Universidad de Oviedo

Programa de Doctorado en Economía:
Instrumentos del Análisis Económico

Ensayos sobre energía y crecimiento económico en un marco de sostenibilidad

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RESUMEN (en español)

Debido a la importancia de la acción humana sobre el cambio climático acelerado, la presente tesis aporta nuevas evidencias empíricas y teóricas al análisis de los límites al crecimiento económico sostenible, en el ámbito del progreso tecnológico asociado a la eficiencia y transición energética. La literatura existente ha tendido a omitir las relaciones de dependencia espacial en este contexto, además de ignorar las teorías del crecimiento endógeno Schumpeteriano y la endogeneización de instituciones económicas en la relación crecimiento-energía-cambio climático. En este sentido, la tesis contribuye a cubrir este vacío, estructurándose en tres capítulos.

El primer capítulo estudia los principales determinantes económicos sobre las emisiones domésticas de CO2 per cápita, así como las proyecciones sobre la evolución esperada de la temperatura global. Para ello, se contrastará la existencia de la Curva Medioambiental de Kuznets, considerando una de las mayores muestras de países empleada hasta el momento, abarcando el periodo 1990-2014. El ensayo analiza la influencia de los efectos espaciales y de la difusión técnica, a la vez que examina la Hipótesis del Refugio a la Contaminación. También se realizan predicciones sobre las emisiones globales de CO2 y sus concentraciones para distintos escenarios, donde se consideran tasas de crecimiento económico normales y aceleradas, así como diversas sendas de eficiencia y transición energética.

El segundo capítulo investiga la convergencia global en términos de intensidad energética. Para ello se emplean métodos paramétricos y no paramétricos con el objeto de analizar la evolución temporal y estudiar sus principales determinantes sobre dos muestras amplias de 173 y 130 países, entre los años 1990 y 2010. Asimismo, se propone un modelo Neoclásico simple que justifique la estimación de regresiones del tipo beta-convergencia. Para los métodos paramétricos, se controla por estados estacionarios domésticos y vecinos. Las estimaciones son replicadas para las diferencias individuales respecto a la media de la intensidad energética.

En el tercer capítulo se realiza una aproximación analítica de la relación entre los límites del progreso tecnológico determinados por la eficiencia institucional y el crecimiento sostenible. Para ello, se presenta un modelo de crecimiento endógeno combinando el marco teórico Neoclásico-Schumpeteriano y de la Nueva Economía Institucional. Se plantea un modelo base de una economía cerrada con diferentes mercados anidados y operados bajo distintos niveles de competencia, considerando la energía contaminante y no contaminante como bienes intermedios y asumiendo dos tipos de tecnologías no excluyentes para cada una de las fases intermedias de producción. Las instituciones económicas (impuestos, subsidios al I+D y la difusión técnica), son escogidas por un agente público representativo que busca maximizar el valor presente de la renta disponible del grupo en el poder. A modo ilustrativo, varias simulaciones son llevadas a cabo en el entorno del estado estacionario.

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Essays on the relationship between energy and sustainable economic growth

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Contents

1 Introducción

De acuerdo a los Quinto y Sexto Informes de Evaluación del IPCC (2014; 2021), las emisiones de gas de efecto invernadero (GEI) han seguido una tendencia creciente desde al año 1750, lo que ha dado lugar a un insólito incremento en las concentraciones de CO2, CH4 y N2O respecto a los últimos 800.000 años. El principal determinante de las emisiones GEI, así como el gas que permanece por más tiempo en la atmósfera, es el dióxido de carbono -CO2-. En concreto, el 78% del total de emisiones GEI durante el periodo 1970-2010 ha sido causado por el CO2, al tiempo que el nivel de sus concentraciones ha aumentado a su tasa interanual más rápida (2.0 ± 0.1 ppm/yr) entre los años 2002 y 2011. Por tanto, existen fuertes evidencias a favor de la acción humana como motor del actual cambio climático a través de las llamadas emisiones GEI de origen antropogénico, habiendo dado estas lugar a un incremento en la temperatura media global de 1ºC en el periodo 1850-1900, y proyectándose un incremento de hasta 2ºC para finales del siglo XXI. Además, este aceleramiento hacia una crisis climática parece ser producto de una retroalimentación entre los efectos de corto plazo del cambio climático, los cuales reducen la efectividad de los sumideros terrestres y oceánicos de carbono, y los derivados del incremento en la temperatura global. Por tanto, surge como principal conclusión la necesidad de alcanzar el objetivo de cero emisiones netas de CO2, y para ello, aquellos organismos encargados de diseñar políticas económicas deberán centrar su atención sobre el consumo energético, el cual parece dirigir las emisiones de CO2.

