} is the dependent variable and x'_{it} is a vector of regressors

Country-specific effects were eliminated because of the first-difference process. However, the transformation of the residual $\left(\varepsilon_i - \varepsilon_{i,t-1}\right)$ is by construction correlated with $\left(y_{i,t-1} - y_{i,t-2}\right)$ due to the association between $y_{i,t-1}$ and $\varepsilon_{i,t-1}$.

To estimate Equation 4, the difference and system generalised method of moments (diff-GMM and sys-GMM, respectively) can be implemented. Both procedures are devised to work accurate, dealing with: 1) lagged-dependent variable as the predictor, 2) independent variables which are not strictly exogenous, 3) fixed-effects components, 4) heteroscedasticity, 5) serial correlation within observations (Roodman, 2006, p. 4).[9]

Diff-GMM, introduced by Holtz-Eakin et al. (1988) and continued by Arellano and Bond (1991), considers the endogeneity arisen in Equation 4. Likewise, an endogeneity could emerge from the association between other regressors that are not strictly exogenous and $\varepsilon_{i,t-1}$. Hence, the utilisation of instruments is necessary to solve the problem. Since the method contemplates the challenge of finding good external instruments, it exploits internal instruments acquired using the levels of the regressors of Equation 4, lagged, as instruments. The crucial assumption for GMM estimators' validity is that those instruments must be exogenous, and that is satisfying because lagged variables are orthogonal to the disturbance (Roodman, 2006).

A shortcoming of the diff-GMM is related to unbalanced panel data. Since in that type of panels, not all the units are observed, differencing the data intensifies the gaps. Nevertheless, it does not occur in this study since my panel is strongly balanced. Another deficiency is originated when the dependent variable is highly persistent, and when the period is small. It could generate small sample bias due to weak instruments, making diff-GMM estimator inefficient (Blundell & Bond, 1998; Roodman, 2006; Cardoso & Fuinhas, 2011). Upon weak instrumentation, the employment of an alternative estimator improves the results. Sys-GMM was developed by Blundell and Bond (1998) to increase efficiency and produce more robust instruments. Behaving as a system of two simultaneous equations, sys-GMM combines the moment conditions of the data in levels and the transformed model (Roodman, 2006). The equation in levels implements lagged-first-difference variables as instruments, and the differenced equation uses lagged-level variables as instruments. Given that my time dimension is small and that sys-GMM produce more efficient estimators, I estimate Equation 4 by this approach.

By the construction of the second equation, additional instruments can be encountered. When too many instruments are implemented, the endogeneity could not be expunged, and the joint validity of the instruments produced by the Hansen test could present suspicious high p-values. Literature generally does not advise about the number of instruments. Therefore, the decision is guided by researcher criteria or empirical works.[10] Instruments proliferation can be overcome, restricting the number of lags, collapsing instruments, or using the previous tools jointly (Çoban & Topcu, 2013).

The overall validity of the instruments is tested by Hansen, where the null hypothesis states that the instruments as a group are exogenous. Hence, with high p-values, there is no statistically valid evidence to reject the null, giving support to the set of instruments applied. Nevertheless, p-values close to one produce doubtful about exogeneity conclusions.[11] Under this scenario, a proliferation of instruments results and a finite-sample bias is derived (Roodman, 2009).

Another diagnostic for the consistency of the estimators is conducted by the test for serial correlation of the idiosyncratic error ε_{it} (Arellano & Bond, 1991). This test is implemented to the differenced residuals to set aside μ_i. Overall, the

[9] Each category of GMM estimator has two versions: one step and two steps.

[10] Another option is to test the robustness of the results until reduce the p-value of Hansen test (Windmeijer, 2005).

[11] According to Roodman (2006), p-values higher than 0.60 needs attention.

test's mechanic looks for autocorrelation of order l in levels by inspecting serial correlation of order $l+1$ in differences (Roodman, 2006, p. 34). Hence, the AR(2) test in first differences is more informative than AR(1) test. A rejection of its null hypothesis suggests a serial correlation in the error term, implying endogeneity.

Results

Static Panel Results

FE and RE carry out the static models' estimation; robust POLS is presented as a benchmark model. Unlike Omri et al. (2015), the unit-roots test was not executed due to the dataset's small-time horizon. Scholars have emphasised that the appliance of unit roots tests in finite samples has arbitrarily low power and could produce misleading results (Schwert, 1987; Lo & MacKinlay, 1989; Cochrane, 1991).

Table 4 displays the results of the two models. In model 1, the standard empirical model is estimated, while in model 2, *auctions* and *kyoto* regressors are incorporated to examine their partial effect on the use of renewable energy.[12] Hausman test is conducted to test the null hypothesis about no-correlation between unobserved effects and regressors. As reported, there is statistically evidence against the null at 1% level, implying that the FE model generates consistent estimators. Thus, the analysis will be done, taking into account this method.

As reported in model 1, CO_2 is the variable with the highest impact on REC, in absolute value. Nevertheless, the negative sign is unanticipated since some studies predict a positive relationship among the factors (i.e., Salim & Rafiq, 2012; Apergis & Payne, 2015). The result indicates that keeping the other variables fixed when countries face more levels of emissions per capita, their response to the use of green energy decreases instead of being promoted. GDP per capita evidences a positive and significant effect at 5 per cent level, implying that income increases may induce to consume renewable energy, ceteris paribus. This result is expected, and it is in line with findings from Sadorsky (2009b) and Omri et al. (2015). Typically, a 1 per cent increase in income per capita raises renewable energy consumption by 0.420 per cent.[13] Regarding RGP, this factor has a positive partial effect on the dependent variable, suggesting that there exists a switch response when its prices increase. This outcome does not contradict the results of Marques et al. (2010).

In model 2, I control two policies induced in LAC countries: *auctions* and *kyoto*. When these regressors are incorporated in the equation, FE estimators do not change dramatically: GDP, CO_2 and RGP continue being statistically significant at the same levels. Moreover, the negative sign of carbon-dioxide emissions remains. Regarding the included covariates, *auctions* is unique with a statistically significant effect. Keeping other variables constant, it seems that adopting *auctions* causes increments in REC. On the other hand, *kyoto* shows the expected sign but is non-significant even at 10 per cent level.

It is worth mentioning that previous estimations may have produced naïve conclusions. Results are jeopardised because of non-strict exogeneity of regressors. Furthermore, it has been evidenced by the literature that the consumption of energy is strongly related with past observations (i.e., Sadorsky, 2011; Nayan et al., 2013; Çoban & Topcu, 2013). Besides, Wooldridge AR(1) test has detected the presence of serial correlation in the idiosyncratic disturbance in both models (Table 4), which imply biased standard errors, not efficient estimators and misleading outcomes.[14] Therefore, the static approach is not accurate.

Dynamic Panel Results

In this study, the sys-GMM framework is preferred over the diff-GMM since it is more efficient and avoid small sample bias (Blundell & Bond, 1998; Cardoso & Fuinhas, 2011). One of the prerequisites of this framework to produce relevant results is that the cross units might be higher than the time horizon. For this reason, the sample cannot be segregated to evaluate the drivers by sub-regions (see Table 3). Following Roodman (2006) recommendations, one and two-step estimations are conducted in both models.

[12] The lagged dependent variable is not included as predictor in static models since it induces endogeneity.

[13] Given the log-log transformation, outcomes could be interpreted as elasticities. However, this interpretation is not meaningful due to the measurement of the dependent variable.

[14] Drukker (2010) demonstrates that Wooldridge test for serial correlation in RE, FE models with small samples have good power properties.

Table 4
Static panel output

Variables	Model 1						Model 2					
	Pooled OLS		Random effects		Fixed effects		Pooled OLS		Random effects		Fixed effects	
	Coefficient	Std. Errors	Coefficient	Std. Errors	Coefficient	Std. Errors	Coefficient	Std. Errors	Coefficient	Std. Errors	Coefficient	Std. Errors
$logY_{it}$	−0.275*	0.093	0.003	0.150	0.420**	0.195	−0.253*	0.087	0.006	0.152	0.454**	0.200
$logCO_{2_{it}}$	−0.638*	0.123	−0.595*	0.101	−0.509*	0.106	−0.662*	0.119	−0.582*	0.100	−0.491*	0.105
$logROP_{it}$	−0.038	0.143	−0.033	0.031	−0.035	0.031	−0.052	0.139	−0.039	0.031	−0.047	0.031
$logRGP_{it}$	−0.0002	0.078	0.056**	0.023	0.099*	0.025	0.065	0.089	0.075*	0.024	0.113*	0.026
$logGCF_{it}$	0.027	0.083	0.106	0.068	0.015	0.075	0.027	0.085	0.114***	0.068	0.018	0.074
$logTO_{it}$	−0.125***	0.067	−0.057	0.090	0.014	0.095	−0.129**	0.062	−0.018	0.091	0.050	0.095
$auctions_{it}$							0.278*	0.077	0.089*	0.034	0.085**	0.034
$kyoto_{it}$							0.016	0.114	0.017	0.025	0.037	0.025
Constant	6.465*	1.340	3.113	1.222	−0.222	1.567	6.166*	1.253	2.810**	1.236	−0.727	1.595
Prob > F		0.000		0.000		0.000		0.000		0.000		0.000
R-squared		0.583						0.602				
N. Groups				22		22				22		22
N. Observations		220		220		220		220		220		220
Breusch-Pagan LM test: p-value						0.000						0.000
Hausman test: p-value						0.005						0.046
Wooldridge test AR(1): p-value						0.000						0.000

Significant at *1%, **5%, ***10% level. Model 1 is the standard equation; Model 2 includes $auctions$ and $kyoto$ covariates for robustness.

Consistency of estimators is validated when the following conditions are satisfied: 1) no-autocorrelation in the error term evidenced by AR(2) test, 2) validity of instruments reported by Hansen test, 3) no instruments proliferation. As reported in Table 5, those conditions are fulfilled in one-step and two-step sys-GMM in model 1.

Regarding the Arellano-Bond test, the p-value provides little evidence against the null hypothesis of the absence of second-order autocorrelation in residuals. Hansen test verifies the joint validity of the instruments. As it is shown, the p-value is not implausibly large. Furthermore, the rule of thumb that the number of instruments must be smaller or equal than the number of cross-sections is achieved. Hence there is no proliferation of instruments, and with that, finite sample bias was avoided (Table 5).

Moreover, the coefficient of REC_{t-1} has a value lower than the unit. Therefore, a convergence or steady-state assumption suggested by Roodman (2009) is satisfied.[15] Its statistical significance at 1 per cent level indicates that the consumption of renewable energy is strongly and positively affected by its previous value, confirming H_1 and is in line with the literature (Ackah & Kizys, 2015; Omri et al., 2015; Akar, 2016).

Although one and two-step estimations are presented in both models, it is recognised that the two-step approach is preferable since it generates more efficient estimators than one-step approach (Roodman, 2009). Hence the next results will be analysed under the two-step approach. In addition to the lagged variable in model 1, per capita GDP evidences a positive and significant effect at 5 per cent level, ceteris paribus. This finding is consistent with Apergis and Payne (2015), Omri et al. (2015). H_2 has been confirmed: GDP per capita enhances the consumption of renewable energy in LAC countries, implying that economic growth has influenced to afford for regenerative sources to satisfy the result in increasing energy demand that the region has experimented since the 2000s.

The negative impact of CO_2 on the adoption of green energy is reinforced at the 10 per cent level, indicating that increments in emissions per capita diminish the demand for renewable sources. It implies that social pressure about environmental concerns is insufficient in LAC countries to increase the consumption of a clean energy source in a short-run scenario. The suspicious about this indirect effect is verified, and H_3 is rejected because of the sign (Section 3.1.2). Although this variable's sign contradicts some empirical evidence (i.e., Omri & Nguyen, 2014; Omri et al., 2015; Berk et al., 2018), other scholars (Marques et al., 2010; Cardoso & Fuinhas, 2011) have found similar results. A rationale for this result could be related to the share of fossil fuels in LAC. This sector is very influential in the region, with higher energy mix participation. Although some countries like Mexico are promoting environmental regulations, they continue strengthening policies that support fossil fuel sector since its private investment enhances their economy. Therefore, there are no strong incentives to reduce gains to benefit the environment. Moreover, the main source of dirty emissions in LAC comes from transport and industry, which use oil as the principal resource.

ROP does not evidence to determine green energy adoption, rejecting H_4. Its small negative magnitude is consistent with findings of Sadorsky (2009a), and its insignificant impact is in line with Cardoso and Fuinhas (2011), and Salim and Rafiq (2012) who manifest that the short period of analysis could be an explanation of the results. Although fluctuations in oil prices bring disadvantages to the energy mix, it is not significant for switching to green systems, unexpectedly. A possible justification might be related to resource endowments and cost savings in a short-run scenario. The region is highly dependent on oil products due to the disposal of large reserves from Venezuela, Brazil, and Mexico. Given that renewable electricity projects require grants or subsidies for starting to be operative, they are not attractive for competing directly with projects that use oil as input. In terms of monetary cost savings, it may be more convenient to use other low-priced energy sources like natural gas when prices run up at the expense of continuing deteriorating the environment (Omri & Nguyen, 2014). Furthermore, OPEC's presence may influence the delay of renewable energy deployment. Upon a free-market approach, its scarcity would be warned by its high price due to higher extraction costs. It could induce a switch response because

[15] The steady state assumption suggests that any deviation from the long-term value must not be systematically correlated with individual-specific effects (Çoban & Topcu, 2013).

renewables become more attractive, as Cardoso and Fuinhas (2011) explained. However, that is not taking place since the cartel controls the price, and it is not set too high to mitigate replacements.

On the other hand, RGP expose a substitute response as expected, being in line with Akar (2016). However, its effect is non-significant (it differs from static panel results). Thus, H_5 is rejected. The sign could be associated with the swap that some LAC countries have done from hydropower to natural gas due to the former's shortages and the latter's abundancy. Currently, LAC experiments a positive natural gas trend as the power generator input because of its efficiency and trading. Also, natural gas is considered as a clean alternative source for electricity.[16]

GCF does not explain changes in REC, rejecting H_7. This result is not consistent with Apergis and Payne (2011) findings who predict a positive linkage among these variables in six Central America countries. A potential justification is that outcome differs because of the analysis period and the methodology applied. Nevertheless, Ackah and Kizys (2015) detect a negative effect from this predictor, concluding that other factors lessen its impact. Although this result is unexpected, a hint about its indirect was anticipated by me. I judge that the negative and non-significant effect of this variable could be related to the increments on tax bases levied on companies oriented to investments, as reported by ECLAC (2004). These policies constrain the expansion of renewable energy projects since they need more investment per unit of installed capacity.

Regarding TO, the sign is analogous to findings from Omri et al. (2015) and Akar (2016), implying that barriers discharges reinforce transfers of goods, services, knowledge, and technologies, which could give advantage to the production of this energy and with that, triggers its consumption. However, this factor does not reflect a significant impact, rejecting H_6. It could be explained by the regulations, taxes and other distortions applied from LAC governments to control the energy sector, which depress the market trade. According to WTO, governments can apply regulations to pursue any policy objective even though the market is liberalised.[17] Furthermore, as Yépez et al. (2011) stated, trade-related with electricity is limited in LAC in absolute magnitude and overall demand.

When *auctions* and *kyoto* regressors are controlled in model 2, sign and significance of REC_{t-1}, CO_2 and GDP are robust to previous results. Moreover, ROP and RGP become significant at the 10 per cent level.

Despite Popp et al. (2011) report that ratifying *kyoto* has a significant impact on renewable energy investment, in this study this commitment has not evidenced a causal effect on REC, rejecting H_9 (Section 3.1.2). This result is not abrupt. Literature discloses that the first phase of this international agreement was ineffective in achieving its target due to weak incentives of enforcement and cooperation (Barret, 2010). According to Mathys and Melo (2010), not using trade as an enforcing mechanism of control and sanction among signatories and non-signatories is related to pessimistic results. Moreover, a report (IDB, 2000) mentions that LAC countries did not succeed in identifying the inventories of their GHG emissions during Kyoto. Finally, *auctions* present statistically significance at 5% level indicating that this regulatory policy has a positive effect on REC, and confirming H_8.

The aim to include the two latter variables in model 2 lays on robustness examination since previous empirical work has not controlled them to explore their influence on REC. Nevertheless, these results are not suitable because a bias could have been generated due to the proliferation of instruments. Although the techniques emphasised by Roodman (2009) were applied, the number of instruments exceeds the number of groups (Table 5). That may happen because many variables held in this model. Consequently, the p-value of the Hansen test gets a high value, representing a warning signal and reduction of power in the overidentification test. Therefore, conclusions from these estimations could be suspicious and not reliable.

Conclusions, Policy Recommendations, Limitations and Future Work

Conclusions

In this study, I analyse the potential drivers of REC in LAC countries, over the period 2005–2014. Applying two econometric techniques (static and dynamic panels), I verified the estimated parameters' sensitiveness. Using two-step

[16] This assumption relies on the fact that natural gas is lower carbon-dioxide emitter than oil.

[17] Information obtained from World Trade Organization website.

Table 5
Dynamic panel output

Variables	Model 1				Model 2			
	One step sys-GMM		Two step sys-GMM		One step sys-GMM		Two step sys-GMM	
	Coefficient	Std. Errors (Robust)	Coefficient	Std. Errors (Robust)	Coefficient	Std. Errors (Robust)	Coefficient	Std. Errors (Robust)
$logREC_{it-1}$	0.950*	0.070	0.947*	0.067	0.942*	0.092	0.896*	0.103
$logY_{it}$	0.446	0.264	0.393**	0.188	0.494***	0.257	0.351**	0.164
$logCO_{2_{it}}$	−0.526**	0.201	−0.425***	0.222	−0.542*	0.181	−0.434*	0.134
$logROP_{it}$	−0.051	0.047	−0.033	0.037	−0.049	0.040	−0.042***	0.023
$logRGP_{it}$	0.031	0.035	0.041	0.029	0.038	0.037	0.051***	0.028
$logGCF_{it}$	−0.031	0.135	−0.030	0.117	−0.042	0.123	−0.003	0.095
$logTO_{it}$	0.090	0.217	0.017	0.145	0.133	0.188	0.001	0.143
$auctions_{it}$					0.068	0.065	0.122***	0.066
$kyoto_{it}$					0.018	0.026	0.031	0.019
Constant	−3.327	2.264	−2.718***	1.531	−3.854***	2.117	−2.348	1.407
Prob > F		0.000		0.000		0.000		0.000
N. Instruments		21		21		23		23
N. Groups		22		22		22		22
N. Observations		198		198		198		198
Arellano-Bond AR(2) test: p-value		0.499		0.461		0.425		0.308
Hansen test: p-value		0.384		0.384		0.662		0.662

Notes.
Significant at *1%, **5%, ***10% level. Following Roodman (2006), one and two-step sys-GMM estimation results are reported. Model 1 is the standard equation. GMM type variables are $logREC_{t-1}$, $logY$, $logCO_2$, $logROP$, $logRGP$, $logTO$. The standard type variable is $logGCF$. Time dummies are not included because of the aim to capture the effect of fossil fuel prices. Instruments are reduced by collapsing option and using the lags range from one to four for $logREC_{t-1}$ and $logCO_2$; from one to two for $logRGP$; from one to one for $logY$, $logROP$, $logTO$. Model 2 includes $auctions$ and $kyoto$ as standard type variables.

sys-GMM, the risks of endogeneity and serial correlation were treated, producing consistent estimators that fulfilled the conditions of no-autocorrelation in the error term, the validity of instruments, and no-proliferation of instruments. Additionally, the convergence assumption was satisfied.

The effect of REC_{t-1} was demonstrated, indicating that renewable energy consumption follows a significant dynamic process. GDP per capita and CO_2 emissions per capita were the determinants of REC throughout the analysis. That means economic growth enhances the demand for this energy source, while higher emissions levels do not induce more consumption. Both findings are in line with previous literature. Therefore, policies implementations may be mainly aligned with these factors.

On the other hand, fossil fuel prices did not evidence meaningful effects to stimulate REC. Regarding oil, the region is highly dependent because of Venezuela, Mexico, Brazil, and Colombia productions. Moreover, OPEC's existence narrows the possibility of switching to renewable sources in the short-run. Fouquet (2016) suggested that resource endowments and powerful groups' pressure could produce reactions for transitions in the energy process. Likewise, GCF and TO did not drive REC. Regulations, taxes, and other distortions applied from LAC governments are possible explanations about their insignificance.

As part of robustness, *auctions* and *kyoto* dummy variables were included. REC_{t-1}, CO_2 and GDP continued being significant. ROP, RGP and *auctions* present statistically significance, too. Nevertheless, conclusions from these estimations are misleading due to the proliferation of instruments which could fail to expunge the endogeneity (Roodman, 2009).

Policy Recommendations

According to Vachon and Menz (2006), green electricity adoption varies among geographic areas because of the incentives perceived by three different stakeholders: citizens, politicians, and lobbying groups. I consider that the LAC framework decisions are influenced mostly by the two-latter factions. As mentioned, a large fraction of the energy mix is composed of oil and natural gas. Since these industries and their partners do not face strong incentives to reduce gains, and their economic interests might be affected, they likely pressure governments. Thus, the transition process for renewable energy adoption is delayed.

Given that LAC countries are also recognised for being rich in renewable endowments such as hydroelectricity, wind and biomass resources, the possibility to attract private investment to develop those and other renewable systems might be an opportunity that national agenda needs to consider the satisfaction of increased energy demand.

Unfortunately, the macroeconomic context has not been favourable for private investment in some Latin American countries. Therefore, governments must work to strengthen the economic environment to attract investment and thereby increase private sector participation. Policies oriented to financial development should be promoted in certain countries and reinforced in others. They can manage some uncertainty and risks related to renewable technologies' investment. Financial instruments that might be applied are, for example, lines of credits, capital grants, insurances, liquidity guarantees.

The more developed is the economy's financial system, the more allowance of investment projects, which is traduced to higher incomes. With that, increments in renewable energy consumption could be expected since GDP is a relevant driver in LAC. Additionally, as recommended by IRENA (2016a), public financial institutions need to support R&D financing to no-mature renewable energy projects. During the early phase, more risks and costs are faced. Hence, public assistance will benefit private investors, given them confidence and shorten costs.

Furthermore, policy implementations might be oriented to the transport sector since this accounts for highly CO_2 emissions. Most of the population lives in cities, and they tend to use public transport. Hence fuel consumption has continued rising. For this reason, Chile has implemented environmental policies oriented to transport services. A private company specialised in electricity generation, transmission, and supply, will be responsible for supplying renewable energy to 100 electric buses that will travel around the main city.

Moreover, Chilean citizens have been able to get credits for buying electric taxis. Currently, 30 electric taxis are travelling around the cities. If other countries implement similar transport policies, it would be a win-win for the environment and clean energy usage.[18]

Finally, but not least important, the removal of fuel subsidies is a decision that governments must take. Subsidies not only affect the economy negatively but its also prompt overconsumption of dirty sources. According to the IMF (2015), gasoline and diesel prices are below the most LAC countries' social-optimal level. Although conventional energy products are taxed, the prices do not entirely internalise the externalities. Therefore, their prices are lower than the prices of renewables, disrupting clean energy deployment.

Limitations

Shortcomings are related to data. Factors such as energy depletion and innovations as a measure of technology have evidenced being drivers on REC in previous studies. However, I cannot control them because of lack of data in LAC countries. It would be interesting to examine their partial effect on the predicted variable throughout the analysis.

Comparison between income levels of countries or sub-regions in LAC was not possible to execute due to the number of observations. If the data would be subdivided, the requirement of dynamic panels that cross units must be higher than the time horizon would not have been fulfilled. Hence, the analysis was limited to a global panel. As shown by previous literature (i.e., Marques et al., 2010; Omri & Nguyen, 2014; Omri et al., 2015), results vary when the sample is subdivided. According to subcategories, Robustness verifies sensitiveness of variables was not possible to implement here.

Finally, it would be convenient to measure the variables in comparable terms. In this study, the dependent and one control variable have a different scale from other regressors. Because of free data unavailability, renewable energy consumption's raw data is in percentage terms. Following Cameron and Triverdi (2009), Marques et al. (2010) and Bhattacharya et al. (2016), it was log-transformed due to the skewed distribution exposed. Although the interpretation of a log-log model is in elasticities, it seems to be not so meaningful in this case.

Future work

Possibilities for future studies: 1) Extension of the time horizon since some events have arisen recently, for instance, Paris Agreement. According to Roman and Morales (2018), this agreement could be a new mechanism to enhance green energy deployment, 2) Use CPI as a proxy for energy price or deflate fossil fuel prices by countries. It would allow the inclusion of time dummies suggested by Roodman (2006), 3) Control for social and political factors.

[18] Information obtained from ElectroMOV website.

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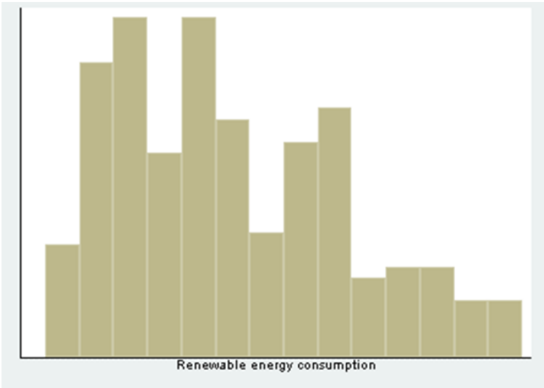
Appendix

Skewness and kurtosis test for normality

Variable	Skewness	Kurtosis	Chi-squared	p-value
Renewable energy consumption	0.002	0.032	12.390	0.002



Потребление возобновляемой энергии и его основные движущие мотивы в странах Латинской Америки и Карибского бассейна: анализ надежности между статическими и динамическими моделями панельных данных

Синди Менендес-Карбо

Аннотация. В статье представлены результаты исследования предпочтений и движущих мотивов потенциальных потребителей возобновляемой энергии в 22 странах Латинской Америки и Карибского бассейна в 2005–2014 гг. Для того чтобы учесть наличие эндогенности, специфичных для конкретной страны компонентов и серийной корреляции в наблюдениях, автор использует метод sys-GMM. В результате исследования подтвердилось динамическое поведение потребителей «зеленой энергии». Определяющими факторами потребления этого чистого источника энергии являются показатели ВВП и выбросы CO_2 на душу населения. Положительный эффект ВВП на душу населения означает, что неистощаемый альтернативный источник использовался для удовлетворения растущего спроса на энергию, который наблюдался из-за ускорения экономического роста в данном регионе. В свою очередь, отрицательный эффект выбросов CO_2 на душу населения отражает вес ископаемого топлива в структуре энергопотребления. Поскольку ряд стран региона являются производителями нефти, существующий уровень нефтяных цен не мотивирует их на переход к возобновляемым источникам энергии.

Ключевые слова: энергия; Страны Латинской Америки и Карибского бассейна; ВВП на душу населения; выбросы CO_2 на душу населения; выбросы парниковых газов; модели панельных данных

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Practical Vitality of Green Bonds and Economic Benefits

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Abstract

Climate change is an overarching challenge for achieving sustainable development. "Green" or "Climate" Bonds are often seen as a financial instrument that may help overcome low-carbon investment defiance. This paper explores green bonds' potential contribution to low-carbon transition and the corporate sector's benefit following the stock market reaction. This paper focuses on a new and fascinating subject because the green bonds market is under constant scrutiny since the emergence of the first green bond in 2007. Anticipating the significance of action towards climate change is continuously increasing over time. This project can be seen as a supporting argument for investing in green bonds and fighting against climate change. This study investigates the recent developments and challenges in the green bond market. I used matching criteria and performed multivariate OLS regression to test whether the green bond is priced differently than conventional ones. The result finds that green bonds are cheaper than conventional bonds with a 1.93–2.24 per cent premium, consistent with prior studies in this topic. I used a sample of 200 corporate green bonds issued after the Paris Agreement, i.e., from December 2015 to December 2019. I further document that the stock market reacts positively to green bonds' announcements. For this, I performed the CAR test on a company's stock price, which gives a statistically significant abnormal return of 0.23 per cent and 1.14 per cent over time windows 10 and 20 days, respectively. Moreover, green bonds' environmental performance on carbon emission reduction proved to be an insignificant player. For this, I tested a relationship between green bond labels and the firms' carbon emission. The mixed results suggest that maybe green bonds are performing well economically, but it is still far from achieving its practical goal.

Keywords: green bonds; corporate social responsibility; corporate finance; carbon emissions
JEL Classification: G12, G14, G32, M14, Q52, Q53

Introduction

The concern over the acceleration of climate change is real. Ever since the tracking of climate change began in 1880, the six warmest years on record for the planet have all occurred since 2010 (National Oceanic and Atmospheric Administration NOAA, 2018). The rising temperature and increasing acidity of ocean water, melting of ice sheets, and glaciers which result in climbing sea levels and the growing frequency of droughts and floods reflect the threat to the planet by increasing atmospheric carbon levels (Baker et al., 2018). There is an urgent need to tackle this problem which comes with the cost of enormous sums of money that adapt to existing conditions or foreseeable changes. Climate has become the most significant theme in ESG (Environmental, Social and Governance) investing and there is an acceleration of product development in the past couple of years, triggered by the Paris Climate Accord in 2015 and the need to keep global warming to below two degree Celsius (*Financial Times*, 2019). So, what exactly counts as a climate-friendly investment strategy? The hottest and efficient way of tackling the problem is green bonds, a way for issuers to raise money specifically for environmentally friendly projects such as renewable energy or clean transport (*Bloomberg*, 2019). Large sums of capital are needed to finance responses to and preparations for climate changes. In order to connect the money to the solution, green bonds are the tool that may be used to reach investors and collaboratively finance low-carbon, and climate-resilient solution. Green Bonds have attracted countries, supranational institutions, corporations, and investors to invest in green investment. For example, Unilever issued a £ 250M green bond supporting "cutting half the amount of waste, water usage, and greenhouse gas emissions of existing factories" in March 2014 (*Financial Times*, 2014). Similarly, in June 2017, Apple issued a $ 1bn green bond to finance "renewable energy and energy efficiency at its facilities and in its supply chain" (*Forbes*, 2017). Henceforth, this study provides an insight into the practical role of the green bonds as raising funds for green projects.

The green bond market emerged in 2007 with a triple-A-rated issuance from multilateral institutions European Investment Bank (EIB) and the World Bank. The green market's broadness acted after a positive reaction of the first USD 1bn green bond sold within an hour of an issue by IFC in March 2013. The following year was the market's turning point as the first corporate green bond issued by Vasakronan, a Swedish property company. Large corporate issuer includes SNCF, Berlin Hyp, Apple, Engie, ICBC, and Credit Agricole. The momentum has continued, with over USD 500bn in green bonds currently outstanding (Climate Bond Initiative). The majority of Green Bonds issued are Green "use of proceeds" or asset-linked bonds. There have also been "Use of Proceeds" Revenue Bond or ABS, Green Project Bonds, Securitisation bonds, Covered Bonds, Loan, and Other debt instruments. Proceeds from these bonds are earmarked for green projects, refinancing green projects, and portfolios of green projects, and ring-fencing the specific underlying green projects.

This study examines the green bond market compared to its counterparts and whether they provide a premium to investors and whether it is impacting the reduction of greenhouse gases such as CO_2. This thesis covers the green bond market of a specific period, that is, after the Paris Agreement of December 2015 to December 2019, four years. This study will focus primarily on non-financial companies where traditional valuations are more applicable. In general, a company's fundamental value can be calculated by discounting its future cash-flows into a present value with a certain discount rate. Here, the only focus will be the divider of that equation, discount rate, or coupon rate. If green bonds proved to be cheaper than conventional bonds, the company's future cash flows are then discounted with a lower rate into a present value, increasing their current value.

To empirically examine the corporate green bonds, I compile a dataset of corporate green bonds from Thomson Reuters Eikon green bond tag. The empirical analysis documented several stylised facts pertaining to corporate green bonds. First, as mentioned above, corporate green bonds have become increasingly popular over time. Second, corporate green bonds are more prevalent in industries where the natural environment is financially material to the companies' operations (e.g., energy). The corporate green bonds are especially pervasive in China, the US, and Europe.

Further, I examined how the stock market responds to green bonds' issuance using an event study methodology. The result indicated that the stock market responds positively in a short time window, which is in line with many previous pieces of literature such as Flammer (2020); Tang and Zhang (2018).

Focusing on the environmental perspective, the orientation of investments to sustainable activities has also been possible because of the Green Bonds. The difference with conventional bonds lies in the issuer's commitments on using the proceeds, which must have positive externalities for the environment. In this study, I carried out a regression of green bond issuers' environmental performance by taking carbon emissions as a dependent variable. The experiment shows no statistically significant relationship between them. One explanation could be the recent emergence of the green bonds market, which is still much far away from the goal to mitigate carbon emission.

Additionally, this study's factual explanation is the companies' greenhouse emission data's lack of details. Following Flammer (2020) methodology, who uses Thomson Reuters ASSET4 for getting environmental rating data, found no mechanical link between the issuance of green bonds and higher environment ratings. To mitigate this issue, they used the ratio of CO_2 emissions divided by the book value of assets as the emissions are more objectively measured. This metric interpreted more sensible results that blend several corporate environmental behaviour dimensions.

Purpose, Motivation, and Limitations of the Study

This study's main purpose is to check the overall performance of the green bond within a company and its impact on the fight against climate change. Firstly, the financial benefits of green bonds are checked by finding whether they are priced lower than ordinary bonds which attract the investors to invest more in climate-friendly projects. Thus, whether green bonds can be proved to be issued with significantly cheaper yield, it should also mean that if a company is using a green bond to fund its operations and investments, the discount rate is lower as resulting in a higher present value of the companies' future cash flows. Secondly, this thesis examines the company's stock price reaction on green bonds' issuance. This study also examines green bonds' environmental performance by checking the relation between the green bond environmental rating and carbon emissions changes.

The impact of climate change poses a significant threat to this planet. There is an urgent need to finance mitigation and adaptation efforts at various levels to combat climate change successfully. Green Bonds are relatively new funding instruments for green projects that have steadily become the first line of defence against climate change. If the green bonds are more attractive with a lower yield than conventional ones, investors consider when making new investments and project strategies. The basic responsibility for good sustainability with issuers and within the organisation internally provides a rational insight into what they are going to invest. It is the primary motivation of this study.

This study's limitations could be the lack of data available and manipulation in the matching of green bond and conventional bond data compared to the prior studies of this subject. It can have some effect on its result. Green bonds and green investment markets are new. Despite in-depth research on the necessity and impacts of green finance and Green Bonds, there is little empirical evidence of these investments' financial performance. But the concern for climate change is growing worldwide, and the demand for green bonds is increasing rapidly. Various studies are on-going, and several prior tests have occurred in recent years and therefore support this thesis, though not very strongly. Another limitation worth mentioning is that this study uses only one valuation method and should not be taken as absolute truth but more as an indicative result.

Green Bonds

Green Bonds are a new asset class issued to raise finance for climate change solutions. This chapter will cover some basic principles of green bonds and their operation. It will also cover one real-life example of green bond issuance and expectations and threats to the market and issuers. Increasingly, investors see both the financial and social imperative for sustainable investing, particularly green bonds' rapid growth.

These figures illustrate the growth in the green bond market over a decade and shows which kind of companies are most active in issuing green bonds. The number is promising, and the bonds' amount of investment is tremendous. In the second figure, we can see that the non-financial sector covers almost 40 per cent of the total green bond issuance which is a notable change as supranational institutions like the European Investment Bank and World Bank were dominant at the beginning of the green bond markets. In 2018, the top market trend for green bonds was the rise of a broader range of socially conscious debt levels. The return of volatility to financial markets negatively impacted overall bond sales and the taxonomies were revised, for example, Loan Market Association (LMA) published the Green Loan Principles (GLP), with the support of ICMA and Climate Bond Taxonomy was updated with new sectors and more exact definitions (Climate Bond Initiative).

Definition and Principles

Green Bonds are a financial debt instrument widely used to fund more energy-efficient technologies, reduce carbon emissions, and further sustainable economic activities. They are mostly issued by the government, corporations, and financial institutions. Investors who want to recast their investments to address climate change will face several decisions over what companies or funds to invest in and how to reduce the risks associated with their portfolio, and what returns they might be sacrificing or gaining by transforming portfolio. Green Bonds create a marketplace that potentially increases the transparency

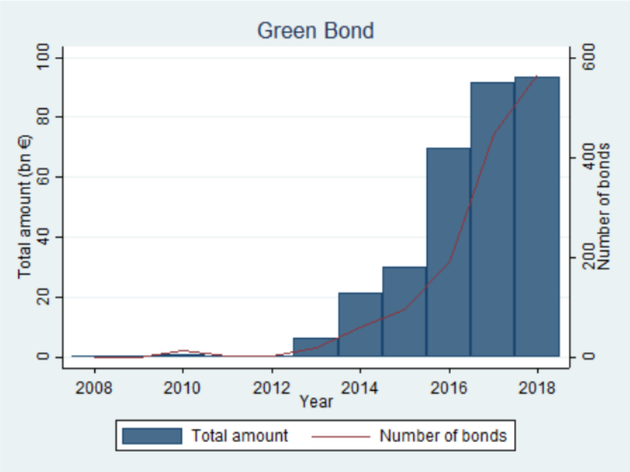

Fig. 1. The Green Bond Market

Note. The figure reports the total amount of Green Bond issued (bars) yearly (billion euros). The line shows the total number of green bonds issued from 2008 to 2018.

Source: Fatica, Panzica, & Rancan, 2019.

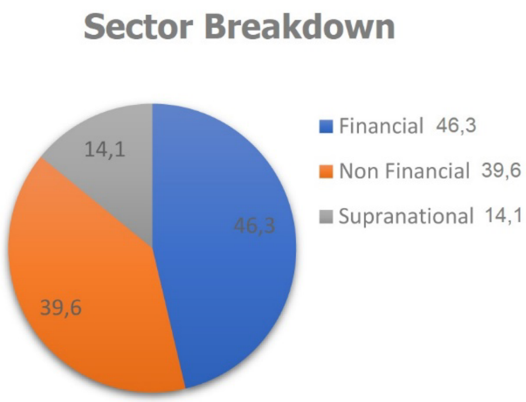

Fig. 2. Green Bond Market Distribution by issuer type in percentage

Source: Chart taken from Fatica, Panzica, & Rancan (2019).

of the information about the underlying asset and the companies using it.

Various papers conclude the set of use of proceeds which describes the subjects of the projects financed by the proceeds. International Capital Markets Association (ICMA) has defined green bond as a "the type of bond instrument where the proceeds will be exclusively applied to finance or refinance, in part or as a whole, new and/or existing eligible Green Projects" (ICMA, 2018). The project categories according to ICMA guidelines for issuing a Green Bonds:

Renewable Energy

Pollution prevention and control

Energy Efficiency

Environmentally sustainable management of living natural resources and land use

Terrestrial and aquatic biodiversity conservation

Clean transportation

Sustainable water and wastewater management

Climate change adaptation

Eco-efficient and/or circular economy adapted products, production technologies and processes

Green Buildings

(*Source:* ICMA, 2018)

According to the guidelines, the green bond market aims to create an opportunity and market-based solution that debt markets, investors and companies could use in funding projects. The next table will present the green bond market's value from 2015 to 2019.

As we can see from the above table, the growth in Green Bonds' revenue has increased over four years, which means both investors' interest and the bonds' performance significantly improve over the years. The alternative energy sector has the highest issuance of approximately 21 per cent revenue. Other sectors are also in increasing trend.

The proceeds of the green bonds should be managed and tracked appropriately through a formal process that should also be transparent to build a positive profile in the market., It is recommended the use of external auditors to enhance transparency. It is also important that the issuer clearly presents the environmental benefits of the green projects and if possible, quantified as well so that independent evaluators can verify them. An external review is very important to increase transparency and develop trust in the green bond market. It is particularly important in the case that the issuer does not have much expertise to provide the required information, or in some cases where project generate negative environmental impact (Sartzetakis, 2020). There are several types of reviews for the same, such as consultant review, verification, certification, and rating (ICMA, 2017). Thus, if the issuers label the green bond, the market could become more substantial.

Green Bond market in 2020

Due to the sharp increase in Climate activism and fear of an apocalypse, green investments

Table 1
The top sectors for Green Bonds issuance in 2015 and 2019

Category	2015	2019
Alternative Energy	$ 30.4B	$ 143.8B
Green Building	$ 10.7B	$ 63.5B
Sustainable transport	$ 3.7B	$ 58.7B
Energy Efficiency	$ 9.5B	$ 47.6B
Sustainable water	$ 3.1B	$ 23.8B
Pollution prevention	$ 1.4B	$ 18.1B
Climate Adaption	$ 1.8B	$ 15.0B
Sustainable forestry/agriculture	$ 1.1B	$ 11.3B

Source: MSCI.

have been rising in popularity (The Trumpet, 2020). The recent COVID-19 pandemic has given more momentum to green bonds around the globe. With its attractive attributes of tax exemption for investors, the market for green bonds has rapidly grown over the years. In 2019, green bonds were issued worldwide for $ 205 billion, more than 20 times as much as 2014 ($ 9 billion). According to the Climate Bond Initiative (CBI), the European Union is the largest international green bond market. The CBI forecast 2020s says the global annual green bond and loan issuance to be $ 350 billion to $ 400 billion, and $ 1 trillion in annual investment by 2021/22.

The Coronavirus Effect

By the end of April 2020, more than $ 50 billion worth of green bonds were issued (Climate Bond Initiative), which was lower than the market's anticipation. The financial market is highly disrupted worldwide, but green bonds, or debt earmarked for specific environmental projects, have held up better than the broader investment-grade corporate market. It is due to less weighted toward cyclical sectors, such as oil and gas (*The Trumpet*, 2020). However, I think this pandemic could work as a catalyst to convince the wider community and transform it into a lifetime opportunity to invest in climate-friendly future and economic sustainability.

Green Bond Pricing

Green Bond costs almost the same as Conventional Bonds (Tang & Zhang, 2018). Kapraun and Scheins (2019) analysed the pricing of a sample of over 1,500 Green Bonds on Primary and Secondary market. They found only certain types of Green Bonds issued by the government or supranational entities or corporate bonds with huge issue size exhibit lower yield, i.e., trade at a premium relative to their conventional counterparts. Further study by Fatica, Panzica and Rancan (2019) compared the pricing implication of Green and Ordinary bonds and examined which determinants of the bonds affect the yield by carrying out the regression model. The study found that there is not always a premium in green bond issuance price unless supranational or corporate is behind the issuance, the premium is found. Their research also suggested that the green bond's repeat issuance has some price difference compared to the conventional ones, and second-time issuance provides some premium on the yield.

Besides, Karpf and Mandel (2017) investigate the yield term structure of green and brown bonds from the US municipal bond markets. They asserted that, although the returns of brown or ordinary bonds are higher than green bonds on average, this spread can be explained by the bond issuing company's profile and determinants. In general, a flattening slope on the yield curve reflects lower returns from the bonds. According to Karpf and Mandel (2017), flattening yield curve is more present in green bonds than brown ones, which undoubtedly favours brown bonds in an investor's eye, but it is cheaper for them to get from issuers angle issue green bonds.

The following picture shows how differently green and conventional bonds are priced in the market.

Their study further concludes that there is a positive and statistically significant spread between ordinary and green bonds on average, which aligns with Fatica, Panzica and Rancan (2019).

In this thesis, the regression on the yield differentials between green and normal bonds explores the significant positive impression with coupon and the other determinants. It ultimately proves the efficiency of green bonds over ordinary bonds.

Practical Vitality of Green Bonds in Investment

This subchapter focuses on Green investment's green bond market's practical usage. A real-life case study is taken from the Climate Bond Initiative case study library, including the summary of bond issuers' experience and challenges.

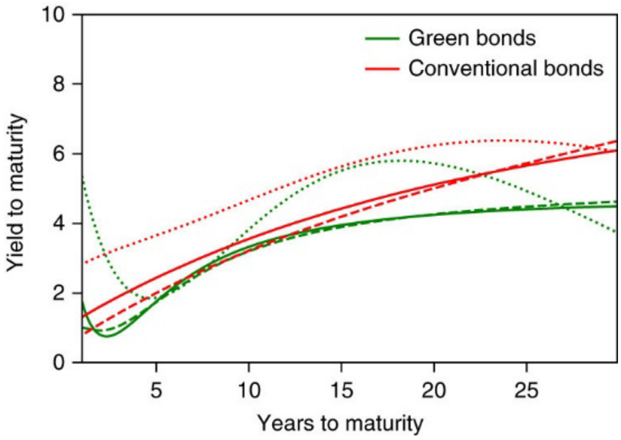

Fig. 3. The yield term structure of Green and Conventional Bonds

Note. Yield curves, representing the relation between the yield(y-axis) and the time to maturity (x-axis). The solid line is overall performance, a hashed line is A-rated bonds, and the dotted line is B rated bonds.

Source: Graph is taken from Karpf and Mandel (2017) study.

DC Water Green Bond: A Case Study

An old infrastructure in Washington DC created risk from severe and frequent storms. The dumping of billion gallons of raw sewage into its river annually, made the area inhabitable. The plan for adaption and mitigation was to build a tunnel to retain water from combined sewer overflow. For that, they decided to fund the part of the project by 100 years, Green Bond. They were first considering issuing a normal bond but looking at the asset's characteristics, and potential positive environmental outcome. A $ 350m bond was planned, upsizing from the $ 300m issuance due to the strong demand. According to them, when the project completes in 2030, it will reduce combined sewer overflow to the Anacostia River by 98 per cent.

The project required a long planning and reviewing phase. From conception to execution the deal was lengthy and complicated than a traditional bond issue process. The project leader developed a relationship with investors, investment bankers (Barclays and Goldman Sachs), and a Second Opinion Provider (Viego). (Irene, 2016) Assessment and modelling of the initiative were carefully developed and implemented. DC Water was already a bond issuer, and Clean Water Project was a big project. It would fit the Green Principles and the World Bank model as a green project with environmental benefits.

The Green Bond model adds layers of complexity and increases integration systems. It adds components to the system: transparency of what is being financed, tracking of cash flows, and reporting the investment impact. The system designed by this company for 100 years term has multiple intentional benefits which include investors numbers and an increase in equity.

We can say Green Bonds provide an opportunity for multiple stakeholders to collaborate. It offers an arena for innovation as new kind of bonds, such as DC Water 100 years bond, are creatively designed. Green Bonds have mobilised development of methodologies to measure and report the impact of environmental solutions. Green Bonds can make green projects less expensive, i.e., high demand for the bond can create a lower interest rate for the issuer (borrower). It can result in cost optimisation of capitals for the organisation that is issuing the Green Bond (as we have seen DC Water reduced its interest rate in response to high demand). It solves the problem of water quality and improves the quality of life and offers economic opportunities in the disadvantaged area of Anacostia River. A bond is issued on many factors, one of which is the length of asset which it finances. In this case, a combined sewer overflow system was expected to last more than 100 years, so the concept of a hundred-year bond was creatively implemented.

Overall, this case study is a perfect example of explaining how green bonds can be used to finance a various project in a cost-efficient way.

Market Mechanism and Risks

With the increasing attention on the green bonds and climate bonds over the past few years as key instruments to finance the transition towards a low-carbon economy, they shall remain small compared to the challenges it is meant to address and the overall traditional bond market. Therefore, it is essential to understand the mechanisms and risks involved in the market. These instruments' positive aspects have been discussed, which is the primary motivation of this study. However, understanding the risk is one of the crucial parts of any project to carry on. According to the studies, there are three major risks involved in the issuance of the green bond and market. Firstly, a lack of liquidity risk is one of the largest detractors. It impacts the issuers and investors as in the current investing environment, the green bonds' investors might need to hold until maturity. Chandrasekaran (2018) examines how liquidity affects the green bond yield spreads and found a significant impact on the green bond yield spreads and urged issuers to improve their liquidity levels to reduce the risks and increase confidence among investors. Furthermore, Febi et al. (2018) analysed the yield spreads between corporate and government bonds using controlled variables by pooled OLS model and found that green bonds are more liquid during 2014 to 2016 than conventional ones. Additionally, their results also suggested that the green bond spread's liquidity risk is becoming insignificant over time and can be associated with the markets' growing maturity.

Another risk for green bonds includes low yields, mispricing, and insufficient complex research, leading to wrong investment decisions. Also, lack of a clear definition for a green bond is a risk- investors might be not knowing where they are putting their money, meaning it could potentially be used for the wrong reasons.

Greenwashing

Although the market for green bonds is in rapid development and significantly shows positive impacts on the companies and environment, corporations are more engaged in socially responsible ways of doing business. Still, there are always some who unethically take advantage without actually involving in real action. Situations where company launder monetary benefits from the environmental-friendly operations creates possibilities of dishonest actions. Hence, this risk of Greenwashing can bring uncertainty and disbelief in the market, whereas they are intended to bring an effective solution and change in the world. In general, greenwashing can be described as a form of marketing and advertising company's ethical and environmental values with a purpose to attract investors and consumers rather than actually implementing environmentally friendly practices. For example, British Petroleum shifted its slogan to green in 1997 when acknowledged a link between global warming and fossil fuel. They hired an advertising firm to launch a $ 200m rebranding campaign and rebranded to Beyond Petroleum. They greenwashed itself by working with green groups and decorating its gas station with green images. Despite British Petroleum's attempt to greenwash, the company is a fossil fuel company that derives its revenues from polluting air and destroying the planet (CFI).

Few prior studies have presented this rationale; for example, Laufer (2003) and Beder (1997) presented problems and challenges of ensuring fair and accurate corporate social reporting. They gave a couple of rationale on companies practising greenwashing and how these actions can be categorised into confusion, fronting, and posturing. According to their studies, greenwashing is pervasive since the introduction and might significantly impact the green bond market. And suppose the green bonds are priced cheaper than the ordinary bonds and claims more investors only by their tag, and other hypotheses of the study hold. In that case, it might be a motivation for the opportunist to practice greenwashing.

A Review of Green Bond as an Instrument to Finance Low Carbon Emissions

One of the most important roles of Green Bond that an investor is anticipating is to finance the economy with low carbon value to mitigate climate change, for that most of the countries are using a combination of Carbon Pricing and Green Bonds.

In the Paris Agreement, countries worldwide made a commitment to transitioning towards low-carbon, climate-resilient economies. Several policy instruments have been proposed to finance this transition, including green bonds and car-

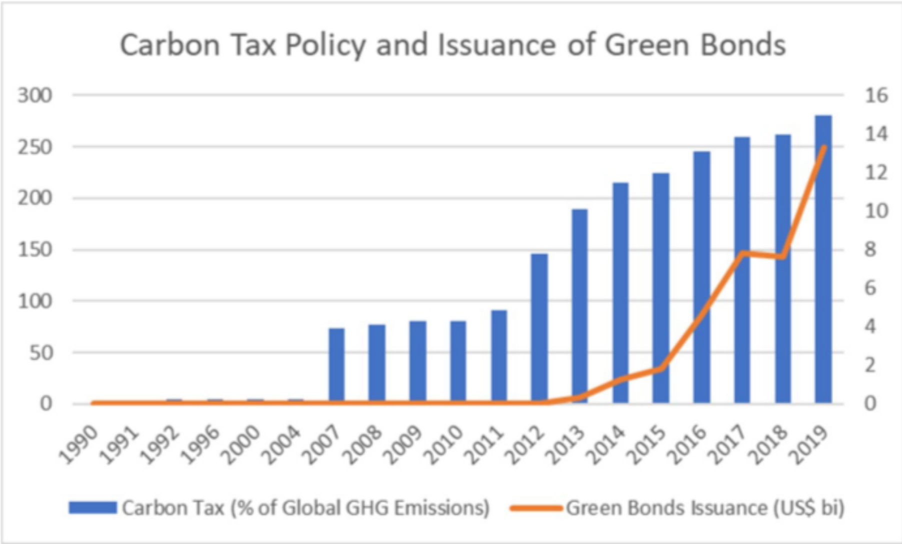

Fig. 4. The increment in carbon pricing since 1990

Source: Climate Bond Initiative (2019) and World Bank (2019).

bon pricing. This instrument still has to prove its credibility, but researches have been carried out to find the important gains from deploying them jointly. Debt levels are rising in many low-income countries (Essl et al., 2019). In such circumstances, climate policy should be financed by taxation or budget reallocation instead of deficit spending (Forni et al., 2019). Heine et al. (2019) observed that Carbon Pricing improves the performance of green bonds, which in turn improve inter-generational equity, political feasibility, and help address multiple market failures with speeding up the transitions.

In the form of carbon taxes or emissions trading schemes, carbon pricing has been used since the 1990s as a stimulus for diminishing greenhouse gas emissions, and since then spread to 46 jurisdictions, rising by up to 43 billion in revenues (Heine et al., 2019). Green Bonds portray a more modern development in the policy toolkit for financing climate change mitigation, adaption, or conservation of natural capital resources. Despite their exponential uptake since 2011–12, the carbon emission coverage is less than 5 per cent under explicit carbon pricing initiatives which says both instruments are still too small for containing climate change.