A la luz de estos datos, surge una pregunta en relación al desarrollo en el largo plazo de toda nación: ¿se pueden alcanzar sendas de crecimiento económico sostenible en términos de cambio climático controlado? Para poder responder a esta cuestión, es necesario definir primero qué se puede entender por crecimiento sostenible en un contexto económico. De acuerdo a Eriksson (2014), el crecimiento sostenible ante procesos productivos contaminantes puede definirse como "PIB per cápita (y consumo per cápita) no decreciente junto a niveles de contaminación constantes en el largo plazo". De todos modos, esta definición parece levemente incompleta, ya que permite la existencia de tasas de crecimiento nulas, lo que parece un sinsentido en el área de estudio del Crecimiento Económico. Tampoco tiene en cuenta la existencia de umbrales o niveles críticos a partir de los cuales la contaminación acumulada puede dar lugar al desastre medioambiental, y por tanto, al colapso económico. Por tanto, esta tesis estará centrada en contribuir tanto a la evidencia empírica como a los marcos teóricos en relación a la idea de crecimiento económico sostenible entendido como PIB per cápita (y consumo per cápita) creciente junto a niveles de contaminación inferiores al estado de colapso climático en el largo plazo. Además, y siguiendo la metodología del IPCC, el colapso climático será definido como un incremento en la temperatura global de 2ºC, debido a que a partir de este nivel crítico es muy probable que los desastres naturales, como inundaciones y sequías, y sus efectos y costes sobre la producción global aumenten de forma exponencial y se vuelvan cada vez más impredecibles.

Como ya se ha comentado previamente, el principal motor de las emisiones GEI es el consumo de energía. Sin embargo, la relación entre energía y crecimiento económico ha sido ampliamente ignorada en la literatura del Crecimiento Neoclásico y Endógeno (Stern, 2004a; 2004b; 2011), lo que representa un problema para el diseño de políticas eficientes y efectivas. De acuerdo al estudio exhaustivo de Stern (2004b), existen dos críticas principales en relación a la no consideración de la producción y uso de la energía en el contexto del crecimiento: la relacionada con los "limites a la sustitución", y la referida a los "límites del progreso tecnológico". La primera se refiere a los problemas que pueden existir en relación a la sustitución entre elementos del stock de capital, ya sea entre o dentro de categorías del mismo. La segunda se refiere a las tasas de innovación, la forma que toma esta y hacia dónde se dirige la misma. Centrándonos en la última crítica, se estudiará el papel del progreso tecnológico asociado a la intensidad energética, la cual contempla los cambios en la composición de la producción agregada y avances en la eficiencia energética (Liddle and Sadorsky, 2021), así como a las sendas de transición energética y su influencia sobre el crecimiento sostenible.

Además, la crisis del cambio climático es un fenómeno inherentemente internacional, donde los cambios observados en las emisiones de CO2 parecen estar fuertemente correlacionados con las relaciones comerciales (e.g. Halicioglu, 2009; Ertugrul et al., 2016). En este sentido, la Hipótesis del Refugio a la Contaminación (Pollution Haven Hypothesis, PHH) aparece como un concepto clave, la cual propondría que los países en vías de desarrollo presentarían menores restricciones medioambientales a la producción, de forma que los países desarrollados trasladarían su producción a los primeros (Copeland and Taylor, 2003; Cole, 2004). Si dicha hipótesis se cumpliera, podríamos anticipar que las emisiones globales de CO2 no mejorarían a pesar de que los países desarrollados cumplieran los objetivos de protección medioambiental. Por tanto, las relaciones espaciales no pueden ser ignoradas en este contexto, y serán tenidas en cuenta en los dos primeros capítulos de la tesis. Además, analizar la PHH a través de regresiones sobre modelos espaciales, una metodología ampliamente ignorada en los análisis globales del impacto económico sobre las emisiones de CO2, nos permitirá relajar la definición de la misma ya que controlaremos por el impacto de cambios en términos continuos en los niveles relativos de desarrollo sobre la contaminación per cápita, prescindiendo así de una división ad hoc entre países "pobres" y "ricos". Asimismo, estas herramientas analíticas nos permitirán también controlar por la duración en el corto y largo plazo de la PHH, así como estimar la importancia de la difusión técnica sobre la distribución global de los niveles de intensidad energética, la cual puede ser determinante para la convergencia hacia menores emisiones CO2 y alcanzar así la sostenibilidad global.

La tesis se estructura de la siguiente forma:

- Capítulo 1. ¿Influyen los países sobre la contaminación de sus vecinos? Un análisis espacial de la EKC para emisiones de CO2.

  El primer capítulo estudia los principales determinantes económicos de las emisiones domésticas de CO2 por persona, así como las proyecciones sobre la evolución esperada de la temperatura global. Para ello, se contrastará la existencia de la hipótesis de la Curva Medioambiental de Kuznets (EKC), considerando una de las mayores muestras de países empleada hasta el momento para el periodo 1990-2014, y controlando por efectos espaciales a través de los modelos Spatial Durbin Error, Spatial Lag of X. Se tendrán en cuenta también los efectos de escala, estructura y tecnológicos a través del uso de variables explicativas estándar, así como la Hipótesis del Refugio a la Contaminación y el efecto de difusión técnica teniendo en cuenta variables retardadas espacialmente. Las predicciones sobre las emisiones globales de CO2 y sus concentraciones son proyectadas para distintos escenarios donde se consideran tasas de crecimiento económico normales y aceleradas, así como sendas de eficiencia y transición energética.

- Capítulo 2. Nuevas perspectivas sobre la convergencia mundial en intensidad energética: Una aproximación Neoclásica considerando relaciones espaciales.

  El segundo capítulo analiza la convergencia global en términos de intensidad energética. Para ello se emplean métodos no paramétricos y paramétricos con el objeto de estudiar la evolución temporal y los determinantes de las diferencias globales de la intensidad energética para dos muestras amplias de 173 y 130 países entre los años 1990 y 2010. También se propone un modelo Neoclásico simple de forma que podamos justificar la estimación de regresiones del tipo β-convergencia considerando variables de control relacionadas con los estados estacionarios de cada economía. En relación a los métodos no paramétricos, se estudia la evolución temporal de las estimaciones kernel de la distribución. Para los métodos paramétricos, las regresiones de β-convergencia son llevadas a cabo considerando los modelos Spatial Durbin Error y Spatial Lag of X , así como controlando por la heterogeneidad no observada y variables explicativas representando los estados estacionarios domésticos y vecinos de las economías. Las estimaciones con la especificación Spatial Durbin Error Model son replicadas también para las diferencias individuales respecto a la media de la intensidad energética de forma que podamos estudiar los determinantes del proceso de convergencia.

- Capítulo 3. El papel de la eficiencia institucional sobre la intensidad energética y el cambio climático: Un modelo de crecimiento endógeno.

  Finalmente, el tercer capítulo versará sobre una aproximación analítica de la relación entre los límites del progreso tecnológico determinados por la eficiencia institucional y el crecimiento sostenible. Para ello, se presentará un modelo de crecimiento endógeno combinando los marcos teóricos del crecimiento Neoclásico-Schumpeteriano y la Nueva Economía Institucional. Se planteará inicialmente un modelo base de una economía cerrada con diferentes mercados anidados y operados bajo distintos niveles de competencia, considerando la energía contaminante y no contaminante como bienes intermedios y asumiendo dos tipos de tecnologías no excluyentes para cada una de las fases intermedias de producción: calidad del bien intermedio y calidad del proceso productivo de cada bien intermedio. Se asumirán distintos grados de apropiabilidad sobre dichas técnicas de acuerdo a unas instituciones económicas exógenas que controlan el grado de difusión técnica, así como se permitirá la existencia de cambio tecnológico dirigido no sólo entre sectores, sino también entre tipos de técnicas. El cambio climático emerge como una consecuencia del consumo de energía contaminante, y tiene un impacto negativo sobre la utilidad de las familias. La endogeneización de la difusión técnica y la inclusión de otras instituciones económicas endógenas, como impuestos sobre la renta y subsidios públicos al I+D, son considerados a modo de extensión del modelo base. El agente público representativo emerge exógenamente de uno de los tipos de familias: las élites y la clase media. Dicho agente toma decisiones sobre las instituciones económicas con el objetivo de maximizar el valor presente de la renta disponible de la familia representativa en poder sujeto a una serie de instituciones políticas exógenas. A modo ilustrativo, varias simulaciones son llevadas a cabo en el entorno del estado estacionario.