The main purpose of carbon pricing is to make consumers and producers of polluting goods more considerate of the costs imposed by this pollution in the environment. The pricing policies, such as carbon taxes or emissions trading systems (ETS), mixed with green bonds, will achieve greater environmental effectiveness and lower overall mitigation costs. In principle, the needed for financing for a low-carbon transition could be met entirely from pricing externalities. The IMF estimates that the gap between the present taxation of fossil fuels and the level of taxation justified by external costs amounts is more than estimated financing needs to contain global warming (Blanchard, 2019). Despite its potential, the present carbon pricing level is entirely insufficient to meet mitigation needs. "Few countries are taking some modest steps forward, yet there is little evidence of better use of taxes on energy which is a mounting environment and climate challenges globally. Instead, real tax rates are gradually eroded by inflation in most countries, suggesting indifference to the environmental efficacy of taxes" (OECD, 2018). Unless a breakthrough in fiscal policy can be achieved, additional financing sources of mitigation, such as green bonds, are indispensable. Therefore, the Finance Ministers and Central Bank Governors that embrace carbon pricing equally call for stepping up green finance instruments (Climate Bond Initiative, 2016). The green technology revolution will require investment across the innovation chain, similar to that observed in the information and communication technology revolution (Mazzucato, 2015; Norberg-Bohm, 2000). Public investments should play a vital role in this change to actively create low-carbon climate-resilient markets (Mazzucato, 2016; Hallegatte et al., 2013).

From 2010 to 2018, the European Union (33.4 per cent), China (14 per cent), Multilateral Organisations (13.7 per cent), and the United States (12 per cent, excluding US municipalities bonds) were the world largest Green Bond's issuers (Heine et al., 2019).

Heine et al. (2019) reviewed the efficiency benefits from including such carbon pricing in a joint policy with green bonds. They analysed the interaction effects which arise when green bonds and carbon pricing are implemented jointly, where there are two options available for implementing carbon pricing: ETS and taxes. According to them, the interaction effect between the value of green bonds and carbon prices is more ambiguous for ETS than for carbon taxes. An ETS puts a cap on emissions, and emissions leakage can occur when green bonds finance climate change mitigation projects for industries covered by the cap, thereby allowing the displacement of emissions rather than their net reduction. To prevent this, green bonds should be introduced to tighten the cap, but those adjustments may be politically impossible precisely when green bonds are sought. However, Green Bond holders have an interest in tightening the ETS caps. The industries' lobbying to loosen emissions caps could be counterbalanced by new lobbying from these investors. By that means, the creation of green bonds could both strengthen or weaken ETS. As the tax is more stable irrespective of green bonds' deployment, the risk that green bonds and carbon taxes will cripple each other diminishes. Another interaction effect between green bonds and carbon prices works through price volatility (Heine et al., 2019). Compared to other bonds, green investment projects can attract green bond financing more easily if returns on investment are less volatile (Gevorkyan et al., 2017).

In this thesis, the effect of the green bond's issuance on carbon emissions has been shown. The fact above concludes that an increase in carbon tax puts a significant cap on emissions and thus reduces carbon emission on firm-level. That also means if the carbon tax is low, green finance may improve welfare. I will further discuss the Green Bond tag's potential benefits on the carbon emission.

Literature Review

This paper revolves around finance and the environment and thus relates to different strands of financial literature. Because the concept of green bonds is relatively new and still under development, it will follow with the latest published literature and working empirical papers along with the older studies. Therefore, I based literature review only on the important findings rather than a comprehensive overview of all the previous research on the subject. This line of the thesis is divided into two parts. Thus, the empirical evidence review will be carried out in two sections: research about the pricing of the green bonds and its on-going effect on carbon emission reduction. The literature review of related studies gives a better picture of the area and supports my study's problem.

Pricing of Green Bonds

Most research carried out in this line of the topic is the pricing of the green bonds compared to the conventional bonds. Fatica et al. (2019) found that the green bond issued by supranational and corporations are priced at a premium while there is no effect for financial institutions. Kapraun and Scheins (2019) studied bond pricing's green credibility in the primary and secondary market. They found 18 bps lower yield at the issuance of green bond issued by the government or supranational entities, denominated mainly in EUR and USD, or corporate bond with very large issue size. They also argued that investors are more likely to consider a corporate bond as Green when the bond is certified by a third party, or when the bond is listed in exchange with a dedicated green bond segment. According to the Climate Bond Initiative, Assurance is an important part of the Climate Bonds standard and certification scheme. It is highly valued by investors and other stakeholders in the green bond market.

In contrast, Karpf and Mandel (2017), Hachenberg and Schiereck (2018), Larcker and Watts (2019) document no significant difference in yields or even higher yield for green bonds. However, most of these studies rely on a minimal set of bonds or focus on special types of bonds (e.g., US municipals) or markets (primary or secondary). Gianfrate and Peri (2019) stated that there is a statistically significant proof when an issued bond is labelled as green, these benefits will exceed costs. Their results observed the yield premium around 18 basis points, which equals 0.18 per cent of the overall bond value. Their study took the additional costs of issuing the green bonds, certifying, monitoring, reporting cost about the green use of proceeds, and the monetary benefits for the issuers who exceed these costs. For example, the Climate Bond initiative takes a 0.1 basis points fee for each to certify the green label. It means that if the amount of green bond issuance is 1,000,000 EUR, these costs will be 1,000 EUR. Third party involvement for assurance also increases the costs.

Ehlers and Packer (2017), Baker et al. (2018) found the premium on average relative to conventional bonds if the currency risks are hedged. The former also documented that green bonds are exposed to a relatively high degree of environmentally-related financial risks. Contrary to their findings, Zerbib (2018) found that the yields of green bonds issued between 2013 and 2017 are on average, two basis points (bps) lower than those of comparable conventional bonds. But the negative premia are more pronounced for financial and low-rated bonds. One common explanation for this yield difference is the high demand and limited supply of green bonds.

These previous findings show that even after all the surplus costs associated with Green Bonds issuance, these debt instruments are still a relatively cheaper and efficient form of financing for the issuers. As a result, green bonds effectively improve the concern of climate change by funding and significantly benefit the issuers in terms of the reduced cost of debt. With this argument of Green bonds being more of a charity investment than a financially interesting instrument, the financing through these instruments against climate change should get more further attention and support.

Market Reaction

So far, the findings suggest that green bonds are priced cheaper than ordinary bonds. It is also essential to find the relation between the green bonds' issuance and those bonds' stock price. Few research studies have been carried out following this topic, for example, using an event study model to determine how investors and shareholders respond to corporate green bond issuance. Tang and Zhang (2018) documented positive stock price reaction to the green bond issuance, but they did not find any premium suggesting that the lower cost of debt does not drive the positive stock market returns. Their study also presented the finding that the proportion of shares owned by domestic institutions tends to increase after the green bond issuance. This finding is also very indicative for this study as it will guide the methodology of this thesis and provide a comprehensive insight for data analysis.

Glavas (2018) found that the stock price reaction grew after the Paris Agreement, which supported the change of equity investors' behaviour after this agreement. They carried a rigorous event-study at each announcement date with regression analysis. This paper is also a very important reflection for this thesis as the data selection period is after the Paris Agreement.

Flammer (2018) used only an event-study as a complementary analysis to test the market response to green bond issuance. However, according to Glavas (2018), there are no tests implemented yet to determine whether the debt component or the "green" component of the green bonds is responsible for this positive market reaction.

On the other hand, Lebelle et al. (2020) used an international sample of corporate Green Bond and used CAPM, the 3-factor Fama and French models and 4-factor Cahart models; they found that the market reacts negatively to the announcement of green bond issuances. They also supported their argument with the first green bond issuance theory and suggested that green debt offerings convey unfavourable information about the issuing firms.

Several event studies document positive abnormal returns in response to the companies' eco-friendly behaviour (e.g., Flammer 2013; Klassen, & McLaughlin, 1996; Krueger, 2015). These findings suggest that bond issuance announcements have a mixed reaction from institutional investors.

Environmental Performance

The orientation of investments to sustainable activities through Green Bonds from the environmental perspective has been studied only in a few cases. For example, Flammer (2020) studied the green bonds' environmental performance post-issuance and found that the issuers indicated higher environment ratings and lower CO_2 emissions. Their finding also suggested that as the companies' environmental performance improves and becomes more attractive for an investor's clientele, it is sensitive to the natural environment. They found a positive link between companies' environmental responsibility and stock market performance.

Heine et al. (2019) used the combination of carbon pricing and green bonds in a three-phase model and used the numerical solution procedure. They modelled the interaction using an intertemporal model that proposes the burden-sharing between current and future generations. Their results showed that green bonds performed better when they are combined with carbon pricing. Sartzetakis (2020) also examined central banks' role in financing the low carbon economy and theoretically argued the intergenerational burden-sharing and long-term infrastructure investments. While most of the literature researched the practical usage of green bonds through the intergenerational burden-sharing method to mitigate future environmental damage, this paper checks if there is a reduction in the carbon emission after the green bond market has taken place, i.e., Paris Agreement. Flammer (2020) is the main motivation to carry out this study.

A recent report on BBVA green bonds mentioned that the project financed with green bonds in 2018 and 2019 avoided a total of 724,000 tons of CO_2 atmospheric emissions, which is almost three times than the previous year. It shows that funding the environment projects through green bonds' issuance helps achieve Sustainable Development Goals (SDG).

Data

This paper focuses on the practical side of Green Bonds. It examines whether the Green Bonds are priced differently from conventional bonds and how Green Bonds' issuance has impacted the issuers. In the second part, whether the low carbon economy is built with the Green Bond tag and carbon emission reduction is discussed. This section describes the data collection method and the synopsis of methodologies used in this paper. As mentioned above, Green bond market is new and continuously developing; there is a mere risk of adequacy and quality in the information extraction. I used three basic econometric methods to check a structured hypothesis and formulate my conclusions. Firstly, an OLS regression intends to give a result on the statistical difference in green and conventional bonds' pricing. Secondly, an event-study analysis examines whether green bond issuance impacts the company's stock price. Cumulative Abnormal Return (CAR) analysis is checked using Microsoft Excel mathematical formulas for this method. The third part of this study again uses OLS regression which checks upon the green bond tag and carbon emission statistical relevance. *R* software is used as a modelling tool mainly to implement regression and descriptive data tables. The data is cross-sectional so a simple OLS regression with some robustness test can give some reliable results.

The main source of data used in this thesis is Thomson Reuters Eikon, which covers primary and detailed data about the corporate bond issuance and other market parameters. This study selected all the corporate bonds issued by non-financial companies after the Paris Agreement, December 2015 to December 2019. I separated the bonds on the qualitative information on the bonds' features, such as the nature of the projects for which the proceeds are used, the issuers' sectors, and the grade. This study selected corporate bonds on their characteristics of the instruments, whether they are green or conventional bonds. For example, government and supranational bonds are excluded in terms of lacking their valuation needs. Data shows that most of the Green Bond issuance has been made by the corporate sector, with financial institutions having the highest cumulative amount so far. It is partially explained by the strong reliance of financial firms on the bond market (Fatica, Panzica, & Rancan, 2019). However, this sample has not included the financial institutions' bond because of these issuers' specificities regarding leverage and regulation. Further, I used all available bond characteristics (such as Coupon, maturity, Duration, Callable, Puttable, Convertible) as a controlled variable in an attempt to limit disparity on bond characteristics between green and conventional bonds.

The initial dataset consists of 12,034 bonds out of which I identified 200 Green Corporate Bonds using the Green classification filter in Eikon. Further, the Use of proceeds classification and matching provides 554 Conventional Bond out of 11,834, which has similar properties as green bonds. It is the final number of bonds this project is based on.

All the data prices are converted to US Dollar to ensure comparability that changes could nega-

Table 2
Summary Statistics of the bond characteristics

Green Bonds					
Yield (bps)					
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
−0.8791	0.5171	0.9865	1.3298	1.6206	6.5969
Issue Amount ($)					
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
1.11E+07	45700000	79970000	174300000	147800000	1071000000
Duration					
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
0.2389	1.7124	3.0309	3.9389	4.4534	19.9647
Coupon					
Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
0.000	0.950	1.379	1.947	2.862	7.500
Conventional Bonds					
Yield (bps)					
Min.	1st Qu.	Median	Mean	3rd Qu.	Max
−4.2238	0.7432	2.3571	3.4133	4.4705	45.2439
Issue Amount ($)					
Min.	1st Qu.	Median	Mean	3rd Qu.	Max
423500	110400000	400000000	491900000	600000000	8070000000
Duration					
Min.	1st Qu.	Median	Mean	3rd Qu.	Max
0.1528	2.6331	4.7763	6.9801	8.7297	43.8285
Coupon					
Min.	1st Qu.	Median	Mean	3rd Qu.	Max
0.000	1.500	3.313	3.599	4.750	11.500

tively influence in exchange and inflation rates. As Eikon has no separate green Bond section, this paper's sample is compiled using the Green bond tag in the Eikon database. The total amount of issued green bonds between 2015–2019 is 35bn USD. The next table presents the green bond's descriptive characteristics and conventional bond.

Here, it is notable that the minimum green bond yield is negative, which possibly means the prices are so high that investors are sure to get back less than what they paid if they hold on the bond up to maturity. However, this is common in the bond market, so I have not dismissed these observations.

For testing the third hypothesis (mentioned in the upcoming chapter), I collected the carbon emission data from the GitHub website. The website conglomerate dataset from two main sources: The Global Carbon Project and the Carbon Dioxide Information Analysis Centre (CDIAC) and the World Bank. The Global Carbon Project typically update CO_2 emissions annually. The dataset consists of the carbon emissions on global aggregates and carbon emissions from different industries (e.g., oil and gas, cement etc.). I matched the countries of major green bond issuance and filtered out the comparison sectors. The matching procedure is performed in Excel as it is easier to identify countries match from there. This study then checks all other indirect emissions from the sectors involved in issuing green projects. This paper intends to examine a simple benchmark whether a firm reduces its carbon intensity after issuing green bonds to achieve the Paris Climate goals to assess how far green bonds might contribute to the transition to a low-carbon economy. An OLS regression tests the hypothesis, and the methodology of regression are explained fully in the next chapter.

Empirical Analysis

This section contains the methodology of this thesis, which comprises the empirical research and the econometric models needed to support the hypothesis. There are two major econometric methods used in the process to study, namely, a simple multi-factor OLS regression analysis to test whether the Green Bonds are priced differently than Ordinary Bonds, and an event-study that examines the reaction on the company's stock price on the issuance of Green Bonds since it is important to know whether the issuers actually benefitted with the new instruments. In the second part, a simple OLS regression is performed to test Green Bonds' practical use of carbon emission's interaction effect when implemented jointly. Following hypotheses are established to check the main issues. As mentioned above, the first hypothesis states the purpose to find out how green bonds are priced compared to conventional ones (H1). It is then necessary to test how the issuance of green bonds affects the stock market (H2), and the third hypothesis illustrates the effectiveness of green bond tag on carbon emissions (H3).

H1: *There is no difference between the price of the green bond and ordinary bond.*

In the literature review section, I noted that several studies showed that supranational and corporations' green bonds are priced with the premium compared to ordinary bonds and are statistically significant. However, Hachenberg and Schiereck (2018) found no lower considerable difference in the pricing of green bonds over conventional bonds in the secondary market. Therefore, this hypothesis will be tested with simple OLS regression to find a significant difference between these yields.

H2: *Stock Market reacts positively on the issuance of the green bond.*

According to Flammer (2020); Tang and Zhang (2018) findings, the stock market responds positively to Green Bonds' issuance. It signals the company's commitment to a green project and environment. Contrary to these findings, Lebelle et al. (2020) found market reacts negatively to green bonds' issuance. Thus, this hypothesis tests if green bonds are cheaper than ordinary ones, it should positively impact the company's stock price. It marks that the first hypothesis should be rejected.

H3: *Green Bond issuance is associated with reducing carbon intensities at the firm level.*

The third hypothesis tests whether a green bond tag helps build a carbon-neutral economy. Since there is limited literature on the connection between Green Bond tag and carbon emission from firms, this would be interesting to test this hypothesis. An OLS regression is performed with added controlled robustness test.

Model for the Firms issuing Green Bonds

This theoretical model explains how firms in bond and stock market choose between the green and conventional projects which explains the desired results. This model follows new literature on Green Finance (Daubanes et al., 2019), which uses the green finance firms' continuum model.

Mass-1 continuum of projects and dates $t = 0,1$.

Suppose 1 unit of capital at date $t = 0$ predicts Revenue 'Y' at date $t = 1$. On day 0, the choice between green (G) and conventional (B) project is 'k'. And CO_2 emissions at date $t = 1$: $x_B > x_G >= 0$. And the tax on CO_2 is w, penalising the green firm less heavily. Firms differ by CO_2 abatement cost: Firm i ∈ [0, 1] has cost c_B if k=B and c_G if k = G. Project financed by bonds that repay $R = 1 + r$ is exogenous. At $t = 1$, a profit of firm i ∈ [0, 1] with project green or conventional is

$$\pi = \pi_k(i) = Y - R - C_k(i) - \tau x_k .$$

At $t = 0$, firm manager observes i and choose $k = G, B$:

$$\max_k U_k(i) = \alpha \frac{\pi_k(i)}{1+\rho} + (1-\alpha) S_k .$$

Where profit at $t = 1$ is anticipated by a manager but not market and stock price S_k at $t = 0$ is the function of k. The stock investors require exogenous return ρ. They observe firms' project choice $k = G, B$ but particularly not projects' type i. The stock price at date $t = 0^+$ is

$$S_k = \frac{E\left[\pi_k(i)|k\right]}{1+\rho}.$$

If the stock investors react positively to the green bond issuance:

$$\Delta S = S_G - S_B \geq 0.$$

Now the volume of green bonds issued by firms is i^e. The stock market reaction in equilibrium is amplified as

$$\Delta S\left(i^e\right) = \frac{\alpha}{1+\rho}\left(c_G\left(i^e\right) - \overline{c_G}\left(i^e\right)\right) > 0.$$

And the abnormal returns at issuance follow:

$$\mathcal{A}_G\left(i^e\right) = \left(1-i^e\right)\frac{\Delta S\left(i^e\right)}{S^0\left(i^e\right)} > 0.$$

Where *ex-ante* stock price is

$$S^0\left(i^e\right) = i^e S_G\left(i^e\right) + \left(1-i^e\right)S_B.$$

Econometric Methodology

Multi-Factor Regression on Bond Prices

To investigate whether Green Bonds are priced differently, or the same as Conventional Bonds, a standard regression for Bond coupons is carried out. This part follows the same econometric strategy explained by Fatica, Panzica, and Rancan (2019), which follows the traditional cross-sectional OLS regression as Fama and French (2007) used. An OLS model's advantage is that it is simple and has a large body of research that discusses suitable determinants. If correctly implemented, it could be used to draw general conclusions. Green Bond are very similar to Conventional bonds, as mentioned in the above section of this thesis, so there is no reason to believe that they differ significantly in terms of explanatory factors. The econometric model is as follows:

$$Coupon_{b,i,t} = \beta_0 + \beta_1 Green_{b,i,t} + \beta_2 X + \varepsilon_{b,i,t}, \qquad (1)$$

where the dependent variable Coupon refers to the coupon at the issuance of the corporate bond *b* issued by firm *i* in time *t*. $Green_{b,i,t}$ is a green bond dummy variable which equals one if a bond is green and zero otherwise, and it is the main variable of interest. Independent variable *X* is a set of controlled variables that may affect the bond's coupon. The control variables are mainly the dummy variable of the other bond characteristics such as Callable, which is equal to one if a bond is redeemed prior to the maturity date, zero otherwise; puttable, which is equal to one if the bond is puttable, zero otherwise. Further, the other variable is the bond's duration, which determines the bond's maturity time, the bonds with shorter maturity return principal to Investors earlier than the long-term bond. The result of the regression is as follows:

Table 3 shows that the Green Bond Dummy variable's coefficient, which is the main variable of our interest, is negative (−2.27) and statistically significant at 1% confidence level. It suggests that the Green Bond is priced approximately 227 basis point cheaper than the conventional bonds, and that is why issuers prefer green bonds over ordinary bonds. Other controlled variables also showed statistically significant results, which can be interpreted as for example, if the company's bond has a putable feature, resulting in a higher coupon rate (2.30) based on the sample taken. In general, a putable feature is an added benefit for the bondholder. It makes able to sell the bond if the market interest rate rises and has a lower yield to compensate the issuer. Duration indicates the average time until the cash flows are received and measured in years. It is equal to the bond's maturity if the bond is a zero-coupon bond, which in this case some conventional bonds are zero-coupon bonds. The positive coefficient (0.04) indicates the significant positive relationship with the coupon which means if there is a high coupon bond, then the repayment will be faster which is in line with the theory of the relationship between coupon and the Macaulay duration of the bond. Green Bond characteristics are no less different from the ordinary bond. This comparison seems somewhat expected compared to prior studies (Fatica, Panzica, & Rancan, 2019) but probably should not be taken as an unquestionable truth but more as an indicative result. In the regression result, R-squared seems to be relatively low, which can affect the determining result. It can be robust by adding more control variables, but the risk of variable robustness can be present. It also means that although the green bonds are

Table 3
The Multi-Factor Regression result on the sample of data from 2015 to 2019

Variables	Coefficients	Std. Error	P–values
C	4.06132	0.17812	2e-16 ***
GreenBondDummy	–2.27116	0.20892	2e-16 ***
CallableDummy	–1.28636	0.20134	3.02e-10 ***
PutableDummy	2.30751	0.67653	0.000684 ***
Mac. Duration	0.04031	0.01614	0.012740 *
Multiple R-squared	0.1737		
Adjusted R-squared	0.169		
F-statistic	37.2		
p-value	2.2e-16		

Notes.
The coupon is the independent variable.
All other specifications include a set of bond fixed effects.
The variable's significance level is indicated as * 10 per cent, ** 5 per cent, and *** 1 per cent.

statistically significant, this analysis should not be considered as too definite with the resulted coefficient level.

The next table consists of the same regression with some robustness checks. It adds more control variables such as the yield spread of the comparable bonds and Sinkable dummy (1) or (0), which adds to bonds' characteristics and limit imbalances between green and conventional bonds. The sector variable is also included in the regression to control potential effects and increase the coefficient of determination.

Robustness check shows that Green Bond's main variable remains statistically significant with a coefficient (–1.93), which is slightly different from the first regression result indicating the result is improving on adding a more controlled variable. Results of Callable and Putable dummy variable remained quite similar to the previous regression. However, the added controlled variable sinkable dummy does not provide a statistically significant result. Yield Spread (0.003) is showing significant coefficients. In this regression, r-squared (50 per cent) seems to be slightly higher than the previous one (32 per cent). It can be explained with the added control variables and sectors dummy, but the risk of variables robustness is still present.

In contrast to the study of Fatica et al. (2019), my study observes much lower r-squared degree; their study received an r-squared of more than 70 per cent. It may be explained by the fact that their study has a large data sample and from a more extended period, and the methodology more comprehensive. For example, their study used a fixed effect *maturity×rating×time* variable and controlled time-invariant unobservable firm-specific characteristics using an issuer effect. However, this paper does not reach the same level of excellence but gives similar results compared with their studies. Improvements could be made by widening the data and period of research and including financial institutions as well. The results taken from the regression used in this study should not be taken certain but more as indicative.

Event Study Analysis

This section explores what happens to a company's stock price that issues the green bonds. According to market efficiency hypothesis stock price reflects all available information and adjust rapidly to any new information (Fama et al., 1969). Hence, this study will check the market's reaction at the time of issuance of the green bond through the change in the stock price. The company chosen for the study is selected from the data sample used in this paper whose stocks are as liquid as possible. The company's stock's liquidity helps to understand the channels and mechanisms underlying positive announcement effects. The null hypothesis assumes that

Table 4
Multi-Factor regression Result

Variables	Coefficients	Std. Error	P-values
C	−0.1485778	1.8312157	0.93536
GreenBondDummy	−1.9274871	0.1946857	2e-16 ***
CallableDummy	−1.3354209	0.1725375	3.67e-14 ***
PutableDummy	2.3016284	0.5554375	3.85e-05 ***
SinkableDummy	−0.1554058	0.5712561	0.78567
Mac. Duration	0.0089604	0.0145913	0.53936
Yield Spread (OTR) to Maturity	0.0031953	0.0002259	2e-16 ***
Sector Dummy	**Yes**		
Multiple R-squared	0.504		
Adjusted R-squared	0.4737		
F-statistic	16.63		
p-value	2.2e-16		

Notes.
Covariance method Huber-White is used for the robustness of the variables.
Statistical significance level of confidence 10%, 5%, and 1% level is denoted by *, **, *** respectively.

the stock prices increase after firms' green bond announcement. This event study's motivation comes from the study of Tang and Zhang (2018) and Glavas (2018), where the impact of the green bond announcement on stock price is examined through CAR analysis. This test is conducted using a 10- and 20-days window, and the market index prices are retrieved from Yahoo finance websites. Stock prices of the company are retrieved from the Datastream. This study uses the issuance date instead of the announcement day to see the market reaction as its announcement date was not clear.

Abnormal returns.

The total return prices were computed using the return index function of DataStream. The return index was based on an annualised dividend yield following Indices (2008):

$$RI_t = RI_{t-1} \times \frac{PI_t}{PI_t} \times \left(1 + \frac{DY_t \times f}{100} \times \frac{1}{N}\right),$$

where RI_t is the return index on day t, PI_t is the price index on day t, DY_t is the dividend yield in the percentage on day t: f is the grossing factor (typically 1) if the dividend yield is a net figure f is used to gross up the yield. N represents the number of working days in a year (usually 260) multiplied by 100.

I used zero to five trading days windows around the bond issuance date to consider the risk of information leakage before or the under-reaction risk after the announcement of bond issuance.

The abnormal return or the firm i and event day t are defined as:

$$AR_{it} = R_{it} - Rm_{it}$$

R_{it} is the firm's return, and Rm_{it} is the market return.

The cumulative abnormal return between t_1 and t_2 is computed as follows:

$$CAR_i(t_1, t_2) = \sum_{t_1}^{t_2} AR_{it}$$

The following table shows the CAR event study results for the mentioned time windows.

As we can see in Table 5 that there are statistically significant returns for the stock during [−5,5] and [−15,5] time windows. It explains that the stock market positively reacts to the green bond issuance which is in line with the study of Tang and Zhang (2018), who found abnormal return at the same time as the company announces the issuance of a green bond. Their study found that the green bond issuer company's stock price tends to increase statistically significantly in the time frame, including the green bond issuance's announcements. The effect on the ordinary corporate issuer is stronger comparatively financial institutions. In this study, the chosen stock gives a statistically significant 0.23 per cent and 1.14 per cent cumulative abnormal return during [−5,5] and [−15,5] time window around the issuance of the green bond. It explains that the market reacts to the green bond price over the short time window, as both the time frame gives statistically significant results. Basically, comparing to regular bond announcements, green bond announcements blend two pieces of information i) a bond issuance, and ii) a signal of a company's commitment to the environment. Since the stock market is typically unresponsive to conventional bond issues (Flammer, 2020), the stock market's positive reaction is likely to reflect the latter. To conclude, this study indicates shareholders also benefit from the issuance of green bonds, which can be taken as an indication that issuing a green bond turns out to be beneficial for its issuer.

Nevertheless, this examination is under the risk of robustness, as it only examines one company. It is due to the lack of adequate data from companies in this thesis data. Hence, this example should not be considered for overall stock market behaviour around the green bond issuances but as supporting evidence with the previous findings. This study could be more profound and comprehensive if it also includes different companies across different sectors and sizes.

Table 5

Event study outcomes through CAR analysis for the green bond issuance date

Cumulative Abnormal Return (CAR)		
	(1)	(2)
Event Window	[−5,5]	[−15,5]
CAR	0.23%	1.14%
T-test	−2.43**	−2.33**

Notes.
The results are computed based on the cumulative abnormal return (CAR) comparing to the company stock and Nasdaq market index.
Data for a company's stock price over time pooled from DataStream and market index data from Yahoo finance.
Testing indicates the stock price at the time of green bond issuance reacted differently or not.
Statistical significance of the variable coefficient denoted with an asterisk: * 10%, ** 5%, *** 1% level of confidence.

Environmental Performance (Green Bond and Carbon emissions)

In this part, I examined the effectiveness of Green Bond on carbon emissions by carrying out OLS regression to understand if there is any significant relationship between how the Green Bond label market covers carbon emissions' reduction.

Table 6

The multi-factor regression result

Environmental Performance			
Variables	Coefficients	Std. Error	P-values
CO_2_growth (C)	2.4302	0.3974	1.59e-09**
GreenBondLabel	−0.6198	0.7376	0.401
Multiple R-squared	0.0009921		
Adjusted R-squared	0.000413		
F-statistic	0.7061		
p-value	0.401		

Notes.
Carbon emissions are the dependent variable.
Green Bond label is the independent variable.
Data for carbon emission is taken from GitHub.
Green Bond Label firm wise data is presented from Thomson Reuters Eikon.
The variable's level of significance is indicated as * 10%, ** 5%, and *** 1%. Sample data is from 2015 to 2019.

The result shows no statistically significant relation between Green Bonds, which are classified according to the environmental rating from the same dataset used in this thesis, and the carbon (CO_2) emission growth over the years (p-value > 5%). However, this result should not be considered truth, as the data collection process wasn't exact. In contrast with the methodology followed by Flammer (2020), which uses three parameters of the Green Bonds issuance; Green Bond pre-issue year which is a dummy variable equal to one in the year preceding the issuance of the green bond, and the CO_2 emissions is the ratio of CO_2 emissions (in tons) divided by the book value of assets. The dataset also consists of a more extensive period. Their results showed that the environmental performance goes substantially in the long run, and emissions are reduced by 13 tons of CO_2, i.e., a reduction by 12.9 per cent. Compared to their studies, this result turns out to be insignificant and does not reach the same level pre-eminence.

Further, encountering the sector-wise emissions of the companies who issues the green bonds as the independent variable to check if the contributing sector has any effect on the carbon emissions, an OLS regression is carried out taking the Green Bond dummy variable and the sectors. Results are shown in Table 7.

Table 7 shows that the values are highly insignificant and have no explanatory power to illustrate that the green label decreases carbon intensity. According to Ehlers, Mojon, and Packer (*BIS Quarterly Review*, September 2020), "the current label of green bonds does not necessarily signal that issuers have a lower or decreasing carbon intensity". In this result, sectors that issue green bond were insignificant in relation to the carbon emission growth over those years. These findings might be abnormal due to the Carbon emission's ambiguity by any specific company. As the carbon emission data is taken from global aggregates, it is hard to explain the sectors' explicit relation and overall emissions. Taking the environment rating factor into narrower scrutiny by disaggregating the data by a company would increase the impact on the results. It can also be improved by adding the certification examination factor and indicating if the green bonds are certified or not certified within the company. It can be assumed consistent with the signalling argument that certification is costlier and reflects

Table 7
Robustness test by including Sector variable

Variables	Coefficients	P-values
CO2_growth (C)	44.33	0.989
GreenBondLabelDummy	−198.62	0.527
Sectors		
Airline	4217.81	0.219
Automotive Manufacturer	306.63	0.926
Beverage/Bottling	423.19	0.905
Building Products	678.25	0.835
Cable/Media	−25.36	0.994
Chemicals	−22.83	0.994
Conglomerate/Diversified Mfg	1283.82	0.694
Products	695.71	0.835
Electronics	529.08	0.872
Processors	−13.26	0.997
Gaming	1208.12	0.756
Gas Utility-local Distrib	648.38	0.849
Gas Utility- Pipelines	−38.94	0.993
Health Care Facilities	32.70	0.992
Health care Supply	−36.15	0.994
Home Builders	1199.18	0.708
Industrials	645.89	0.846
Indformation/Data Technology	5035.85	0.128
Leisure	−41.49	0.991
Lodging	−43.02	0.991
Machinery	1477.79	0.678
Metals/Mining	−33.85	0.992
Oil and Gas	1004.76	0.756
Pharmaceuticals	1922.18	0.562
Publishing	397.59	0.914
Railroads	834.73	0.799
Retail Stores-Food/Drugs	130.75	0.972
Retail stores-Other	528.40	0.876
Service-Other	740.39	0.816
Telecommunications	546.71	0.865
Textiles/Apparel/Shoes	122.13	0.978
Tobacco	69.18	0.988
Transportation- Other	263.66	0.935
Utility-Other	758.23	0.812
Vehicle Parts	32.35	0.993
Multiple R-squared	0.05362	
Adjusted R-squared	0.003222	
F-statistic	1.064	
P-value	0.3705	

Notes.
Carbon emission is the dependent variable and Green Bond being an independent variable.
The regression control result for each sector is introduced in the model.
The variable's level of significance is indicated as * 10%, ** 5%, and *** 1%.

a more robust commitment towards the natural environment (Flammer, 2019).

It is a simple benchmark. More sophisticated methods of assessing the climate-related impact of green bond issuance would require a full multivariate model to precise layout the counter fact that the change in carbon emission intensity had a firm not issuing a green bond. Overall, this analysis is merely laying out important consideration of different sector ratings to foster carbon efficiency in economic activity. Obviously, data on broader emission scopes would further help assess the overall sector's carbon footprints.

Conclusions

This paper examined the green bond market after the Paris Agreement. There are significant measures taken after that period and investigates whether the green bonds are priced lower than conventional bonds. The rapid growth in the green bond market since the genesis in 2007 and should reach $ 1 trillion in the coming years. Taking four years of data from 2015 to 2019 of corporate green bonds, especially issued by non-financial companies, the main results are observed after regression testing and with some robustness check by adding more controlled variables. I thus tested three hypotheses. The first hypothesis stated that the green bond is issued with a premium compared to conventional bonds. The second tested hypothesis stated that green bonds have positive returns on stocks. The third hypothesis asserted that the green bond reduced carbon intensity at the firm level.

According to the examined sample, the result finds that the green bonds are priced cheaper than the conventional bond with 1.93 per cent premium. This finding is similar to the prior research by Fatica et al. (2019), and Baker et al. (2018) who found that bonds are priced cheaper than the conventional bond. The market has similar risk compared to the traditional market. Even though I found a slightly stronger coefficient compared to their studies, the results are in the same direction of proving the premium of green bonds. However, a wider range of robustness check is needed to get more accurate results to improve the study's quality.

The second part of this thesis investigates how the stock market responds to corporate green bonds' issuance. By carrying out an event study (CAR-model) on different time windows [−5,5] and [−15,5], I get statistically significant excess returns (0.23 per cent and 1.14 per cent) on both time windows. The robustness test is missing from this experiment as it investigates only one company, but it shows consistent results as previous studies; Flammer (2020) who also observed the stronger response for green bonds that are certified by independent third parties and first-time issuers, and also aligns with the study of Tang and Zhang (2018).

Finally, this thesis explores the interaction effects of green bond and carbon emission. It is a very interesting part as it focuses on the efficiency of green bonds towards the practical use of these instruments, which is the vital purpose of their issuance. However, the result shows an insignificant high coefficient of change in carbon emission over the years taken in this study. Robustness check is carried out by adding the carbon emission sector-wise, and most of the sector shows an insignificant relationship with the green bonds. Overall, this part of my results is inconsistent with the line of other literature (e.g., Flammer, 2020). It can be explained because of the conciseness of the study's period. Since the high carbon emission has already become a serious concern, it can be supported by this argument that we are still far away from achieving our goal of reduction of the emissions by a remarkable amount. Prior studies use the same hypothesis but carried out different approaches to explain their results. Flammer (2020) measured environmental performance of green bonds by taking the ESG ratings of the company's and compared it with the ratio of carbon emissions divided by the book value of the assets and used a matching procedure to ensure that the treated and control firms have similar environmental performance prior to the green bond issuance. Their results found a significant positive relationship with the environment rating of a bond which goes up by seven percentage points and carbon emission reduced by 12.9 per cent indicating companies improve their environmental performance with the green bonds. Another study by Heine et al. (2019) observed this instrument to finance low-carbon emissions by imposing carbon pricing taxes. Their study uses a three-phase model to explain how green bonds performed better when combined with carbon pricing.

This study still calls for further research as the corporate green bonds are a new financial instrument and are relatively based on a small number of observations and criteria. However, substantially using all the previous literature finds and this thesis' results, it is somewhat clear that the green bond market has tremendous efficiency to become a financial weapon against climate change. Efforts are currently underway to enhance the green bond's performance for a better future.

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Практическая жизнеспособность зеленых облигаций и экономические выгоды

Аникита Кант

Аннотация. Зеленые, или «климатические», облигации часто рассматриваются в качестве финансового инструмента, который способен преодолеть отказ от зеленых инвестиций. В статье представлены результаты исследования потенциального вклада и роли зеленых облигаций, связанных с переходом к низкоуглеродным технологиям, а также выгоды корпоративного сектора. Рынок зеленых облигаций находится под постоянным контролем с момента их появления в 2007 г. С течением времени значение их воздействия в борьбе с изменением климата постоянно растет, что можно рассматривать как аргумент в пользу инвестирования в зеленые облигации. Используя критерии соответствия и выполнив многомерную регрессию OLS, автор задался целью проверить, отличается ли цена зеленой облигации от цены обычных. Результат показывает, что зеленые облигации дешевле обычных с премией 1,93–2,24%, что согласуется с предыдущими исследованиями по этой теме. Используя выборку из 200 корпоративных зеленых облигаций, выпущенных после Парижского соглашения (с декабря 2015 по декабрь 2019 г.), автор с помощью теста CAR документально подтвердил, что фондовый рынок положительно реагирует на объявления о зеленых облигациях. Полученные в ходе исследования результаты предполагают, что, возможно, зеленые облигации работают хорошо с экономической точки зрения, но все еще далеки от достижения своей практической цели.
Ключевые слова: зеленые облигации; изменение климата; выбросы углекислого газа; налог на выбросы парниковых газов; корпоративные финансы

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The EU ETS and Aviation: Evaluating the Effectiveness of the EU Emission Trading System in Reducing Emissions from Air Travel

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Abstract

Over the past 30 years, the aviation industry has seen record-breaking growth whilst enjoying exemptions from most taxes and VAT charges. Currently, the aviation sector is considered one of the fastest-growing greenhouse gas emissions sources. Attempting to reduce these emissions in a cost-effective manner, the EU decided in 2012 to include all flights entering and leaving the EU in their Emission Trading System (EU ETS). It was quickly changed to only include travel within the EU. Nevertheless, as the largest cap-and-trade system in the world, the purpose of the EU ETS is to control the growth of emissions by issuing pollution permit rights. The idea is that by setting an emission ceiling and allowing trade between sectors, emission abatement will happen where it is cheapest and easiest to do. This paper explores whether the EU ETS succeeded in reducing the aviation sector emissions over the period 2012–2018 by employing a General Synthetic Control model to estimate a counterfactual scenario. When using jet fuel consumption as a proxy for emissions, the results indicate that on average the EU ETS led to a 10 per cent increase in jet fuel consumption relative to a scenario where it was not implemented. However, the paper fails to conclude a causal relationship between EU ETS and jet fuel consumption due to drawbacks with the data. Nevertheless, it provides a starting point for future ex-post research concerned with aviation and carbon pricing in the European market.

Keywords: Emissions trading system; aviation industry; General Synthetic Control model; greenhouse gas emission; air pollution

JEL Classification: C20, L93, Q20, Q35, Q52, Q53, Q58, R41

Introduction

The EU's Emission Trading System (EU ETS) is the largest cap-and-trade scheme globally and was implemented to combat climate change and reduce greenhouse gas (GHG) emissions in a cost-effective manner. It covers more than 11,000 energy-intensive installations in 31 countries, in addition to airlines operating between these countries, accounting for approximately 45 per cent of EU's GHG emissions. For convenience, throughout the paper, the term "EU" will include all EU-28 countries plus Iceland, Liechtenstein, and Norway, unless explicitly stated otherwise (see **Annex 1**).

The EU ETS was developed to facilitate the goals set out in the Kyoto Protocol. The Kyoto Protocol required emission reductions in industrialised countries, and the common EU-wide target was set at an 8 per cent reduction in GHG emissions by 2012 compared to 1990 levels (Transport and Environment, 2016). How to achieve the EU-wide reductions was left up to the member states, and in 2003 the EU agreed to an emission trading scheme across borders (EC, 2003, Directive 2003/87/EC). The member states received emission permits, called EU Allowances (EUAs), by the European Commission (EC) after submission and approval of their National Allocation Plans (NAPs) outlining the reduction target and regulated installations. The ETS sets an emission cap which is slightly reduced every year with the intention of polluters having to either reduce their emissions or purchase additional allowance which should progressively grow scarcer and more costly. The first phase of the EU ETS (2005–2007) was used as a trial period to develop experience and find potential improvements for later stages, whereas phase II (2008–2012) coincided with the Kyoto commitment goals made by the EU (Wråke et al., 2012). Phase III (2013–2020) is a continuation of the previous two phases, including more sectors and a single EU-wide cap than the national caps previously used. The next trading period, phase IV (2021–2030), adopts emissions targets in line with the Paris Agreement for 2030 (EC, n.d.).

Since the start of the EU ETS, its scope has expanded in terms of geography, sectors, and type of greenhouse gases. The first two phases of the EU ETS included the most GHG-intensive sectors in the power and manufacturing industry (EC, 2015). During Phase I, the focus of emission reduction was solely put on CO_2. However, in Phase II, other GHG emissions, such as nitrous oxide, was included by several countries. When referring to "emissions" throughout this paper, it can be assumed this only includes CO_2 emissions, unless explicitly stated.

Although the EU ETS marks the first international ETS, there are up to 61 carbon pricing initiatives worldwide (World Bank, 2020). It includes 31 ETS's and 30 carbon taxes. Collectively they cover around 22 per cent of global GHG emissions. Out of the 61 initiatives; however, only the EU, China and the Republic of Korea have ETS's that cover the aviation sector.

In 2008 it was agreed that aviation should be included in the EU ETS from 2012 (EC, 2009, Directive 2008/101/EC). It resulted from the forecasted rapid growth in the industry and the International Civil Aviation Organization (ICAO) failing to adopt a global measure for aviation (Transport & Environment, 2016). Initially, it was set out to cover all flights departing or arriving in the EEA area — however, due to strong foreign (non-EU) and industry objections it was decided shortly after implementation that only intra-EU flights (flights departing *and* landing in EU) were subject to the policy. The legislation referred to as "stop the clock", exempts international (extra-EU) flights from submitting pollution permits. It was initially set to last until 2016; however, it was extended until 2024 to support the development of a global measure by the ICAO (EC, 2015).

The emission cap for aviation is separate from the overall EU ETS cap, with individual permits called EU Aviation Allowance (EUAA). It is set at 97 per cent and 95 per cent of historical emission between 2004 and 2006, for 2012 and 2013–2020, respectively. Out of these, 82 per cent are granted for free, whilst 15 per cent are auctioned. The remaining 3 per cent are reserved for fast-growing airlines and new entrants. Based on verified tonne-kilometre data for 2010, airlines have received approximately 0.6422 allowances per 1,000 tonne-kilometre flown between 2012–2020 (ibid).

Commercial aviation, mainly international, has historically enjoyed exemptions from most taxes and VAT charges, unlike other transportation methods. It is partially due to the restrictions set out in the Chicago Convention, in addition to ICAO's recommendations (EASA et al., 2019). Furthermore, air travel is closely associated with economic growth, with many papers indicating the contribution of aviation to economic growth directly linked to traffic volume (Marazzo et al., 2010; PwC 2017; Dimitrious & Maria, 2018). Global air travel supports $ 2.7 trillion in world economic activity, equivalent to 3.6 per cent of global gross domestic product (GDP), and would rank 20th in the world in terms of GDP if it was a country (ATAG, n.d.). Taxing airlines, either directly or through a market-based measure (MBM) like the EU ETS, in the hope to reduce emissions, will arguably lead to more substantial economic issues associated with GDP growth. Recognising that depleting air traffic growth could essentially hurt economic prosperity, the EC, in addition to their generous cap, allows a one-way trade between aviation and stationary sources to facilitate the growth in the sector. The aviation sector can purchase EUAs from all actors; however, it can only sell their permits to other airlines (Kopsch, 2012).

The aviation sector is considered among the fastest-growing sources of GHG emission. GHG emissions from international aviation have increased by 141 per cent from 1990 to 2018 and accounted for 167 million tonnes of CO_2 equivalent emissions in 2018 (EEA, 2020a). The EU is one of the world's largest aviation emitters, and intra-EU flights are predicted to grow by over 80 per cent relative to 2005 levels by 2030. Without action, emissions can expect growth up to 300 per cent by 2050 (ICAO, n.d), threatening the 2°C target set by the Paris Agreement. Since the inclusion in EU ETS, aviation emissions have increased by 28 per cent[1] in absolute terms and now represent approximately 3.6 per cent of total EU emissions.

In comparison, other ETS sectors have seen a decrease in GHG emissions by 19.7 per cent[2] (Transport & Environment, 2020b). Even with 17 member states in the EU levying VAT or taxes on domestic aviation, arguments that stronger measures are needed to address the negative environmental externalities exist. Hemmings (via Transport & Environment, 2020a) claims that the EU aviation industry is still severely under-taxed and under-charged. They suggest that Europe should levy fuel taxes, ticket taxes and/or VAT at a higher price than today.

An emission trading scheme intends to reduce emissions by affecting firms' marginal costs. It establishes a right to emit and allows for permit trade across sectors, leading the market towards the ultimate cost-effective allocation of permits (Montgomery, 1972). The incentive for trade exists as long as marginal abatement cost differ. As the cap tightens, permits grow scarcer, and it becomes more costly for actors to pollute, thus it creates an incentive for environmental-friendly innovation (Porter, 1991).

Due to certain characteristics, the aviation sector is not fully comparable to other sectors of the economy (EASA et al., 2019). Unlike other forms of transport, or other industries, the primary energy source of aviation (jet fuel) is not readily substitutable (Stern, 2007). Technological progress in aircraft design and flight operations has been successfully achieved over the past 30 years, and average fuel consumption per passenger kilometre (PKP) has reduced by 24 per cent since 2005 (Fukui & Miyoshi, 2017). The number of passengers carried in Europe has increased by over 60 per cent in the same period (EASA et al., 2019). Thus, even with "green" innovation and technological improvements, the emissions associated with forecasted growth in the sector is unlikely to be offset (EASA et al., 2019; Nava et al., 2018). Nevertheless, aviation still needs to deliver more in-sector emissions reductions than currently witnessed.

The one-way trade in the EU ETS allows airlines to compensate for their emissions by purchasing allowances from sectors where abatement is cheaper and more easily attainable (EASA et al., 2019). However, the increased costs of these permits should have positive environmental effects. Vespermann and Wald (2011) outlined that the increased cost associated with the pollution permits should lead to airlines increasing ticket prices or reducing supply. Either way, it suggests less demand, thus reducing fuel consumption, ultimately reducing emissions. A counterfactual needs to be calculated to analyse the relationship between ETS and emission reductions. Only looking at absolute values makes it easy to conclude that EU ETS has not led to abatement. However, one cannot merely conclude the EU ETS is the cause of CO_2 reductions, or increments in this case, by looking at differences in total CO_2 emissions during the period. These outcomes could have happened in the policy's absence due to technological considerations, exogenous shocks, or other macroeconomic factors. Instead, to assess the EU ETS's effectiveness, a counterfactual need to be calculated. That is, the emissions that would be observed had the EU ETS not been in place, sometimes called the Business-as-Usual (BAU) scenario.

This paper attempts to evaluate whether aviation's inclusion in the EU ETS has led to emissions reductions relative to a BAU scenario. It will do so by estimating a counterfactual using a Generalized Synthetic Control (GSC) model proposed by Xu (2017), which have proved effective in addressing policy impacts on aggregate values, where heterogeneous effects of unobserved confounders are likely to exist. Using jet fuel consumption as a proxy for emissions, aggregate values are collected for 45 countries, with 30 being subject to the EU ETS and the remaining 15 acting as control variables (see **Appendix 2** for list of countries).

Literature Review

The following section will review literature aimed at assessing the effectiveness of the EU ETS in its various phases. Due to this study's macroeconomic nature, the papers examined also focus on sector and countrywide effects. The review includes an overview of the cap-and-trade system. The first two phases of the EU ETS is discussed, followed by literature focusing on the impacts of carbon pricing on aviation.

[1] Between 2013 and 2018.

[2] Compared to 1990 levels.

The Idea Behind EU ETS (Cap-And-Trade Market)

The EU ETS' main objective is to "promote reductions of greenhouse gas emissions in a cost-effective and economically efficient manner" (EC, 2003, Art. 1). Theoretically, carbon markets reduce emissions at the lowest cost, making it the most appealing method (Aldy & Stavins, 2011). Wagner (2003) observes that there are mainly three instruments used for environmental regulation; (1) Standards/emission limits, (2) Environmental taxes and charges, and, (3) Tradable and transferable emission permits and certificates. Instruments are also distinguished between market-orientated and judicially-orientated (command-and-control). Command-and-control regulatory standards are generally technology-based or performance-based. According to Aldy and Stavins (2011), neither tend to achieve a cost-effective solution.

When assessing the different regulatory instruments mentioned above Wagner (2003) finds that permits yield the most favourable results in terms of (cost) efficiency, dynamic incentive effects, structural and regional policy effects, distortions of competition and environmental effectiveness. Besides, they are also more likely to lead to the effects proposed in Porters hypothesis — which state that properly constructed regulatory standards aiming at outcomes will encourage companies to innovate, leading to less pollution, lower cost and better quality (Porter, 1991; 1995).

Although the empirical literature does not support Porters hypothesis due to its special assumptions about company and market functions (Brännlund & Lundgren, 2009), the hypothesis does provide arguments for preferring incentive-based over command-and-control type regulations. As an incentive-based regulation, a trading emission permit system encourages firms to reduce emissions through innovation, provide cost-effective allocation and abatement solutions, and, as a result, is less likely to limit the profitability of a firm (Wagner, 2003).

Moreover, the market-based system allows firms to value the emission allowance that reflects the cost of emission reductions possibly avoided by surrendering that allowance — famously called 'opportunity cost' (Aldy & Stavins, 2011). Thus, carbon's market price is equal to the lowest marginal abatement cost among all controlled sources (Egenhofer et al., 2011), and not explicitly fixed by an authority. Egenhofer et al. (2011) also highlight that the reason EU opted for the cap-and-trade system might be due to previously failed implementation of other instruments — drawing on examples like the rejected 1992 carbon tax proposal and poor voluntary agreements covering EU industries.

The EU ETS Phase I and Phase II

One of the first to evaluate the impact of the EU ETS on CO_2 abatement was Ellerman and Buchner (2008). The authors created a counterfactual using NAP data and found abatement efforts of about 7–8 per cent compared to a BAU scenario. Even if they found significant abatement in the period, there exist drawbacks in their calculations. Namely, the data used to calculate the counterfactual was collected voluntarily, sometimes unverified, and due to different estimations standards, the data was not perfectly comparable across countries. Furthermore, industries' incentive to exaggerate emission numbers as their allowance (EUAs) allocations were based on these unverified reports. A previous study by Ellerman and Buchner (2007) found an overallocation of allowances during the pilot phase — most prominently seen as CO_2 emissions were about 3 per cent lower than the allocated allowances. Although it is unlikely that there was no abatement during the pilot phase, Ellerman and Buchner (2008) result most likely contain an upward bias.

To improve their previous study, Ellerman, Convery and de Perthuis (2010) used United Nations Framework Convention on Climate Change's (UNFCCC) Common Reporting Format (CRF) data as a second source to estimate their counterfactual calculations. Herold (2007), being the first to investigate the legitimacy of using UNFCCC data as a proxy, find the two datasets (UNFCCC CRF and EU ETS verified emissions) to not match perfectly due to the scope of the EU ETS sectors and the different source categories in the CRF data. However, he concludes that since the share of CO_2 emissions reported by EU ETS is similar across the Member States in the UNFCCC data, there is proof of consistency between the datasets. Ellerman et al. (2010) conclude that even if their evidence suggests the EU ETS created emissions reductions of between 2–5 per cent during 2005–2007, the strongest evidence of the effectiveness of the EU ETS is that sector emissions stopped growing despite continued economic growth and development in relative fuel prices that would otherwise have led to higher emissions.

Anderson and Di Maria (2011) were interested in testing both the abatement of CO_2 and whether over/under allocation took place during the first phase. Contrary to Ellerman and Buchner (2008), they use historical data from Eurostat and match past emissions classified by NACE codes to the sectors participating in the EU ETS. Using a dynamic panel data estimation that controls historical data on European industrial emissions, industrial economic activity levels, weather effects, and energy prices, they estimate the counterfactual. Their results show overall GHG abatement in Phase I to be 2.8 per cent.

Extending the analysis of Ellerman et al. (2010), Egenhofer et al. (2011) estimate emission abatement during the first two years of Phase II. They used the average emission intensity[3] improvement from the pilot phase to create the counterfactual projecting BAU in 2008–09. Even though they find reductions to be higher in Phase II than the pilot phase, the abatement under this simplified approach depends to a large extent on the BAU assumptions. They point out several drawbacks with their study. Firstly, sector-level analysis is needed to confirm the macro trends. Secondly, there exist emission intensity fluctuations among sectors. Thirdly, Phase I data might not be reliable for BAU projections due to the economic crisis. Finally, the basis of two years being too short of forming a robust projection. Nevertheless, even if causality remains a problem, they conclude the EU ETS being correlated with emission reductions.