2 Introduction

According to the IPCC Fifth and Sixth Assessment Reports (2014; 2021), anthropogenic greenhouse gas (GHG) emissions have increased since 1750, creating a situation where atmospheric concentrations of CO2, CH4 and N2O have reached unprecedented levels over the past 800,000 years. The major contributor to GHG emissions, as well as the gas that remains longest in the atmosphere, is carbon dioxide -CO2-. More precisely, 78% of total GHG emissions were caused by CO2 emissions in the 1970–2010 period; at the same time, CO2 concentrations increased at their fastest observed decadal rate of change (2.0 $\pm$ 0.1 ppm/yr) during 2002–2011. Human action is shown to be unequivocally related to global warming through anthropogenic GHG emissions, which have likely increased the global temperature by more than 1ºC with respect to the 1850-1900 period, and under all scenarios, the temperature is predicted exhibit a 2ºC increase by the end of the XXI century. Moreover, climate change seems to have accelerated in recent decades, probably due to a feedback effect between the short-term effects of global warming, which seem to diminish the effectiveness of land and ocean carbon sinks, and the global temperature. A major conclusion is the need for net zero CO2 emissions. To achieve this goal, policy-makers must address energy consumption, as it is the major driver of carbon emissions.

In light of all this information, a crucial question regarding the long-term development of all nations emerges: is sustainable economic growth feasible in terms of controlled climate change? I therefore first require a comprehensive definition of what sustainable growth means. According to Eriksson (2014), sustainable growth regarding polluting production can be defined as “non-declining per capita GDP (and per capita consumption) along with non-increasing pollution in the long run". However, this definition has some flaws. For instance, it allows for null rates of growth, which seems to contradict the scope of study of Economic Growth theories, and it does not consider the existence of thresholds related to an environmental collapse. Thus, the present thesis will focus on contributing to both theoretical frameworks and empirical evidence regarding sustainable growth understood as growing per capita GDP (and per capita consumption) along with pollution levels inferior to those leading to an environmental collapse. Moreover, following the IPCC, environmental collapse is defined as an increase in average global temperature exceeding 2ºC, due to unpredictable and costly natural disasters such as floods or severe droughts affecting global production, as well as to the likelihood of the emergence of a point of no return beyond which global temperatures follow an exponential trend.

As noted, the key driver of anthropogenic GHG emissions is energy consumption. However, the growth-energy nexus has been widely ignored in the mainstream literature of both neoclassical and endogenous economic growth (Stern, 2004a; 2004b; 2010), which represents a major gap for efficient and effective policy-making. In Stern's (2004b) exhaustive review, two major lines of critique are highlighted regarding the omission of the specific role of energy production and consumption on aggregate production: the "limits to substitution" critique, and the "limits to technological change" critique. The former refers to physical limits to substitution between and within categories of capital stock, while the latter refers to the arrival, embodiment and direction of innovations. Focusing on the second critique, this thesis studies the role of technical change associated with energy intensity, by measuring changes in output composition and energy efficiency (Liddle and Sadorsky, 2021), and identifying transition paths to nonpolluting or renewable sources of energy on sustainable growth.

Furthermore, the climate change crisis is an inherently international phenomenon, with changes in CO2 emissions strongly correlated with trade relationships (e.g. Halicioglu, 2009; Ertugrul et al., 2016). In this sense, the pollution haven hypothesis emerges as a key argument proposing that relatively weaker environmental restrictions in developing countries attract polluting productive processes from developed countries (Copeland and Taylor, 2003; Cole, 2004), leading to nondecreasing CO2 emissions for the world as a whole. Therefore, spatial relationships cannot be ignored in this context, and they will be accounted for in the first two chapters. Moreover, testing the PHH with spatial regression models, an approach widely overlooked for global analyses, allows us to relax its definition by considering the impact of continuous changes in relative levels of development on per capita pollution, without the need to establish a dichotomous division between the "poor" and "rich" countries, which also permits us to test for its duration in the short and long term. In addition, these models allow us to estimate the importance of technical diffusion on worldwide distribution of energy intensity, which is determinant for worldwide convergence to lower levels of per capita CO2 emissions and global sustainable growth.