Bel and Joseph (2015) used historical emissions and a dynamic panel data approach to evaluate the EU ETS impact on GHG emissions during the first two trading periods. Their key finding is that most emissions reduction was due to the great recession in 08/09, not the EU ETS. Their main critique of previous studies is that they tend to over-estimate the emission reduction attributed to the ETS since they do not account for the economic recession in their calculations. Since the shock was not foreseen, this specifically affects the BAU-conditions that has been estimated. It is not to say the EU ETS led to zero-emission reductions. However, the emission abatement magnitude is likely to be smaller than previously estimated. Indeed, several other authors conclude the economic recession was the main reason for a decline in emissions in Phase II (Cooper, 2010; Kettner et al., 2011).

Dechezleprêtre et al. (2018), look at the causal impact of EU ETS on carbon emissions focusing on four countries due to data limitations: France, Netherlands, Norway, and the United Kingdom. They indicate that their sample is a relatively good representation of the rest of the EU, although strictly speaking their findings cannot be extended beyond these countries. Focusing on data from the first and second phase, they match installations with similar emissions before implementing EU ETS. Further, they use a difference-in-difference model on the 240 EU ETS-installations and 160 non-ETS installations and find that the policy led to a 10–14 per cent emission reduction. This number is the average for the two trading periods; however, their estimations suggest most reductions happened in Phase II.[4] It supports the findings from both Wagner et al. (2013), and Petrick and Wagner (2014), who look at manufacturing plants in France and Germany, respectively.

Bayer and Aklin (2020), using a generalized synthetic control approach, concluding that the EU ETS lead to a reduction of 1.2 billion tonnes of CO_2, or 3.8 per cent relative to total emissions in the period 2008–2016, compared to a world without EU ETS. The authors look at sectors like energy, metal chemicals and minerals and find that emissions decreased between 20 and 25 per cent against the counterfactual. They also check for abatement effort in the transportation sector, which is considered unregulated, however, concludes that no significant emission reduction was found. They do not include aviation emission in any of their calculations.

Not surprisingly considering the emission trading scheme's nature, abatement has not evenly occurred across either member states or sectors. Ellerman et al. (2010) concluded that 80 per cent of abatement happened in EU-15 in Phase I. Further, Delarue et al. (2008; 2010) conclude the major abatement taking place in the power sector, with

[3] Emissions per unit of GDP.

[4] 6 per cent insignificant reductions in Phase I and 15 per cent significant reduction in Phase II.

fuel switching being the main driver of emission reductions during the first phase. The industry sector has also seen increasing abatement levels, despite the over-allocation of permits — most likely attributed to the trade of allowances with the energy sector (Ellerman et al., 2010). As mentioned previously, if the price of carbon permits (EUAs) is higher than an industry's marginal abatement cost, then it would be advantageous for them to trade the allowances given and invest in abatement efforts instead.

It has been argued that the EU ETS has not been as efficient in generating emission abatement due to the oversupply of EUAs (Dechezleprêtre et al., 2018; Ahmad, 2015; de Perthuis & Trotignon, 2014; Anderson & Di Maria, 2011). The issue with an oversupply of allowances surfaced already in Phase I. It was mainly due to the allowances (and cap) of Phase I being based on poorly verified estimates, resulting in the total amount of allowances issued exceeding actual emissions (EC, 2015). Consequently, the price of EUAs fell to zero in 2007. In Phase II the cap on allowances was reduced, as actual data was available. However, the recession in 2008/09 led to emission reductions much greater than anticipated — again leading to a large surplus of allowances. Even if the European Commission has tried to counteract these outcomes by delaying the auction of about 900 million EUAs to 2019/20, the response to the generally oversupplied market has been a low EUA price. As pointed out by Dechezleprêtre et al. (2018), a cap-and-trade system effectively reduces emissions so long as the cap is set tightly enough. Therefore, a surplus of allowances amounting to 2.1 billion in 2013 can be argued not to send the right incentives to participants to invest in low-carbon technology (de Perthuis & Trotignon, 2014). Despite this, there has been a total reduction in emissions.

The EU ETS and Aviation

Most studies that have addressed the inclusion of aviation in the EU ETS were published before the implementation. To my knowledge, no paper to-date attempts to analyse the impact of the inclusion of aviation in the EU ETS directly concerning CO_2 abatement in an ex-post fashion.

Anger (2010) analyses the aviation industry at an aggregate level using a data-driven model based on historical data combined with econometric forecasting, called E 3ME. To assess the short- and medium-run GHG mitigation, the author assumes based on the EC's then-current proposal. Furthermore, the author assumes aviation activity to grow by 2.5 per cent annually, with 1 per cent fuel efficiency improvement. Considering ICAO (2010) forecasted annual growth to be 4.8 per cent from 2010 onwards, in terms of revenue passenger kilometres (RPK), the growth prediction is relatively conservative. Anger (2010) concludes, assuming a 100 per cent cost pass-through rate, that including aviation in the EU ETS result in a yearly increase of CO_2 emissions by 0.09 and 0.24 per cent under the low and medium allowance prices, € 5 and € 20 respectively, but a decrease of 0.30 per cent with a high allowances price, € 40, in 2020 compared to a no-action scenario.

Schaefer et al. (2010), using a DLR-developed simulation model, analyse how the EU ETS will affect the air transport sector economically and ecologically. Based on 3.4–6 per cent forecasted growth in RPK and an assumed price of EUAs of € 40–55 for the period 2012–2020, they conclude the total cost for the aviation sector is expected to range between € 1.9 and € 3.0 billion in the year 2012 alone. Additionally, if successful in integrating non-EU carriers, the regulation will cover roughly one-third of global aviation emissions. It means that the aviation industry will need to buy allowances worth the equivalent of 48.1 million tonnes of CO_2 from stationary sources.

Vespermann and Wald (2011) employed a simulation model to estimate the effects of the EU ETS policy. Using input variables such as allowance price, average ticket price, efficiency gains, market growth, transport activity, and the price elasticity of demand, they find the financial burden on the industry to average € 3 billion a year but mentions that this number might vary according to fluctuating allowance prices and demand growth. They expect the cost of carbon permits to account for about 1.25 per cent of total industry costs. Further, they conclude the annual growth rate of CO_2 emissions to be 1 per cent lower under EU ETS than an unrestricted scenario — with emission reductions starting at 0.9 per cent in 2013 and rising to 7.7 per cent in 2020. The authors point out that the ETS system's ecological effects assume less air transportation demand due to increased costs will entail reduced fuel consumption because of less air traffic activity, thereby reducing emissions.

Although the restriction of growth in the aviation sector is not met — being a net buyer of EUAs, the industry will likely induce emission reductions in stationary sectors instead.

There has been no ex-post study that explicitly analyses EU ETS's effects on competitiveness in the aviation sector. However, Nava et al. (2018) develop a microeconomic model to explore the effects of applying EU ETS to the aviation sector. They conclude that two main factors influence airline profits; the share of allowances distributed for free, and the airlines' abatement effort costs. The latter negatively impacted, and the former quite intuitively a positive one. Anger (2010) asserts that it would be advantageous for non-EU airlines if they were exempt from the scheme, as they would be able to gain market share.

In contrast, Schaefer et al. (2010) point out that the competitive disadvantage for EU-airlines will happen when non-EU airlines are included in the scheme. It is because non-EU airlines operate mainly long-haul flights, which have comparably lower specific emissions under the ETS. Thus, the percentage of allowances allocated for free would be lower for EU-airlines than non-EU airlines. Vespermann and Wald (2011) believe competition distortions to be low, although dependent on the cost of EUAs.

In general, ex-post studies done on other sectors covered by the EU ETS do not find a significant negative impact on economic performance (Anger & Köhler, 2010; Commins et al., 2011; Chan et al., 2013; Martin et al., 2016; Dechezleprêtre et al., 2018), suggesting that the general concern for the loss of competitiveness might be exaggerated. Dechezleprêtre et al. (2018) imply that the insignificant effect on economic performance tends to be a combination of generous free allocation and low carbon prices.

Several authors (Anger, 2010; Schaefer et al., 2010; Vespermann & Wald, 2011) correctly anticipated that the aviation industry would be a net buyer of allocation emissions. Scheelhaase et al. (2012) estimated the EU ETS cost for airlines to be significant within the sector, amounting to € 20,502 million in 2012–2020. However, as with most research, the permits' allowance price has been grossly overstated. Instead of an allowance price of € 20, as generally assumed (Scheelhaase, et al., 2012; Albers et al., 2009; Anger & Köhler, 2010; Barbot et al., 2014; Malina et al., 2012; Schaefer et al., 2010; Pagoni & Psaraki-Kalouptsidi, 2016), between 2013–2017 the average price of an EU allowance varied between € 4 and € 6 and has not until recently increased above € 15 (EEX Group, 2020). The total cost for aircraft operators purchasing allowances needed for their emissions levels increased from € 89 million in 2013 to € 189 million in 2017 (EASA et al., 2019)—both numbers substantially smaller than the € 1.9 billion estimated by Schaefer et al. (2010). Moreover, for intra-EU operators, these costs only represent about 0.3 per cent of total operating costs (EASA et al., 2019). The operating costs have likely increased after the price jump in 2018. However, no report has yet been released confirming this.

While the research mentioned above is useful, it is all based on modelling scenarios of future events. There is still little known in practice about carbon pricing's effectiveness to reduce aviation emissions (Markham et al., 2018). All simulation studies rely on strong assumptions of EUA price, cost pass-through rates and demand elasticities, and unsurprisingly none predicted the "stop the clock" legislation to come into place.

Markham et al. (2018), analyse the effect of the Clean Energy Future (CEF) policy levied in Australia between 2012 and 2014. Using an OLS model with per capita RPK being the outcome variable, they found the carbon price (ranging between $ 23.00AUD to $ 24.15AUD per tonne of CO_2 equivalent) did not affect domestic air travel reduction. They suggested that infeasible fuel source switching and insignificant price signal generated by the carbon price in a very turbulent period to be partly reasons for this result. On the other hand, González and Hosoda (2016), analyzing a domestic fuel tax reduction in Japan, find that CO_2 emissions increased significantly (by 9.7 per cent) compared to a counterfactual scenario after the reduction date. Using a causal impact approach, a Bayesian structural time-series model proposed by Brodersen et al. (2015), they constructed the counterfactual time series with a set of covariates explaining jet fuel consumption behaviour before implementation.

Larsson et al. (2019) highlight that almost half of the EU population is subject to an air passenger tax. Although the taxes do not stimulate technological change the same way a carbon price intends to, it can reduce demand for air travel and emissions. To support this, Falk and Hagsten (2018), using a difference-in-difference model, investigate the impact of a flight departure tax introduced in Germany and Austria in 2011. They find that the tax, which leads to an increase in airfares, reduces the number of passengers — however, this is predominantly seen in airports used by low-cost airlines.

Fageda and Teixidó-Figueras (2020) provide the first complete ex-post evaluation of the EU ETS applied to the aviation sector. They investigate the causal impact of EU ETS on aviation supply. For data availability reasons, they measure aviation supply as available airline seats offered per route. They argue that due to the increased cost for regulated airlines, they will react by reducing supply and increasing prices, resulting in less demand. Similar to Falk and Hagsten (2018) they find that the overall effect of the policy has had a significant impact on low-cost carriers (LCC), resulting in LCCs supplying 7 per cent fewer seats than the counterfactual scenario (Fageda & Teixido-Figueras, 2020). The supply effects that occur can be due to LLCs withdrawing certain connections because of the tax. It has been seen done by Ryanair in several European countries when a passenger/flight tax was introduced, namely Germany (Zuidberg, 2015), England (Malighetti et al., 2016) and Norway (Halpern, 2018).

The effect of EU ETS on ticket prices has yet to be investigated. However, Pagoni and Psaraki-Kalouptsidi (2016) simulate how a market-based measure (MBM) in the American aviation industry would impact ticket prices and corresponding market shares. The carbon fee is incorporated in the airlines' marginal cost, and the increased cost forces airlines to adjust ticket prices to maximize profits. They find that ticket fares would increase by 1.2–11.8 per cent depending on the carbon price. A 1.2 per cent ticket increase represents a carbon price of $ 10 per tonne of CO_2; for an average Ryanair ticket fare in 2016, this would mean a price increase of approximately € 0.5. The authors also find that travel demand would at most decrease by 2.6 per cent under a high carbon price scenario ($ 100), so competition distortions are expected to be rather low. These findings reinforce what other researchers have concluded when analysing environmental policies in European and other markets (Anger, 2010; Malina et al., 2012; Miyoshi, 2014; Scheelhaase et al., 2010).

Methodology

This section presents a macroeconomic model intended to capture an emission trading system's causal impact on jet fuel consumption. The theory underlying the hypothesis will be explained, and the research design and data limitations of the estimation method outlined. The Generalized Synthetic Control method used to estimate the counterfactual and find the average treatment effect of the treated will be given in more detail before the model specification, and a summary of the data is shared.

Hypothesis

The permit price generated by the ETS becomes part of an airline's cost structure. Regardless of the allowance being purchased or freely allocated, the opportunity cost remains the same. In the margin, the freely allocated EUA has an opportunity cost equal to the revenue earned if sold. Thus, emitting an extra tonne of CO_2 means the airline either must buy an allowance or forgo the possibility of selling a freely allocated one. A profit-maximizing firm will factor these costs into their output and price decision (Fageda & Teixido-Figueras, 2020). Brueckner and Zang (2010) point out that the permit price (the EUA price) is effectively added to fuel price. Hence the ETS can be viewed as a carbon-tax scheme applied to aviation. Therefore, the effect of this policy should work in the same way a fuel-price increase would.

Intuitively, a carbon tax increases carbon-based production cost, leading to a decreased demand or a substitution between production or technologies. The latter is mainly seen in stationary sectors (Martin et al., 2016; Dechezleprêtre et al., 2018). As appropriately pointed out by Markham et al. (2018), in air travel, an initial effect of carbon pricing should lead to decreased travel demand since technology improvements such as replacing aircraft fleets cost time and money. An effective carbon price should theoretically reduce aviation emissions by increasing the airlines' cost, leading to less supply and less demand. Even if the ETS system's cost is wholly or partially passed through to the passenger, the resulting higher ticket prices should lead to the same reduction in demand (Vesperman & Wald, 2011). Fageda and Teixido-Figueras (2020) shared this view, who predicts that the increased cost of the EU ETS should result in airlines lowering their supply. Therefore, it is reasonable to assume that the same increased cost will negatively impact jet fuel consumption due to the lowered transportation activity, hence reducing emissions.

Emissions produced by aircraft primarily come from jet fuel combustion, where CO_2 accounts for approximately 70 per cent whilst the rest is mainly made up of water vapour (EUROCONTROL, 2018). Airlines reporting to the EU ETS calculate their emissions by multiplying jet fuel consumption (in tonnes) by 3.15, which is IPPCs default emission factor. Therefore, this paper uses jet fuel consumption as a proxy for emissions.

It is known that overall emissions have increased in the aviation sector over the past 30 years, mainly attributed to strong passenger growth and limited technology improvements. Even though we assume the cost imputed by the ETS system should discourage emissions, most studies conclude the EU ETS is having a relatively small impact on aviation emissions, generally due to the high marginal abatement costs (Malina et al., 2012). Further, if the general assumption is that market prices should equal the social cost of carbon (Nordhaus, 2017), when a mismatch is seen it is logical to conclude that market prices are not high enough to encourage abatement. Following this, even if the hypothesis suggests a negative impact, with the recent trend of EUA prices, it is unlikely that any evidence of abatement attributed to the EU ETS will be found. However, Bayer and Aklin (2020) point out that even if the oversupply of permits leads to low prices, the reverse might not be true. Prices can be low because of decreasing demand for carbon permits; therefore, market prices should not be relied on when evaluating a policy's effectiveness.

Accordingly, this paper will explore the EU ETS hypothesis, leading to a reduction in jet fuel consumption by implementing a GSC method to estimate the counterfactual.

Research Design

Many factors impact an aircraft's fuel consumption; these can be technological, operational, socio-economic and/or fuel-specific (Singh & Sharma, 2015). Papers concerned with modelling aviation fuel demand tend to focus on factors like economic growth (GDP), fuel price, airline traffic data, and efficiency gains (Mazraati & Faquih, 2008; Mazraati & Alyousif, 2009; Chèze et al., 2011b; Singh & Sharma, 2015; Lo et al., 2020).

GDP is the economic driver of passenger traffic and deemed the most important determinant for leisure travellers (Gately, 1988; Eyers et al., 2004; Mazraati & Faquih, 2008; Lee et al. 2009). The real GDP growth rate is also shown to be correlated with a growth rate of Passenger Kilometre Performed (PKP) (Mazraati & Faquih, 2008). PKP is strongly associated with air traffic and provides information on a number of kilometres travelled by all passengers (EUROCONTROL, 2018).

The number of passengers carried by aircraft, in terms of weight, and the flight's length play an important role in terms of fuel consumption. It is logical to assume that fuel consumption will increase if the total kilometres flew increases and/or if the aircraft's weight increases (Fukui & Miyoshi, 2017). An aircraft's efficiency gains tend to focus on fuel consumption used per passenger kilometre flown. The less energy an aircraft can spend on moving a set amount of passengers from A to B, the more efficient the aircraft is (Jordão, 2016). Fuel efficiency is related to the type of aircraft used and the type of flight. Short-haul flights are generally less fuel-efficient than longer-haul flights due to the more frequent take-off and landing phases and offer higher daily frequency and lower average passenger load factors[5] (Chèze et al., 2011b; Miyoshi, 2014; Jordão, 2016).

It would be ideal for including PKP to control air traffic, as some countries experience more traffic than others due to tourists' higher levels. Additionally, considering fuel consumption per mile flown has decreased over the past 25 years (Fukui & Miyoshi, 2017), it would be intuitive to adjust total consumption by the length of flights. Unfortunately, this data is either sparse, behind payment walls or reported differently than the outcome variable.[6]

Ticket prices are also an important consideration measuring consumers' willingness to pay, or price-demand elasticity. Since ticket prices are primarily driven by jet fuel price (Chèze et al.,

[5] Load factor measures the capacity utilization of an aircraft, that is, the average ratio of available seats to passengers carried.

[6] Generally reported as scheduled traffic of airlines registered in the country — and not the total number of passengers departing the country.

2011b), one can use jet fuel price as a proxy for measuring the relative changes.

When analysing a policy implementation, it is crucial to have data containing values, both pre- and post-treatment. The method used in this paper, the Generalized Synthetic Control, uses information from the pre-treatment period to create a counterfactual. As Ellerman and Buchner (2008, p. 277) point out, "*forming a good estimate of the counterfactual is complicated by the lack of historical data corresponding to the installations included in the scheme*".

Ex-post studies done on a sectorial level tend to use the UNFCCC CRF data as a proxy for EU ETS sectors' historical emissions (Ellerman & Feilhauer, 2008; Ellerman et al., 2010; Egenhofer et al., 2011; Bayer & Aklin, 2020). Aviation activities, being a non-stationary emission source, lack an explicit agreement among countries of *who* is responsible for emission from flights crossing borders. The UNFCCC divides aviation activities into two groups: Domestic Aviation, and International Aviation, with the latter not counted in any national inventories, rather it is part of an "international bunker" category. UNFCCC (1996) outlined eight options to allocate GHG emissions from international bunker fuels (see **Appendix 3.1**). The EU ETS uses option (4) for data gathering and permit distribution purposes, whilst the UNFCCC uses option (3) in their CO_2 emission data reporting. Therefore, looking at emission data in the overlapping period (2012–2018), the EU Transaction Log (EUTL) data far from corresponds with UNFCCC observations.

Thus, this study encounters two major issues: (1) there exists no source distinguishing intra-EU flights from extra-EU flights at an aggregate level; and (2), there exists no freely available source that reports emission data, or jet fuel consumption data, in the same format as EUTL.

Unfortunately, the data gathering needed to get past these issues is too complicated and time-consuming for this project. Instead, this paper will focus on whether aviation's inclusion in the EU ETS has impacted aggregate jet fuel consumption in the member states. The jet fuel consumption will refer to all jet fuel sold in a country for international or domestic (commercial) travel or freight transport. However, this paper recommends gathering data on the specific airlines and affected routes for a more accurate analysis of EU ETS's impact on CO_2 abatement in the aviation sector for future research.

It is worth noting that since the analysis will include all air travel, and not just the one directly affected by the EU ETS, it will be difficult to conclude any causal relationship. The results produced will, therefore, have to be interpreted with caution. Since the EU ETS covers a whole region, the effects being picked up merely reflect a growth pattern in the affected area that differs from the control countries.

Because of the nature of the aviation market, specifically in terms of market maturity, the dataset includes observations from OECD and Annex I countries (see **Appendix 2**). In addition to data availability, these countries will likely show similar trends in growth, technology- and efficiency improvements due to their economic situation. Previous studies modelling jet fuel demand have also distinguished between developing and OECD regions (Mazraati & Alyousif, 2009) or, matured and growing markets (Mazraati & Faquih, 2008). The latter authors, supported by Chèze et al. (2011a), point out that variables affecting demand for aviation, hence fuel, differ in magnitude depending on the market's maturity and economic development.

According to a report from Transport & Environment (2020b) the top six EU emitting groups are Germany, Spain, Nordics, Benelux, France and Italy, account for 73 per cent of intra-EU fuel burn. The UK is also part of this group, with the largest emissions in EU-28, at 18 per cent. Considering the EU ETS only regulates intra-EU flights, a sub-group including these countries is separately analysed. Their total fuel consumption could potentially "pick up" the ETS effect better due to their high share in intra-EU fuel burn.

Empirical Strategy

The analysis in this paper aims to explore whether the inclusion of aviation activity in the EU ETS has led to emission abatement relative to a counterfactual where the EU ETS was not implemented. Issues with the counterfactual estimations have been prominent throughout most EU ETS studies.

The difference-in-difference (DiD) method is one of the most used empirical designs in social science, specifically on a micro-level. Several studies use DiD trying to draw a causal inference of the EU ETS on ecological or economic factors using firm-level data (for example Martin et al., 2016; Dechezleprêtre et al., 2018; Fageda & Teixido-Figueras, 2020). However, when data becomes aggregate, the assumptions underlying the DiD method are likely to fail. Most prominent is the parallel trend assumption, where treated and control units follow parallel paths in the pre-treatment period. This assumption most likely fails due to unobserved time-varying cofounders (Xu, 2017), thus leading to biased estimates (Abadie, 2020). The synthetic control method first proposed in Abadie (2003) and further developed in Abadie, Diamond and Hainmueller (2010; 2015) was created to deal with this and handle estimated effects of aggregate interventions. That is, interventions affecting a small number of large units (like cities, regions, countries etc.) (Abadie, 2020). In fact, due to the limitations of traditional regression analysis techniques, it is not possible to claim any causality using aggregate data on country or sector level — rather it produces estimates on the economy- and sector-wide effects (Dechezleprêtre et al., 2018).

The basic idea behind synthetic control is to provide a combination of control units compared to the unit exposed to the intervention, rather than one control unit. Furthermore, to ensure a parallel trend, treated and control units are matched based on pre-treatment covariates and outcomes (Abadie, 2020). The "synthetic control unit" created is thus a combination of reweighted control units. The drawback is that it is only applicable to data with one treated unit. As mentioned previously, Bayer and Aklin (2020) focus on the impact of EU ETS on CO_2 emissions at the sector and country levels. They argue that due to their data's nature, as the simultaneous implementation of the EU ETS in multiple countries, the best estimation technique is the Generalized Synthetic Control (GSC).

The Generalized Synthetic Control method was developed by Xu (2017) to further build on the method developed by Abadie et al. (2010). Similar in spirit to the synthetic control, the GSC uses a reweighting scheme to construct the counterfactual. However, instead of matching, it estimates a linear interactive fixed effects (IFE) model using only the control variables before assigning weights. The IFE model, proposed initially by Bai (2009), is another way to model unobserved time-varying cofounders, called latent factors. The latent factors represent common shocks, like the financial crisis, and their heterogeneous impact on countries' economies. If the appropriate control variables are included, the model can also pick up other legislation and policies affecting the outcome variable, like a carbon tax. The GSC, therefore, links synthetic control and IFE to addresses several treated units whilst accounting for heterogeneous treatment effects (Xu, 2017).

Empirical Model

To estimate the average treatment effect of the treated (ATT), this study follows the procedures outlined in Xu (2017). Firstly, we have $N = N_{tr} + N_{co}$ number of units, where N_{tr} and N_{co} are the numbers of treated and control units, respectively. All units are observed for $t = 1,\ldots,T_0,\ldots,T$ periods, and all treated units are exposed to the treatment at the same time, T_0.

A linear factor model gives the functional form of the model:

$$Y_{it} = \delta_{it} D_{it} + X'_{it}\beta + \lambda'_i F_t + \varepsilon_{it},$$

where the treatment indicator D_{it} equals 1 if unit i has been exposed to the treatment at the time $t \geq T_0$ and equals 0 otherwise. δ_{it} is the heterogeneous treatment effect on unit i at time t; X_{it} include observed covariates, and β represent their unknown parameters; F_t is the unobserved common factors (time-varying coefficients) and λ_i is their unknown factor loadings (unit-specific intercepts). Finally, ε_{it} represents unobserved idiosyncratic shocks for unit i at time t, with an assumed mean of zero.

The factor component of the model, $\lambda'_i F_t$, takes a linear, additive form by assumption. So long as the unobserved random variable can be decomposed into a multiplicative form, it will be absorbed. However, the factor component does not capture unit-independent unobserved confounders.

The GSC estimator for the treatment effect of treated unit i at time $t \geq T_o$ is given by the difference between the actual outcome and the estimated counterfactual: $\hat{\delta}_{it} = Y_{it}(1) - \hat{Y}_{it}(0)$. Xu (2017, pp. 62–63) refers to it as an out-of-sample prediction method based on Bai's (2009) factor augmented model. $Y_{it}(1)$ denotes the actual observed outcome of treated units and $\hat{Y}_{it}(0)$ is the estimated counterfactual. The counterfactual is calculated in three steps:

$Y_{it} = X_{it}\beta + \lambda_i F_t + \varepsilon_{it}$, for control group data N_{co}, $t = 1, \ldots, T$,

$Y_{it} = X_{it}\hat{\beta} + \lambda_i \widehat{F}_t + \nu_{it}$, for treatment group data N_{tr}, $t < T_0$,

$\widehat{Y}_{it}(0) = X_{it}\hat{\beta} + \widehat{\lambda_i}\widehat{F}_t$, for treatment group data N_{tr}, $t \geq T_0$.

The first step estimates the IFE model using only the control group data to obtain $\acute{\beta}, \acute{F}$. The second step estimates factor loadings, $\acute{\lambda}_i$, for each treated unit by minimizing the mean squared error of the predicted treated outcome in pre-treatment periods. The third step uses $\acute{\beta}, \acute{F}, \acute{\lambda}_i$ obtained previously to calculate the counterfactual $\acute{Y}_{it}(0)$ for the treated had they not been subject to treatment. The average treatment effect (ATT) for all treated units will thus be:

$$\widehat{ATT}_t = \left(\frac{1}{N_{tr}}\right)\sum_{i \in T}\left[Y_{it}(1) - \widehat{Y}_{it}(0)\right] for\, t \geq T_o.$$ [7]

One additional strength to this method is that the data algorithm developed to use a cross-validation procedure to select the number of factors included in a model that gives the most accurate predictions before estimating the causal effect. It works well in practice where limited knowledge of exact numbers of unobserved factors often is a problem.

Model Specification

The output variable, Y_{it}, is *Jet fuel consumption per capita*. It is an annual measure of all jet fuel (in metric tonnes) sold for commercial use in a selected country i for the period $t = [1990, \ldots, 2019]$. The model specification used in this analysis is as follows:

$$\left(\frac{Jet\ fuel\ consumption}{Population}\right)_{it} = \hat{\delta}_{it}\, ETS_{it} + \hat{\beta}X_{it} + \widehat{F}\hat{\lambda}_i + \varepsilon_{it} \quad (1)$$

Where $ETS_{it} = \{1, 0\}$ is the binary treatment indicator, and X_{it} is a vector of control variables, $\widehat{F}$ represents common shocks and $\hat{\lambda}_i$ picks up the heterogeneous impact of these shocks on country i. Finally, ε_{it} is the country-specific error term of output.

When we use macroeconomic data, the control variables should include important drivers for the dependent variable (Bai, 2009). Therefore, in a similar fashion to Bayer and Aklin (2020), the main specification includes *GDP per capita* and *GDP per capita*^{2} as control variables (Model 1). Although simple, the model captures the data's variability well, especially when allowing interactive fixed effects. It is common to assume the underlying relationship between GDP and jet fuel consumption to be concave. It is also the expected relationship if following the Environmental Kuznets Curve (EKC) hypothesis.

A second model specification includes *inbound tourists* as an additional control variable (Model 2). It adjusts for a high jet fuel consumption per capita in countries with the strong tourism industry. Although the measure includes all overnight tourist entering the country via any transportation method, since over half of all international tourists fly to their destinations (ATAG, n.d.), it will hopefully control some of the effects of aviation passengers. This control variable enforces the results seen in the first specification, thus providing robustness to the results.

Other factors previously identified as good determinants of jet fuel consumption should be picked up as latent factors due to the IFE estimations' mechanisms. It includes jet fuel price and efficiency gains, as they are both common regressors. Further, ticket prices cannot be easily measured at an aggregate level; instead, GDP per capita acting as a proxy for household income should represent general affordability (Markham et al., 2018). Finally, exogenous shocks either affecting economic activity, or the aviation industry specifically, do not need to be explicitly modelled as all regions will experience them. The IFE will pick up the heterogeneous effects of these.

Like most econometric methods, the GSC works best when the model is correctly specified. Xu (2017) performs Monte Carlo exercises to test the method and find that in the presence of decomposable time-varying confounders the GSC has less bias than the two-way fixed effects estimator, where DiD is a specific version. Further, it corrects the IFE estimator's bias when the treatment effect is heterogenous; and finally, it is generally

[7] For further explanations and step by step calculations, please refer to Xu (2017).

more efficient than the SC method. However, it is worth noting that insufficient data — either a short pre-treatment period or a small number of control units[8]—can cause bias in the estimated treatment effect. Due to this dataset's characteristics, this is something to be cautious of when interpreting the results.

Data

Data on annual jet fuel consumption, measured in 1000 metric tonnes, is downloaded from U.S Energy Information Administration. Across the 45 countries included in the sample, the panel data is slightly unbalanced with 1,297 observations in total for Model 1, and 1,053 observations for Model 2. Figures 1 and 2 show an overview of the missing observation in the two models, in addition to control and treatment countries.

Annual data for GDP, GDP per capita and Population are all obtained from the World Bank Development Indicators database. GDP and GDP per capita are expressed in current US dollars. Finally, numbers on international inbound tourists are also taken from the World Bank database and refer to the number of overnight tourists arriving in a country other than those they usually reside.

Jet fuel consumption per capita is established by first multiplying jet fuel consumption by 1000 to change the measurement from mmt[9] to metric tonnes (mt). It is then divided by the corresponding population measurement.

Although it is correct to assume that EU ETS came into effect in 2012, the original directive included all routes to and from the EU. The "stop the clock" legislation was only applied right before airlines were supposed to surrender their allowances for 2012, with backdating properties. Therefore, it was not until 2013 when officially only flights within the EU were affected. Because of there being no clear control group in 2012, in the estimations, 2013 is regarded at the official start of the EU ETS (Fageda & Teixido-Figueras, 2020).

Descriptive statistics are reported for the entire period by treatment and control group in **Appendix 3.2**, and for the pre-treatment period in **Appendix 3.3**. As seen in both tables, the mean values for control and treatment groups are quite different. It supports using a GSC method rather than a DiD method, as the parallel trend assumption would be violated.

Results

The results from the GSC estimation are shown in Table 1. The ATT coefficient row shows the aggregate average treatment effect, which is the difference between the treated countries' average outcome against its estimated counterfactual. Although it is reported as one number, the treatment effect is not constant over years or countries and would differ depending on the country, or year looked at.

The programming code, *gsynth*, provided by Xu (2017) includes an option to implement the Expectation Maximization (EM) Algorithm developed by Gobillon and Magnac (2016). The EM method uses pre-treatment information for the treated group, thus providing more precise estimated coefficients. Applying this method leads to a better pre-treatment fit and improves the results' significance. Considering the sample includes more treated than control variables, using pre-treatment information of treated units can prove important when calculating the counterfactual. Therefore, all results reported are calculated using the EM method.

A parametric bootstrapping with 1000 runs is used to generate a 95 per cent confidence interval around the ATT estimates, following what was implemented in Xu (2017, p. 65). Due to the small sample size of treated variables, it is impossible to approximate this nonparametrically, without risking biased results. An appealing alternative to bootstrapping when the number of treated units is small is a jack-knife resampling (Liu, Wang & Xu, 2020). Although it might not provide better uncertainty estimates, it can offer a worthwhile robustness check to see whether a single observation is driving our results due to our sample size. The results from using a jack-knife resampling reinforce the legitimacy of the findings below and a full description is provided in **Appendix 4.1**.

All specifications outlined in Table 1 impose additive country and year fixed effects. In addition to the two model specifications outlined earlier, column (1) runs the estimation with no controls included. When controlled for the covariates included in (2) and (3) are assumed to have a con-

[8] $t < 10$ and $N_{co} < 40$.

[9] Reported by the EIA source to equal 1000 metric tonnes.

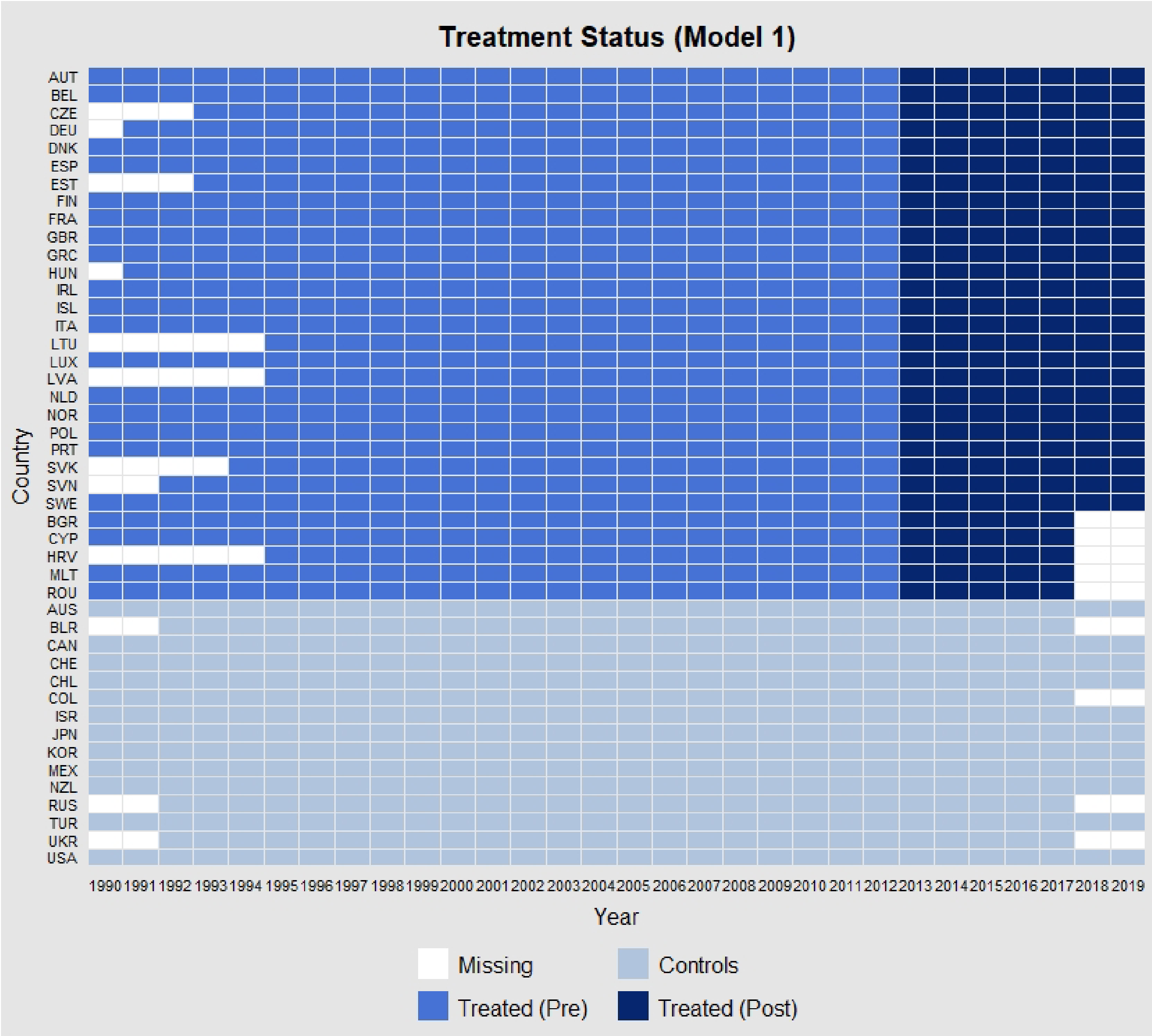


Fig. 1. Observations and treatment status Model 1

stant effect on the outcome variable. Three unobserved factors are found to be important with both specifications, using the cross-validation scheme. Focusing on the main model (1), the estimated ATT predicts jet fuel consumption per capita to increase by 0.01531 when countries are subject to the EU ETS. Dividing the ATT by the mean jet fuel consumption per capita seen in treated units for the post-treatment period, reported in **Appendix 3.4**, we find that the EU ETS is associated with a statistically significant increase of 10.2 per cent in jet fuel consumption per capita.

Figure 3 show the dynamics of the estimated ATT.[10] The left figure depicts the mean path for actual jet fuel consumption per capita figures for treated countries (solid line) relative to a counterfactual scenario (broken line). The average consumption and the average predicted consumption match well before treatment before diverging after EU ETS took effect. It demonstrates that the statistical method has provided a good counterfactual. The right figure reinforces that that gap is essentially zero before treatment and the effects happen after implementation. Since the GSC method minimizes gaps between the actual and predicted outcomes in pre-treatment periods, this result is not surprising. However, it is surprising that the EU ETS has led to affected countries having a higher jet fuel consumption (per capita) than what is estimated had the EU ETS not come into effect. It goes against the theoretical hypothesis outlined above.

The results for each of the 30 countries subject to the EU ETS are reported in **Appendix 4.3**. Approximately 14 are experiencing a negative ATT differing in significance, though the pre-treatment fit for some of these countries is debatable. In

[10] The period shown in the figures have been limited to 1995–2017, where a perfectly balanced panel dataset is present.

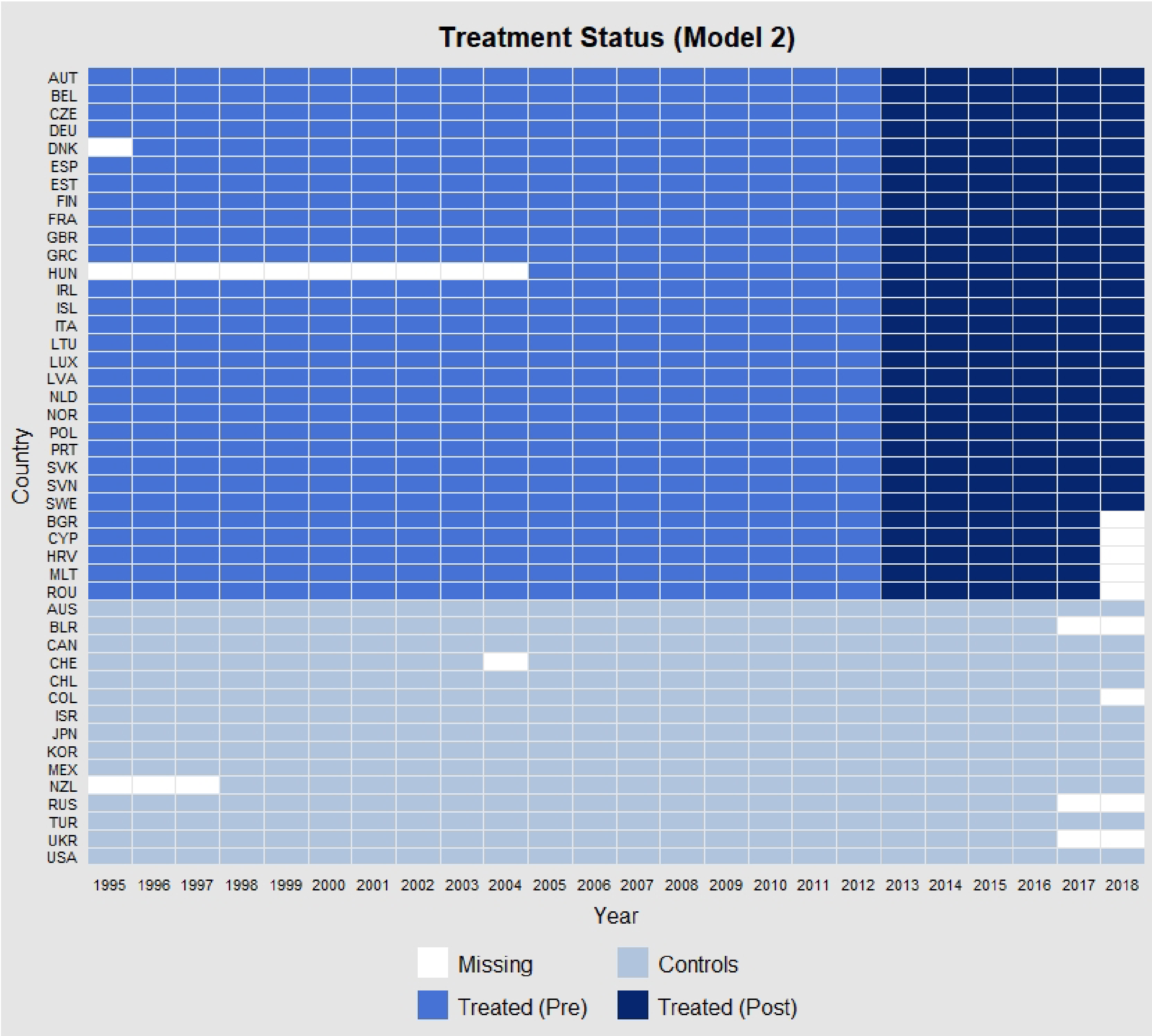


Fig. 2. Observations and treatment Status Model 2

general, better plots tend to follow the positive trend shown above. Overall, countries with larger jet fuel consumption values have a clear pattern, driving counterfactuals results.

In addition to looking at the treated and counterfactual averages, the estimated factors and factor loadings produced by the GSC method are shown in Figure 4. Figure 4a plots the three estimated factors. The x-axis shows the year and the y-axis the magnitude of the factors. Figure 4b depicts the estimated factor loadings for each treated and control variable, with the x-and y-axes indicating the magnitude of the loadings for the respective factors. The estimated factors might not be directly interpretable, as they are, at best, linear transformations of the true factors (Xu, 2017). Factor 3 in (a) looks to plot out the negative relationship between jet fuel consumption and jet fuel price. The negative impact after the year 2000 corresponds to the sharp price increase between 2000–2009. Jet fuel consumption responded positively to the short drop in prices after 2008/09. However, the negative trend associated with high prices continued until around 2015, where prices started to fall considerably. Factor 1 and 2, set almost orthogonal to each other, seem less interpretable, although both point to a positive effect on jet fuel consumption post-2013. The estimated factor loadings (b) of the treated units tend to overlap the control units. It is a reassuring finding, as it shows more reliable interpolations rather than extrapolations mostly estimate the counterfactuals produced.

Often researchers log variables to either normalize the values or reduce the influence of outliers. The main model estimations have been repeated for a log-log specification, with results reported in **Appendix 4.2,** to explore whether

Table 1
Results

Outcome Variable: Jet Fuel Consumption per capita (mt)	(0)	(1)	(2)
ATT Coefficient	0.01745***	0.01531***	0.01581***
Standard Error 95% Confidence Interval	(0.00457) [0.00898–0.0271]	(0.003842) [0.009349–0.02416]	(0.003218) [0.00874–0.02138]
GDP per capita[a]		1.813*** (0.2185)	1.317*** (0.217)
GDP per capita^2 [a]		−0.000006568* (0.000002274)	−0.00000261 (0.000001741)
Inbound tourist[a]			−0.00007903 (0.0001187)
Country & Year fixed effects	Yes	Yes	Yes
Unobserved factors	2	3	3
Observations	1297	1297	1039
Treated countries	30	30	29[b]
Control countries	15	15	15

Notes.
***, **, and * denotes significance at 1%, 5%, and 10% levels, respectively.
Standard errors are presented in parentheses, and 95% confidence intervals are presented in brackets.
a: values are adjusted for visualisation purposes and should be multiplied by 10^{-6} to show true results
b: Hungary is dropped from the sample due to too few (< 12) pre-treatment observations.

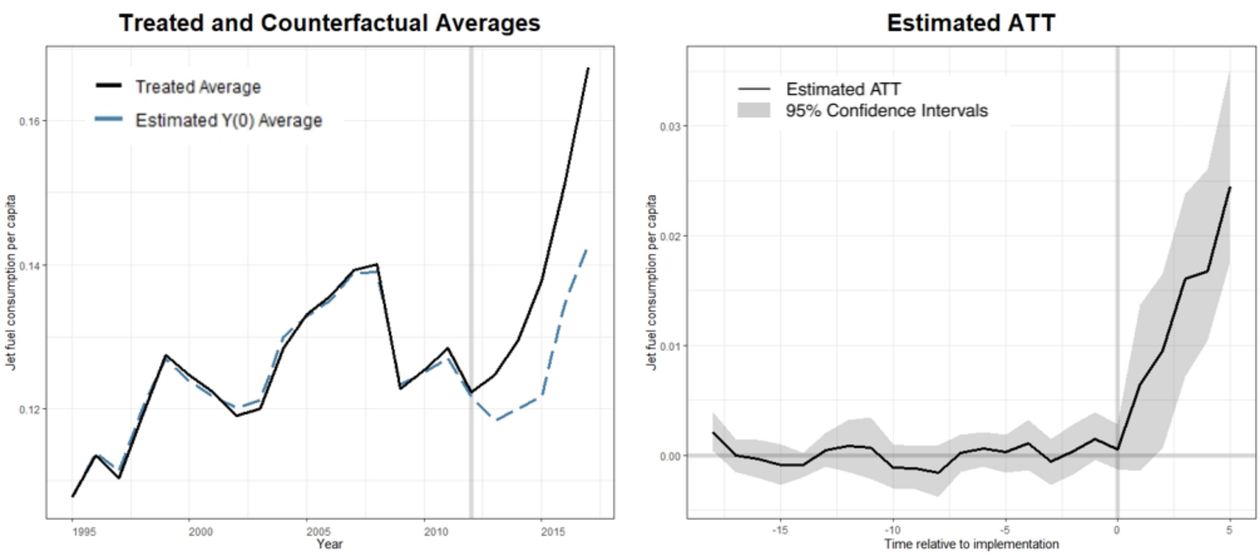
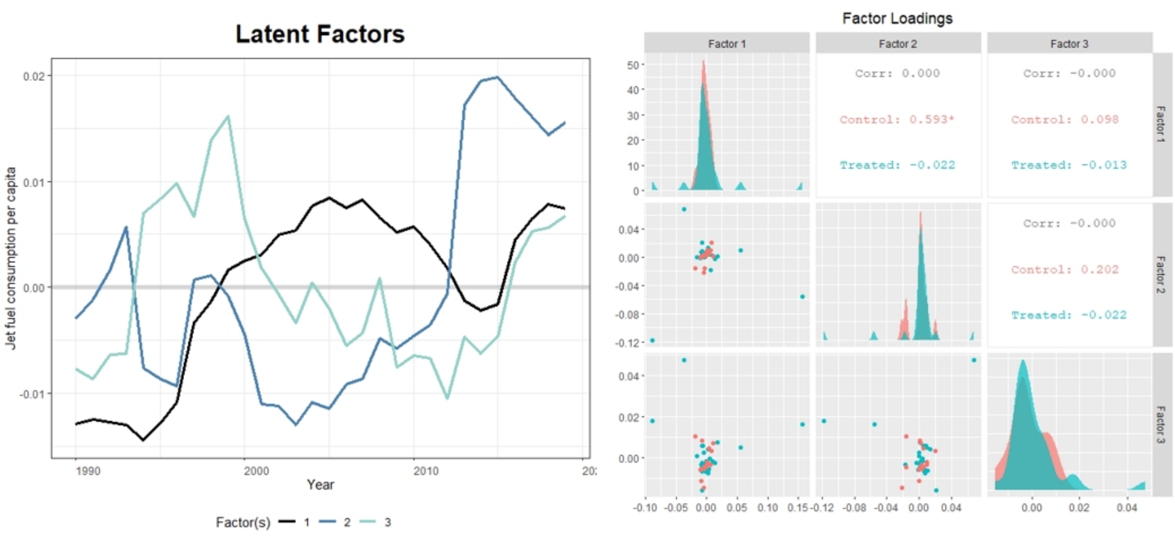


Fig. 3. The effect of the EU ETS over time, sample averages

this would affect the results. The log-log model results underpin the findings above, although the ATT varies in magnitude. Convincingly, the level model presents a "cleaner" result, with easier interpretable coefficients. Moreover, by adjusting aggregate jet fuel consumption by population, it captures consumption relative to a country's size and makes some control units, like the USA, more comparable to smaller countries. Nevertheless, there remain outliers in the sample with reported values much higher than the rest. However, with the GSC method assigning both positive and nega-



(a) Factors *(b) Loadings*

Fig. 4. The estimated factors and factor loadings produced by the GSC method

tive weights and not relying on a parallel trend assumption, this should not be a significant issue.

To strengthen the robustness of the GSC model results, Xu (2017) recommends benchmarking the results with estimates from the IFE model, if possible. Using a programming code, *fect*, developed by Liu, Wang, and Xu (2020), the IFE model is estimated. The IFE estimations are run only including GDP per capita as a control variable due to estimation issues when including a square value. The estimation yields a positive ATT, very similar to the one in the GSC estimation, although not statistically significant. Finally, a placebo test will run on the IFE model to test whether the estimated ATT is significantly different from zero for the range –3 and –5 years before the ETS implementation. The test returns the desired result, indicating that the policy's effect was not significantly different from zero before treatment. However, considering the IFE model results' insignificance, the placebo test does, unfortunately, not contribute to any valuable insights. The result and figure for the IFE model and the placebo tests figures are included in **Appendix 4.4** and **4.5**, respectively.

Sub-Group

As mentioned in the methodology, due to their high share of intra-EU fuel burn, 12 treated countries[11] are evaluated in a separate sample. Table 2 outlines the results. An overview of missing observations and treatment status is found in **Appendix 4.6.**

Following the same model specifications and estimation techniques as the full sample, the ATTs reported in Table 2 represent a negative effect after including controls (column 2–3). However, the results are not statistically significant. The ATT of the main model (1) represent a 1.5 per cent decrease in jet fuel consumption per capita for the countries affected by the EU ETS in the sub-sample, relative to a counterfactual.

Figure 5 shows the effect of the EU ETS over time. Again, a good-pre-treatment fit is seen in both panes, and the effect looks to take off right after implementation. However, this time the magnitude of the EU ETS is not as clear, including both negative and positive spikes, thus not ruling out its effect being zero.

Limitations and Discussion

Carbon pricing is an approach used to reduce carbon emissions by impacting firms' marginal costs, regardless of being delivered through carbon taxes or cap-and-trade systems. The results obtained from the full sample model, however, contradicts this.

There are several liable reasons why the effects were seen opposite from the predictions, most prominent is the limitations regarding the data. Not being able to distinguish jet fuel consumption used for intra-EU travel from consumption used for extra-EU travel makes it difficult to at-

[11] Belgium, Denmark, Finland, Germany, France, Italy, Luxembourg, Netherlands & Norway.

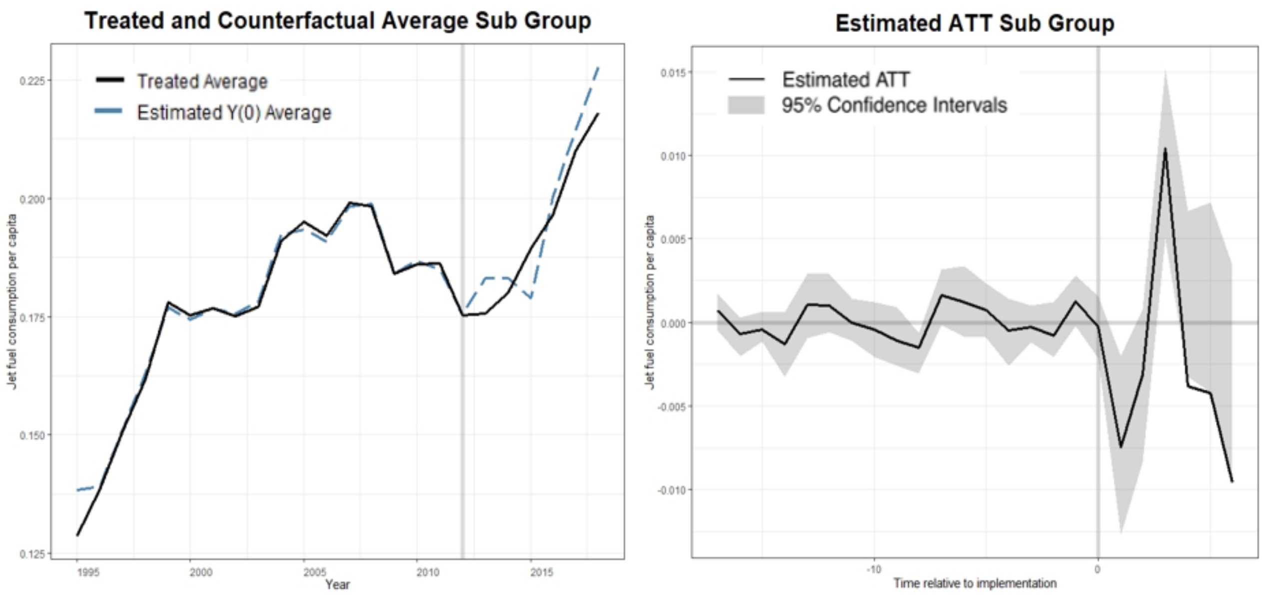


Fig. 5. The effect of the EU ETS over time, sub-group sample averages

Table 2
Sub-group Results

Outcome Variable: Jet Fuel Consumption per capita (mt)	**(0)**	**(1)**	**(2)**
ATT Coefficient	0.00007498	−0.002971	−0.004158
Standard Error 95% Confidence Interval	(0.005167) [−0.01153–0.008304]	(0.001876) [−0.003595–0.003336]	(0.001819) [−0.004648–0.002513]
GDP per capita[a]		0.831*** (0.1034)	0.6185*** (0.1035)
GDP per capita^2 [a]		0.000002192*** (0.000000754)	0.000003539*** (0.0000007591)
Inbound tourist[a]			−0.0004237*** (0.00006808)
Country & Year fixed effects	Yes	Yes	Yes
Unobserved factors	2	4	4
Observations	636	636	636
Treated countries	12	12	12
Control countries	15	15	15

Notes.
***, **, and * denotes significance at 1%. 5% and 10% levels, respectively.
Standard errors are presented in parentheses, and 95% confidence intervals are presented in brackets.
a: values are adjusted for visualisation purposes and should be multiplied by 10^{-6} to show true results.

tribute the whole treatment effect to the EU ETS. Moreover, the EU ETS measures emission from airlines registered in a country, rather than all flights departing from that country as reflected in this papers' outcome variable. Therefore, it is likely that the treatment variable picks up impacts on jet fuel consumption caused by confounding variables not included in the model. Not accounting for all confounding variables violates the assumption of strict exogeneity and generates the results to be biased.

As previously mentioned, the factor component cannot capture unobserved confounders independent across units. Knowing that many of the countries included in the sample levies either a ticket tax or an exercise duty on domestic jet fuel, including a factor variable indicating whether a country has such a tax, and when it came into effect, might affect the results. Researchers have found both a tax on domestic fuel (González & Hosoda, 2016) and a flight departure tax (Falk & Hagsten, 2020) to have adverse effects. A ticket tax can be a reason why the sub-group estimates resulted in a negative ATT. A report from CE Delf and EC (2019) points out that the highest average aviation tax rates are found in the UK, Italy, Norway, Germany, and France. Ticket taxes have recently been included in Sweden as well. Although it should be possible to control such a factor in theory, it was left out of the model due to the data programming proving too difficult.

Assuming that the model is correctly specified and none of the assumptions underlying it is violated, one can argue that the EU ETS has failed its goal to reduce emissions in aviation. Although many researchers have concluded that the EU ETS has led to emission reductions during its first three phases, these studies have solely been based on stationary sources with abatement primarily seen in the power sector (Martin et al., 2016). In contrast, the aviation sector analysis has found inconclusive evidence that a carbon price has led to increased abatement efforts (Seetaram et al., 2014; Markham et al., 2018; Fageda and Teixido-Figueras, 2020). Significant, albeit small, reductions have been concluded through stimulations studies, although all assume a high allowance price (€ 50 and up).

Although this does not answer why a cap-and-trade system like the EU ETS should cause airlines to increase their emissions relative to a scenario where it was not implemented, the results are somewhat in line with Anger's (2010) predictions. When a relatively small permit price is seen (< € 20), a yearly increase of CO_2 emissions was calculated to be positive. Although Angers' (2010) estimations were smaller in magnitude than what this paper reports, the growth rate assumed in the paper is also one-third of actual passenger growth seen over the past seven years. Statista (2020) reports passenger traffic growth associated with all domestic and international flights by European airlines during 2013–2019 to average 6.2 per cent yearly, with fuel efficiency seeing an annual average improvement of 2.3 per cent (Enviro.aero, 2019). Thus, it is not unreasonable to believe that if the growth rate in Angers' estimations was increased, it could reflect similar results to what is seen in this paper.

The EC published a report (CE Delf & EC, 2019) that concluded that on average a 10 per cent increase in ticket prices would lead to a 9–11 per cent reduction in demand followed by a similar reduction in emissions, in the 27 member states included in the analysis. Empirical ex-post analysis of ticket taxes has found similar results (Falk & Hagsten, 2020). In contrast, IATA (2019a) argues that no government has demonstrated that a ticket tax has led to reduced emissions. Considering the highly competitive market that airlines operate in, instead of contributing to the decarbonizing of the aviation industry, taxes with "green" incentives have negative financial impacts on airlines hence limiting their ability to invest in newer, cleaner, and quieter technology. Arguably, without a tax, airlines already have an incentive to maximize fuel efficiency, considering fuel represents up to 30 per cent of operational costs (IATA, 2019b). The estimated costs of purchasing permits for intra-EU airlines in 2017 only represented about 0.3 per cent (EASA et al., 2019). Consequently, compared to large market swings in jet fuel prices, a tax set with a modest price, is thus expected to have little effect.

It underlines that the effectiveness of the ETS is reliant on EUA prices. When prices are set at an appropriate level, the incentives to abate are higher. Further, when the permit market is competitive, an appropriate price ensures no more profitable trade opportunities exist (Thomson Reuters Point Carbon, 2012). In turn, prices rely primarily on supply and demand. The EU ETS has arguably been oversupplied with allowances for most of its existence, limiting its economic and environmental impact. One could wonder whether the situation of allowances and the "willingness to purchase" these by the aviation sector would differ with a tighter cap.

Nonetheless, even if EU ETS has not had the desired impact on emission reductions in the aviation industry, it can still be effective. Returning to a carbon tax; it should encourage emitters to adopt the cheapest GHG abatement measures available to them. The EU ETS has proved that the cost of marginal abatement for airlines is far greater than the market price of permits, especially with continued growth in passenger traffic. Thus, this can be positively interpreted as the market-based mechanism working as intended. That is, emission abatement primarily taking place in sectors where it is cheapest and easiest to do so, whilst other industries, with little to no low-carbon substitutions, continue to pay to pollute (Markham et al., 2018). During 2012–2019 the aviation industry has purchased over 172 million tonnes worth of CO_2 equivalents either via auctions or other industries (EEA, 2020c). In a way, by purchasing emission allowances from stationary sources — the aviation sector is effectively offsetting their emissions.

Ahmad (2015) states that although the success of unilateral measures, like the EU ETS, is limited — it has led to ICAO speeding up its processes toward reducing emissions from international civil aviation. CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) was ratified by the 39th ICAO assembly in October 2016. Another market-based measure, CORSIA realise that emission abatement is unlikely in the aviation sector with continued positive passenger growth. Thus its focus is on making sure aviation growth is offset elsewhere. CORSIA was agreed by 192 countries and marked the first MBM covering an entire international sector. Participation in voluntary until 2026, and as of 5th November 2018, 76 States have indicated that they will volunteer — representing 76 per cent of international aviation activity in terms of RTKs (EASA et al., 2019).

Conclusions

This paper has attempted to evaluate the effectiveness of the EU ETS by analysing whether the aviation industry's inclusion in 2012 has led to emission abatement. The GSC model results show that a 10 per cent increase in fuel consumption per capita is associated with being regulated by the EU ETS relative to a counterfactual scenario. Although the result is surprising, there is reason to believe that taxing aviation does not have the intended effect theory predicts. Since 2005 passenger kilometres flow have increased by 60 per cent, whilst average fuel consumption for commercial flights has decreased by 24 per cent. Thus, with the continued growth of passengers and limitations for technological improvement, there is no reason to believe a carbon tax will effectively lead to this trend changing. Instead, a tax might reduce the already low-profit margins and push airlines into financial difficulties with increasing operations costs.

However, the 10 per cent ATT predicted by the model fails to distinguish between intra- and extra-EU travel. Therefore, this leaves inconclusive results regarding the effects actually being attributed to the ETS. Attempting to account for this a separate model (including only the top intra-EU fuel burner countries) was estimated, and showed the effect, although insignificant, of the EU ETS to be −1.5 per cent. It is more in line with the theoretical hypothesis and other research suggesting a carbon tax, or cap-and-trade system, will effectively suppress demand (Fageda & Teixido-Figueras, 2020; Falk & Hagsten, 2020; González & Hosoda, 2016).

Arguably, even if EU ETS has not led to direct emission abatement through reduced jet fuel consumption, the aviation industry has still achieved emission reductions up to 172 million tonnes CO_2 equivalents in other sectors. It has also helped speed up the process of implementation of an international MBM, CORSIA. Whether CORSIA, including up to 76 per cent of all international aviation, will be more successful than the EU ETS remains to be seen.

This study is limited by data availability, and because of the likelihood of biased estimates, fails to conclude a causal impact of the EU ETS on aviation emissions. However, what is shown is that countries regulated by the EU ETS are associated with an increase in jet fuel consumption per capita, whether this is due to the EU ETS or other macroeconomic trends cannot be disentangled. Air travel is best analysed at the route level, as that is where competition occurs. By using aggregate values, the route-specific trends will not be picked up. Therefore, for all future research, it is recommended that data is gathered on the airline and/or route level.

Furthermore, one should distinguish the analysis by network and low-cost airlines and short, medium, and long-haul flights, as the different characteristics are likely to cause different results. There is still a lack of ex-post research concerned with aviation and carbon pricing. Some areas to address for future research can include; evaluating emissions directly; analysing changes to tickets prices, and; estimating effects on airlines revenue.

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APPENDIX

Appendix 1. EU enlargement glossary

Country	Part of EU enlargements:
Austria	EU-15, EU-25, EU-27_2007, EU-28, EU-27
Belgium	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Bulgaria	EU-27_2007, EU-28, EU-27
Croatia	EU-28, EU-27
Cyprus	EU-25, EU-27_2007, EU-28, EU-27
Czechia (former Czech Republic)	EU-25, EU-27_2007, EU-28, EU-27
Denmark	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Estonia	EU-25, EU-27_2007, EU-28, EU-27
Finland	EU-15, EU-25, EU-27_2007, EU-28, EU-27
France	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Germany	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Greece	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Hungary	EU-25, EU-27_2007, EU-28, EU-27
Ireland	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Italy	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Latvia	EU-25, EU-27_2007, EU-28, EU-27
Lithuania	EU-25, EU-27_2007, EU-28, EU-27
Luxembourg	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Malta	EU-25, EU-27_2007, EU-28, EU-27
Netherlands	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Poland	EU-25, EU-27_2007, EU-28, EU-27
Portugal	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Romania	EU-27_2007, EU-28, EU-27
Slovakia	EU-25, EU-27_2007, EU-28, EU-27
Slovenia	EU-25, EU-27_2007, EU-28, EU-27
Spain	EU-12, EU-15, EU-25, EU-27_2007, EU-28, EU-27
Sweden	EU-15, EU-25, EU-27_2007, EU-28, EU-27
United Kingdom	EU-12, EU-15, EU-25, EU-27_2007, EU-28

Appendix 2. Countries included in analysis

id	Country	Country Code	Treatment status	Specification
1	Australia	AUS	Control	
2	Austria	AUT	Treated	
3	Belarus	BLR	Control	
4	Belgium	BEL	Treated	Sub-group
5	Bulgaria	BGR	Treated	
6	Canada	CAN	Control	
7	Chile	CHL	Control	
8	Columbia	COL	Control	
9	Croatia	HRV	Treated	
10	Cyprus	CYP	Treated	
11	Czechia (former Czech Republic)	CZE	Treated	
12	Denmark	DNK	Treated	Sub-group
13	Estonia	EST	Treated	
14	Finland	FIN	Treated	Sub-group
15	France	FRA	Treated	Sub-group
16	Germany	DEU	Treated	Sub-group
17	Greece	GRC	Treated	
18	Hungary	HUN	Treated	
19	Iceland	ISL	Treated	
20	Ireland	IRL	Treated	
21	Israel	ISR	Control	
22	Italy	ITA	Treated	Sub-group
23	Japan	JPN	Control	
24	Latvia	LVA	Treated	
25	Lithuania	LTU	Treated	
26	Luxembourg	LUX	Treated	Sub-group
27	Malta	MLT	Treated	
28	Mexico	MEX	Control	
29	Netherlands	NLD	Treated	Sub-group
30	New Zealand	NZL	Control	
31	Norway	NOR	Treated	Sub-group
32	Poland	POL	Treated	
33	Portugal	PRT	Treated	
34	Romania	ROU	Treated	
35	Russian Federation	RUS	Control	
36	Slovakia	SVK	Treated	
37	Slovenia	SVN	Treated	
38	South Korea	KOR	Control	
39	Spain	ESP	Treated	Sub-group
40	Sweden	SWE	Treated	Sub-group
41	Switzerland	CHE	Control	
42	Turkey	TUR	Control	
43	Ukraine	UKR	Control	
44	United Kingdom	GBR	Treated	Sub-group
45	United States	USA	Control	

Note. Monaco and Liechtenstein are omitted as they do not have a commercial airport.

Appendix 3.1. Allocation options for emissions from bunker fuel use (UNFCCC, 1996)

Option 1	No allocation, as in the current situation
Option 2	Allocation of global bunker sales and associated emissions to Parties in proportion to their national emissions
Option 3	Allocation to Parties according to the country where the bunker fuel is sold
Option 4	Allocation to Parties according to the nationality of the transporting company, or to the country where a ship or aircraft is registered, or to the country of the operator
Option 5*	Allocation to Parties according to the country of departure or destination of an aircraft or vessel; alternatively, the emissions related to the journey of an aircraft or vessel could be shared by the country of departure and the country of arrival
Option 6*	Allocation to Parties according to the country of departure or destination of passenger or cargo; alternatively, the emissions related to the journey of passengers or cargo could be shared by the country of departure and the country of arrival
Option 7*	Allocation to Parties according to the country of origin of passengers or owner of a cargo
Option 8*	Allocation to the Party of all emissions generated in its national space

Notes.
* Options considered to be less practical because of data requirements or inadequate global coverage.
All information is taken directly from UNFCCC (1996) under paragraph 27.

Appendix 3.2. Descriptive Statistics, mean values for 1995–2018

Variable	Control	Treated
Jet fuel consumption (mt)	8011341 (17857040)	1649801 (2696242)
Jet fuel consumption (mt) per capita	0.10741 (0.08)	0.133771 (0.17)
GDP (Current million US $)	1736569 (3587576)	506667.4 (813998.1)
GDP per capita (Current US $)	23058.5 (20101.8)	29210.83 (21349.05)
Inbound Tourists	13673150 (15548100)	13115280 (18023720)
Population	66568990 (76855470)	17185150 (22365270)
Number of observations	349	693
Number of countries	15	30

Note. Standard deviations in parentheses.

Appendix 3.3. Pre-treatment mean values, for period 1995–2012

Variable	Control	Treated
Jet fuel consumption (mt)	7746432 (17763680)	1583855 (2612476)
Jet fuel consumption (mt) per capita	0.1 (0.08)	0.13 (0.16)
GDP (Current million US $)	1531127 (3143231)	468677.8 (763313.5)
GDP per capita (Current US $)	20108.28 (18050.84)	26792.1 (19909.79)
Inbound Tourists	11872060 (13486310)	11882140 (16771540)
Population	65391440 (74906220)	17079850 (22173390)
Number of observations	266	518
Number of countries	15	30

Note. Standard deviations in parentheses.

Appendix 3.4. Post-treatment mean values, for period 2013–2018

Variable	Control	Treated
Jet fuel consumption (mt)	8860325 (18236010)	1845000 (2929423)
Jet fuel consumption (mt) per capita	0.12 (0.09)	0.15 (0.2)
GDP (Current million US $)	2394975 (4702911)	619116.7 (941767.4)
GDP per capita (Current US $)	32513.35 (23306.18)	36370.26 (23788.09)
Inbound Tourists	19445320 (19847020)	16765390 (20934490)
Population	70342840 (83161830)	17496840 (22985690)
Number of observations	83	175
Number of countries	15	30

Note. Standard deviations in parentheses.

Appendix 4.1. Results for Jack-knife resampling

Outcome Variable: Jet Fuel Consumption per capita (mt)	**(0)**	**(1)**	**(2)**
ATT Coefficient	0.002102	0.01531	0.01581
Standard Error 95% Confidence Interval	(0.01459) [−0.0265–0.0307]	(0.02403) [−0.03178–0.0624]	(0.01675) [−0.01703–0.04865]
GDP per capita[a]		1.813 (1.674)	1.317 (1.369)
GDP per capita^{2} [a]		-0.000006568 (0.00002457)	-0.00000261 (0.00001702)
Inbound tourist[a]			-0.00007903 (0.000822)
Country & Year fixed effects	Yes	Yes	Yes
Unobserved factors	4	3	3
Observations	1297	1297	1039
Treated countries	30	30	29[b]
Control countries	15	15	15

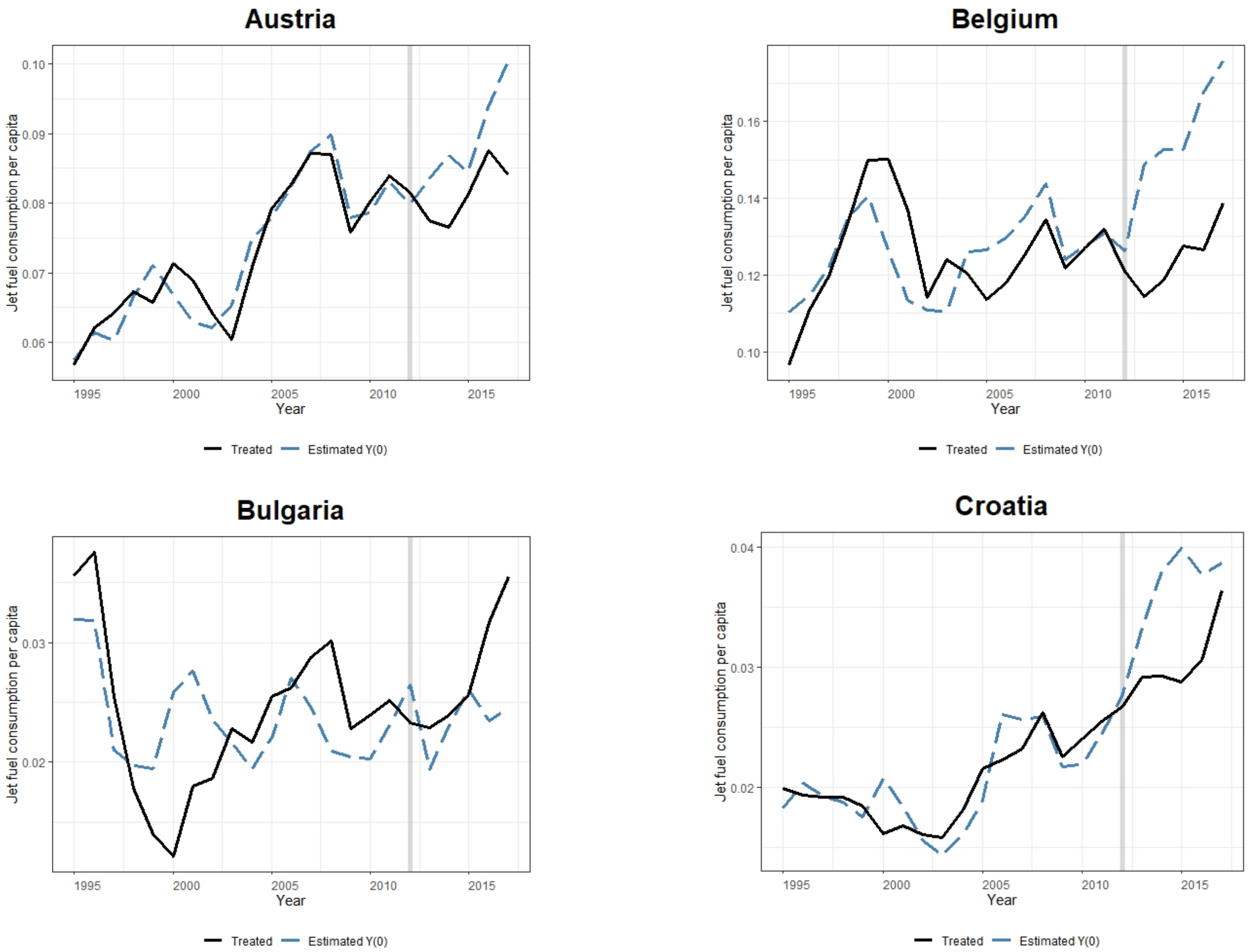
Notes.
***, **, and * denotes significance at 1%. 5% and 10% levels, respectively.
Standard errors are presented in parentheses, and 95% confidence intervals are presented in brackets.
a: values are adjusted for visualisation purposes, and should be multiplied by 10^{-6} to show true results.
b: Hungary is dropped from the sample due to too few (< 12) pre-treatment observations.

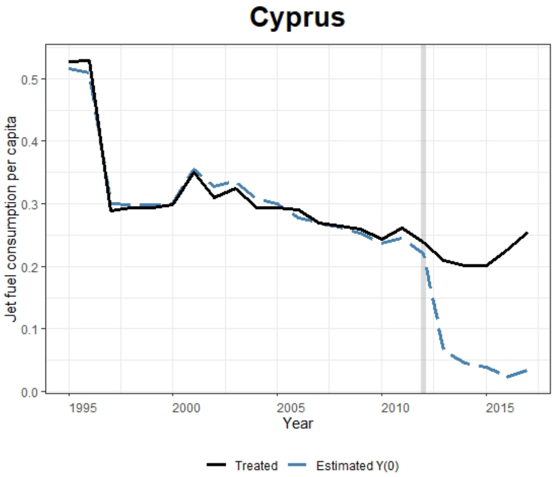
Appendix 4.2. Results from the log-log model

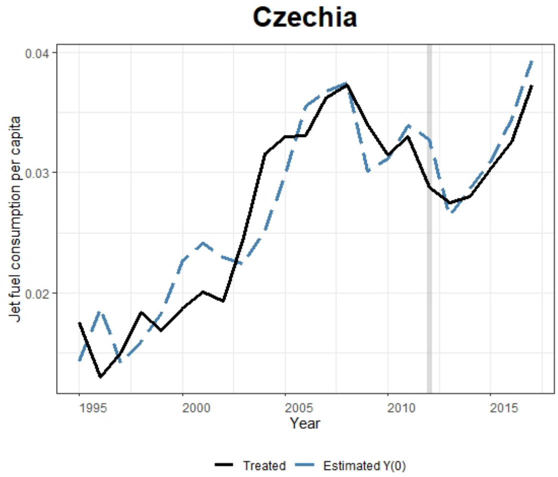
Outcome Variable: Log (Jet Fuel Consumption per capita (mt))	(0)	(1)	(2)
ATT Coefficient	0.1513***	0.143***	0.08925***
Standard Error 95% Confidence Interval	(0.01442) [0.1658−0.2214]	(0.01895) [0.1668−0.2398]	(0.01675) [−0.01703−0.04865]
Log(GDP per capita)		-1.0625*** (0.060357)	-0.32516*** (0.056749)
Log(GDP per capita)^2		0.0819*** (0.003701)	0.04039*** (0.003459)
Log(Inbound tourist)			-0.17046*** (0.007701)
Country & Year fixed effects	Yes	Yes	Yes
Unobserved factors	5	5	5
Observations	1297	1297	1039
Treated countries	30	30	29[b]
Control countries	15	15	15

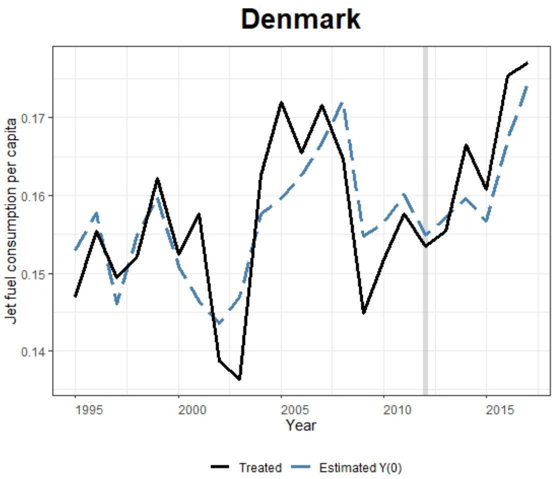
Notes.
***, **, and * denotes significance at 1%, 5%, and 10% levels, respectively.
Standard errors are presented in parentheses, and 95% confidence intervals are presented in brackets.
b: Hungary is dropped from the sample due to too few (< 12) pre-treatment observations.

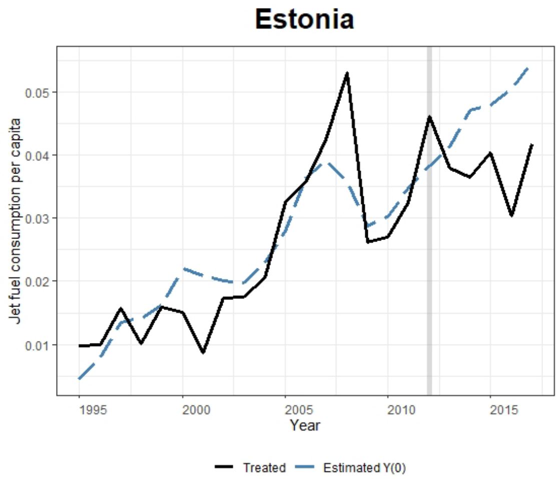
Appendix 4.3. The effect of the EU ETS over time, country-specific results

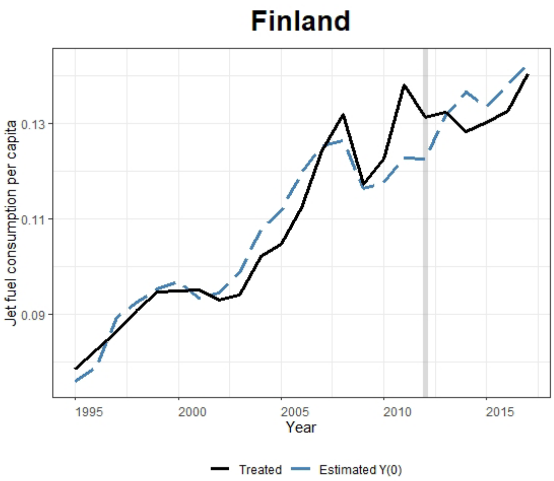


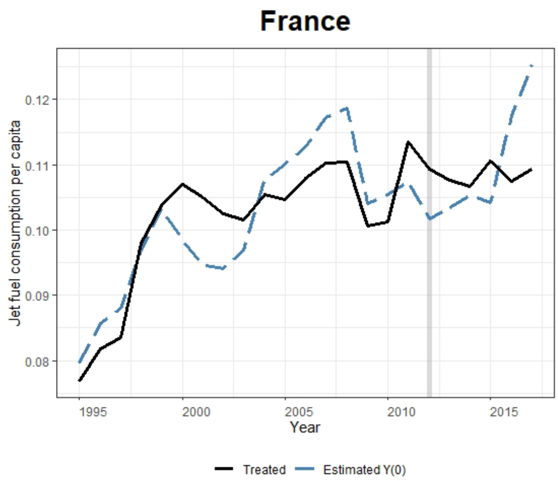

Cyprus
Jet fuel consumption per capita
Year
Treated
Estimated Y(0)

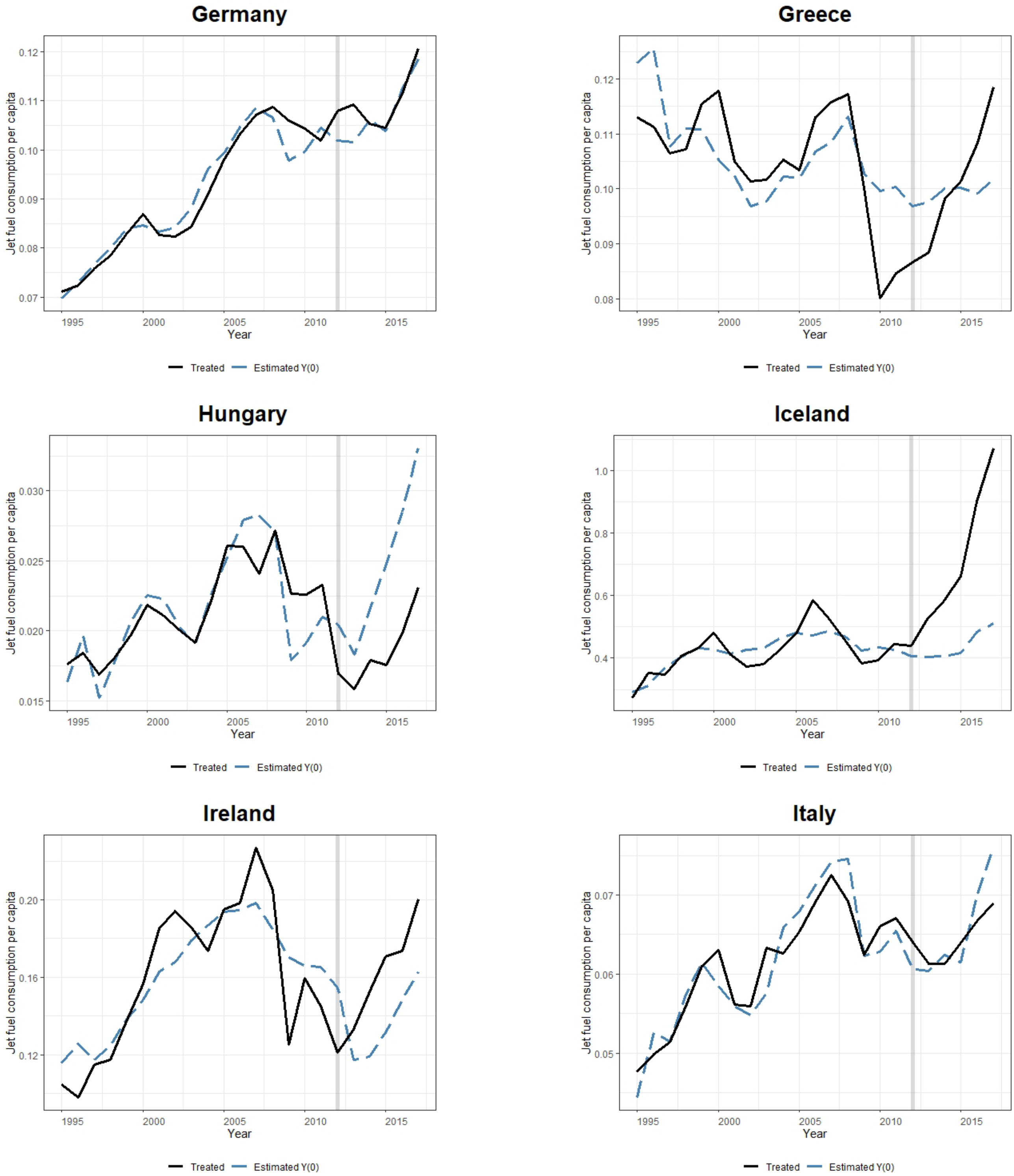

Czechia
Jet fuel consumption per capita
Year
Treated
Estimated Y(0)

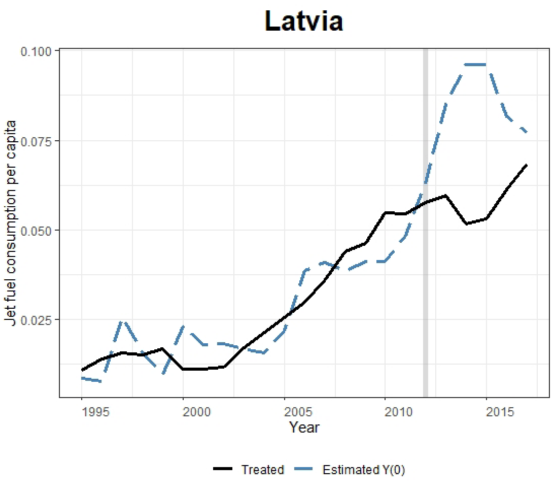

Denmark
Jet fuel consumption per capita
Year
Treated
Estimated Y(0)

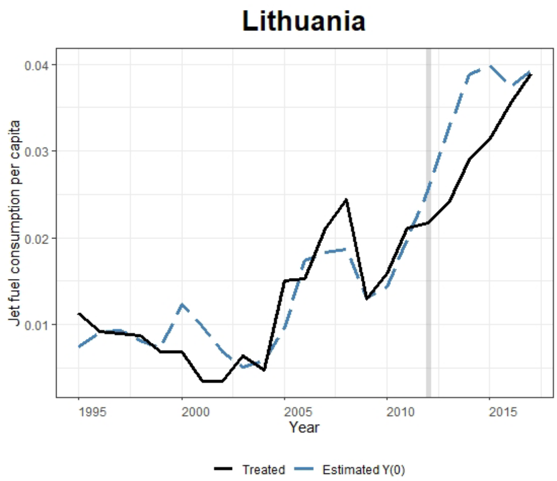

Estonia
Jet fuel consumption per capita
Year
Treated
Estimated Y(0)

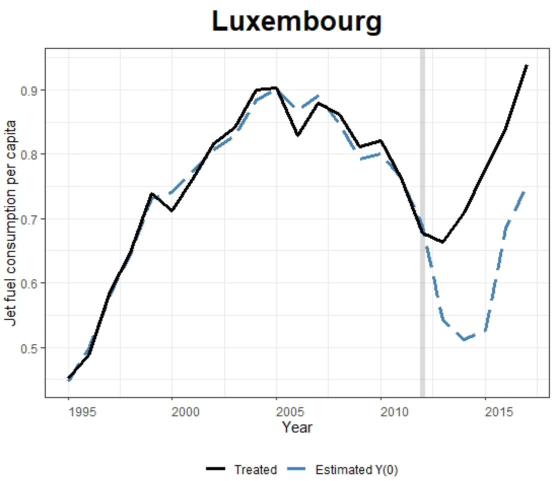

Finland
Jet fuel consumption per capita
Year
Treated
Estimated Y(0)

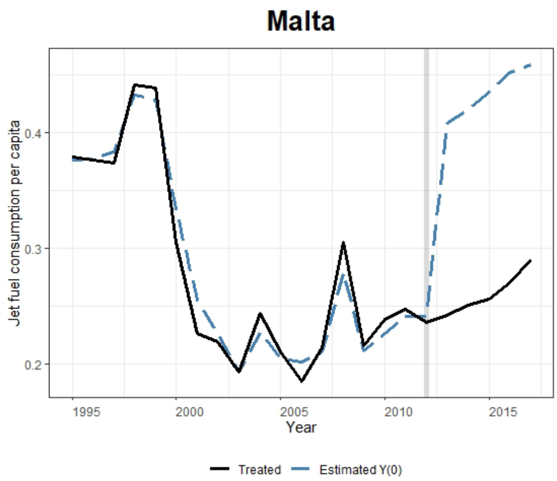

France
Jet fuel consumption per capita
Year
Treated
Estimated Y(0)

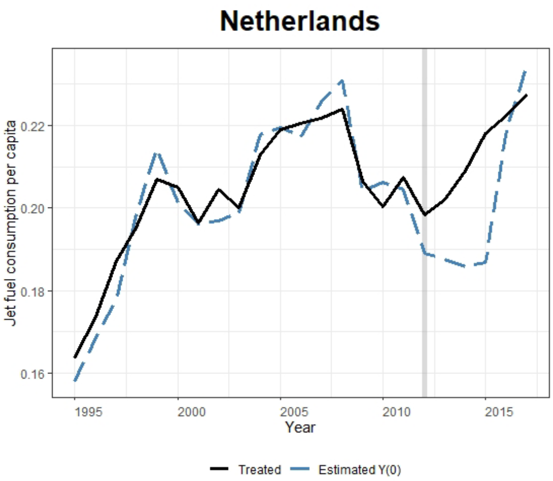

Germany
Greece
Hungary
Iceland
Ireland
Italy
Jet fuel consumption per capita
Year
Treated
Estimated Y(0)

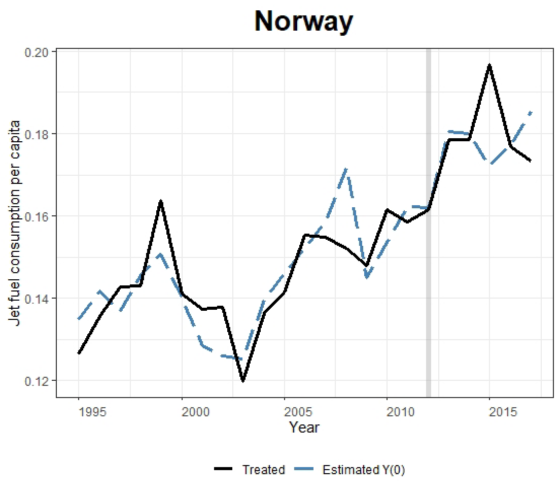

Latvia
Jet fuel consumption per capita
0.100
0.075
0.050
0.025
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

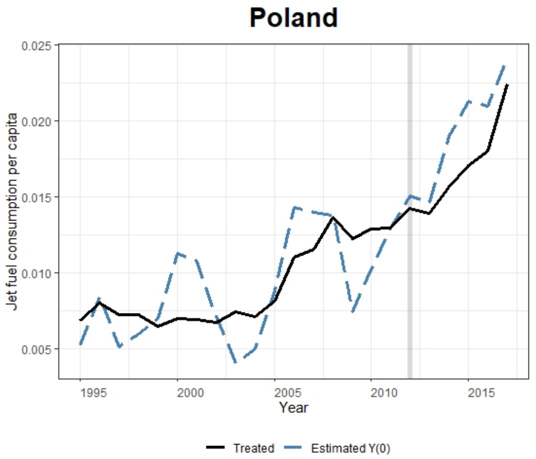

Lithuania
Jet fuel consumption per capita
0.04
0.03
0.02
0.01
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

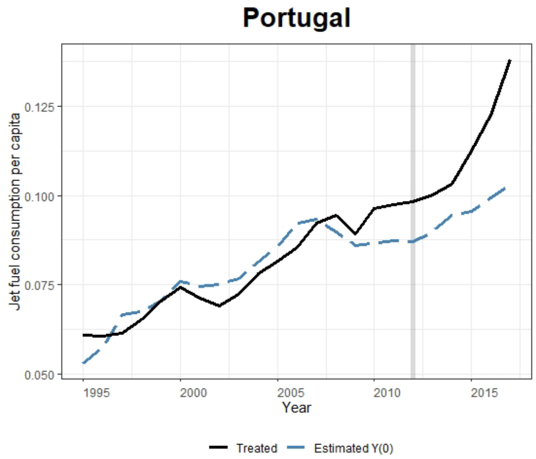

Luxembourg
Jet fuel consumption per capita
0.9
0.8
0.7
0.6
0.5
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

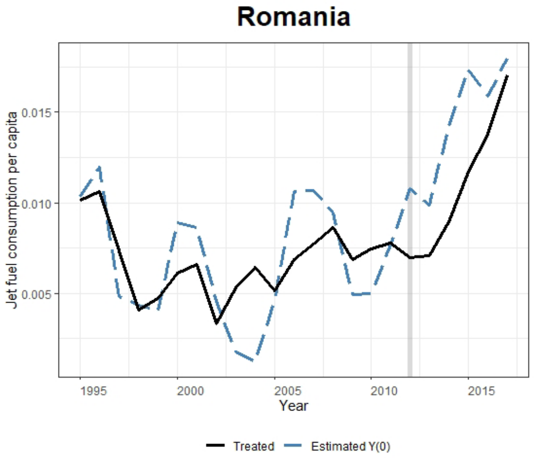

Malta
Jet fuel consumption per capita
0.4
0.3
0.2
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

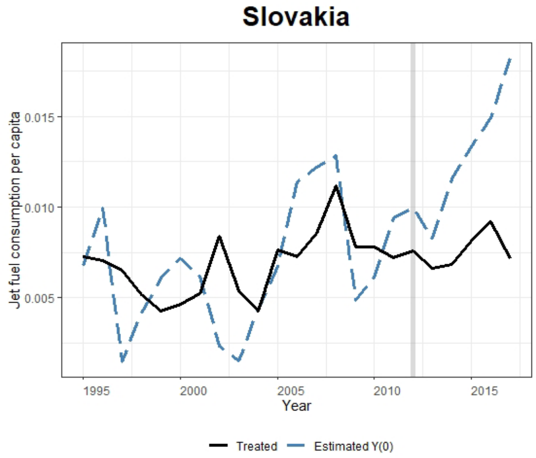

Netherlands
Jet fuel consumption per capita
0.22
0.20
0.18
0.16
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

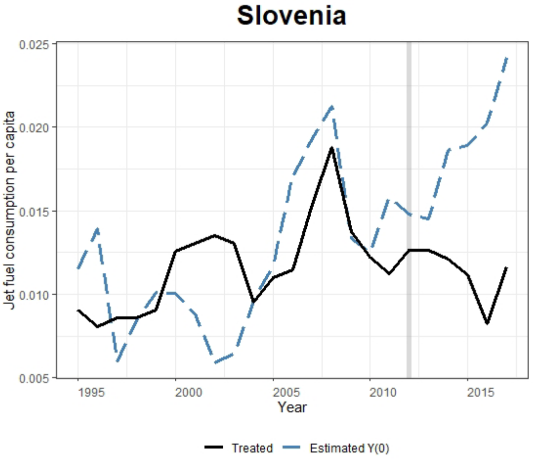

Norway
Jet fuel consumption per capita
0.20
0.18
0.16
0.14
0.12
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

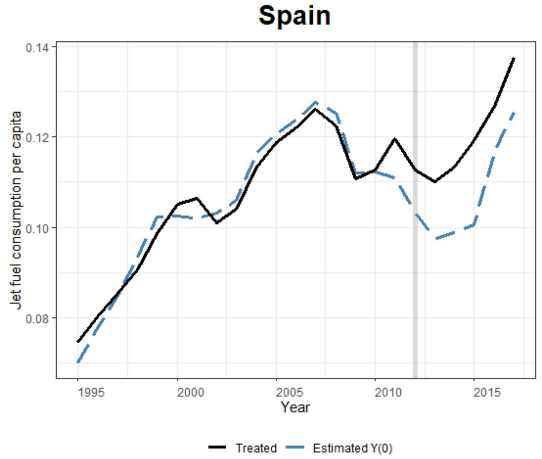

Poland
Jet fuel consumption per capita
0.025
0.020
0.015
0.010
0.005
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

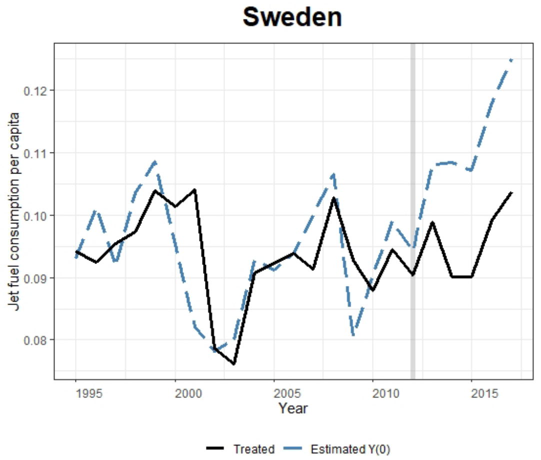

Portugal
Jet fuel consumption per capita
0.125
0.100
0.075
0.050
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

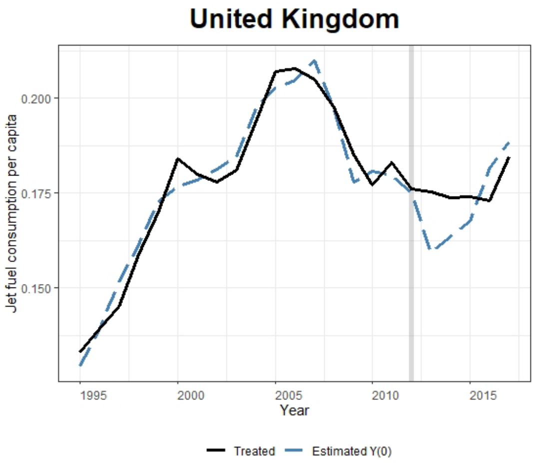

Romania
Jet fuel consumption per capita
0.015
0.010
0.005
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)


Slovakia
Jet fuel consumption per capita
0.015
0.010
0.005
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)


Slovenia
Jet fuel consumption per capita
0.025
0.020
0.015
0.010
0.005
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)


Spain
Jet fuel consumption per capita
0.14
0.12
0.10
0.08
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)


Sweden
Jet fuel consumption per capita
0.12
0.11
0.10
0.09
0.08
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

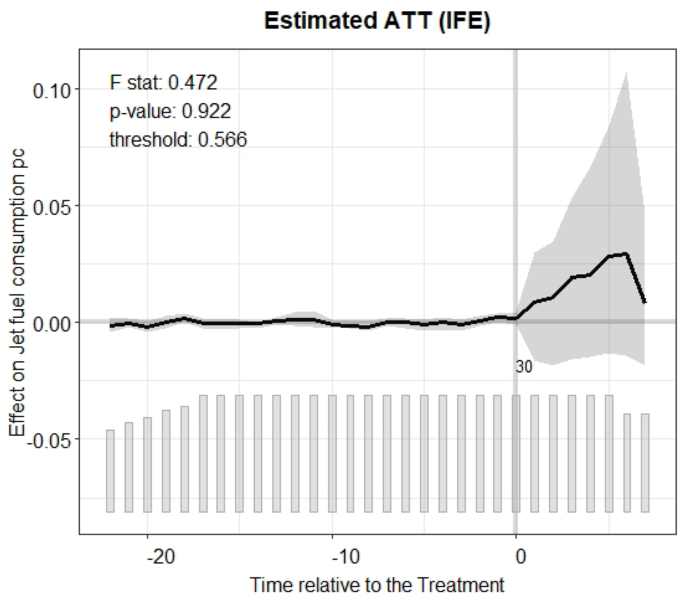

United Kingdom
Jet fuel consumption per capita
0.200
0.175
0.150
1995
2000
2005
2010
2015
Year
Treated
Estimated Y(0)

Appendix 4.4. IFE model results and plot

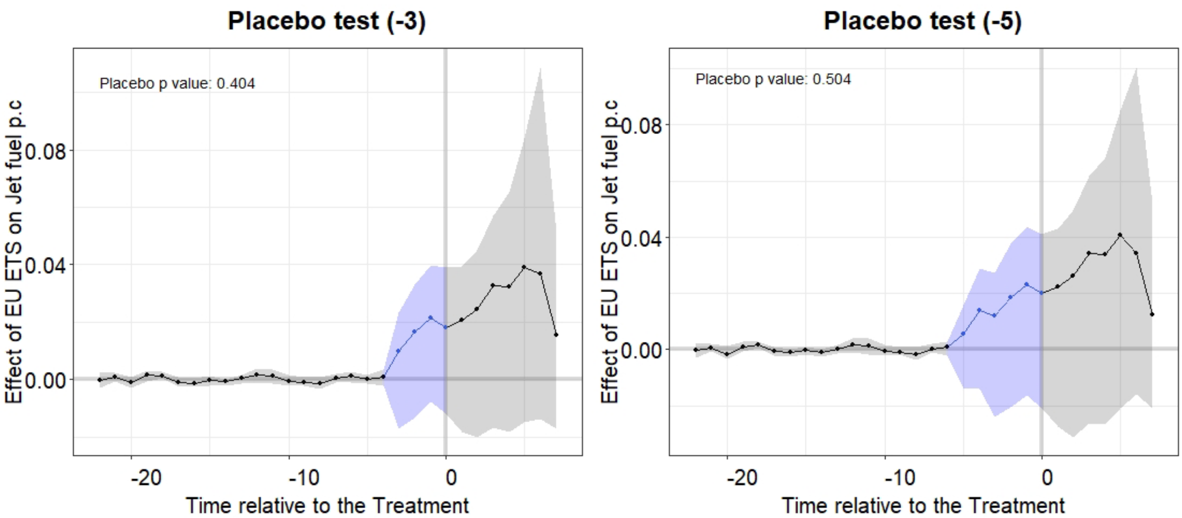
Outcome Variable: Jet Fuel Consumption per capita (mt)	**IFE MODEL**
ATT Coefficient	0.01777
Standard Error 95% Confidence Interval	(0.01728) [−0.009431−0.05675]
Control	GDP per capita
Country & Year fixed effects	Yes
Unobserved factors	3[a]
Observations	1297
Treated countries	30
Control countries	15

Notes.
a: Manually enforced based on GSC results.
Note: it is impossible to estimate the IFE model with a squared variable; thus, only one control variable is included.

The effect of EU ETS on Jet fuel consumption estimated by the IFE model follows a similar pattern to that of the GSC model. The downward trend after 2017 is likely due to missing observations when treated countries drop from 30 to 25. The GSC model better accounts for missing observation than the IFE model.

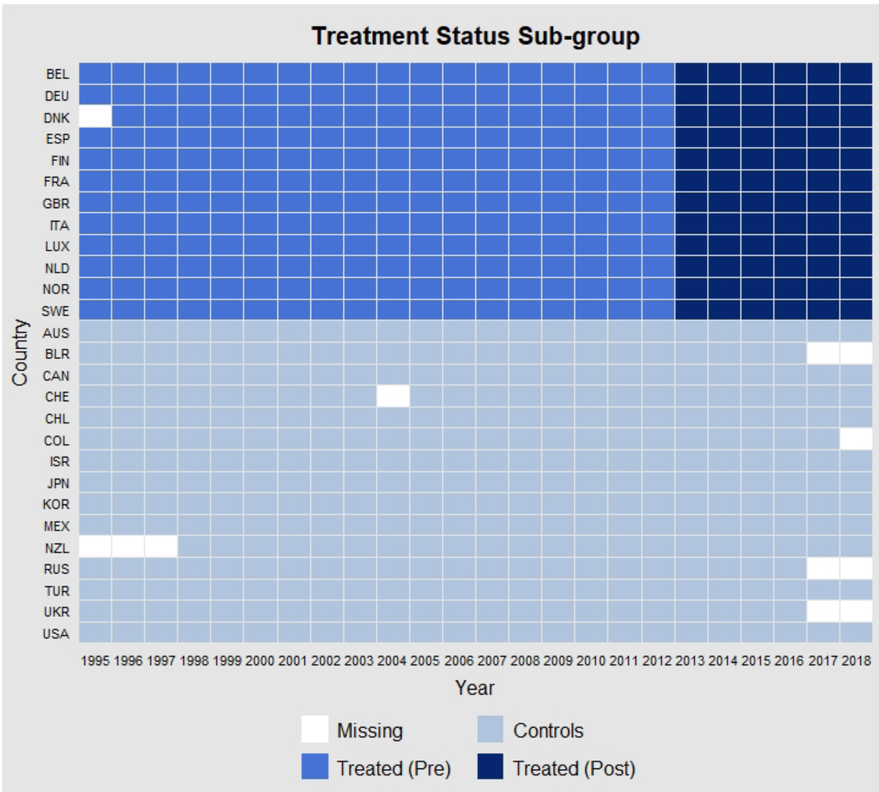


Appendix 4.5. Placebo test results from IFE model



In both cases, we reject the null hypothesis that the ATT is different from zero before implementation.

Appendix 4.6. Overview of treatment and missing observation in sub-group



Система коммерциализации выбросов Евросоюза (EU ETS) и авиация: оценка эффективности системы торговли квотами на выбросы в Евросоюзе для сокращения выбросов от авиаперелетов

Анн Марит Хейас

Аннотация. В настоящее время авиационный сектор считается одним из наиболее быстрорастущих источников выбросов парниковых газов. Пытаясь сократить эти выбросы рентабельным образом, Евросоюз в 2012 г. решил включить все рейсы, прибывающие и вылетающие из Евросоюза, в свою Систему коммерциализации выбросов (EU ETS). Идея ETS состоит в том, что, установив потолок выбросов и разрешив торговлю квотами между секторами, заниматься сокращением выбросов можно там, где это дешевле и проще всего сделать. В какой мере EU ETS, используя модель общего синтетического контроля для оценки противоположного сценария, удалось сократить выбросы авиационного сектора в 2012–2018 гг.? Результаты исследования свидетельствуют: при использовании расхода реактивного топлива как показателя выбросов применение ЕС ETS привело к 10%-ному увеличению расхода данного вида топлива по сравнению со сценарием, в котором он не был критерием.

Ключевые слова: система коммерциализации выбросов; авиационная индустрия; модель общего синтетического контроля; выбросы парниковых газов; загрязнение воздуха