The thesis is structured as follows:

- Chapter 1: Do countries influence neighbouring pollution? A spatial analysis of the EKC for CO2 emissions.

  The first chapter studies the major economic determinants of domestic per capita CO2 emissions and projections for the evolution of global temperature increases. I test the existence of the environmental Kuznets curve for one of the largest sets of countries not considered during the 1990-2014 period and control for local spatial spillovers with the spatial Durbin error model and the nested model of spatial lag of X. I control for the standard scale, structural and technological effects by employing standard explanatory variables, and for the pollution haven hypothesis and technical diffusion effect by considering spatially lagged variables. Forecasts of global CO2 emissions and concentrations are projected under different scenarios considering base and accelerated growth rates and paths of energy efficiency improvements and energy transition.

- Chapter 2: New Insights into the World's Energy Intensity Convergence: A Neoclassical Approach Considering Spatial Spillovers.

  The second chapter analyses global convergence in terms of energy intensity levels. I employ nonparametric and parametric methods to assess the time evolution as well as determinants of worldwide differences in energy intensity for two large datasets of countries between 1990 and 2010. I also propose a simple neoclassical model to establish a theoretical justification for estimating of β-convergence regressions considering control variables related to steady states of economies. Regarding nonparametric methods, I study the time evolution of kernel estimated density functions. Regarding parametric methods, β-convergence regressions are carried out considering spatial Durbin error and spatial lag of X models, and accounting for country unobserved heterogeneity and control variables measuring for domestic and neighbouring steady states. The spatial Durbin error model estimations with the same control variables are replicated for individual differences with respect to the cross-country mean of energy productivity to estimate the determinants of convergence.

- Chapter 3: The Role of Institutional Efficiency in Energy Intensity and the Climate Change: An Endogenous Growth Model.

  Finally, the third chapter takes an analytical approach to the relationship between limits to technical change determined by institutional efficiency and sustainable growth. I present an endogenous growth model considering the neoclassical-Schumpeterian and new institutional economics theoretical frameworks. A base model is presented of a closed economy with different levels of nested markets operated under various degrees of competition, considering polluting and nonpolluting energy as intermediate goods and assuming two types of nonexcluding technologies for each intermediate phase of production: quality- and process-improving techniques. Different degrees of appropriability in techniques are assumed through exogenous economic institutions measuring technical diffusion, and endogenous directed technical change is considered at not only a between-sector level but also a within-sector level. Climate change emerges as a consequence of polluting energy consumption and impacts on households' utility functions. Endogenization of technical diffusion and inclusion of other endogenous economic institutions, such as income taxes and R&D public subsidies, are considered a major extension of the base model. The representative public agent emerges from one of the two types of households depending on who exogenously controls power: the elite or the middle class. The agent makes decisions regarding economic institutions with the aim of maximizing the discounted value of disposable income of the household in power constrained to exogenous political institutions. For illustrative purposes, several simulations are carried out in the neighbourhood of the steady state.

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3 Do countries influence neighbouring pollution? A spatial analysis of the EKC for CO2 emissions

3.1 Introduction

Carbon dioxide pollution is highly correlated to the usage of energy derived from exogenous sources to manpower; more specifically, to fossil fuel consumption. Since the Industrial Revolution, the increasing production scale and needs of trade of Western countries required new forms of automated production and faster transport (Maddison, 2007). This would probably not have been possible without the development of better techniques that seized the energy potential of fossil fuels, such as coal in the first stages, or petroleum and natural gas in the mid-late nineteenth century. In this regard, recent economic literature has pointed out the importance of growing and non-decreasing trade relationships around the world. More precisely, Jones and Romer (2010) state that "Increased flows of goods, ideas, finance, and people—via globalisation, as well as urbanisation—have increased the extent of the market for all workers and consumers. (...) World trade as a share of GDP has nearly doubled since 1960". Previous EKC studies have also noted that international trade may be a key factor for explaining changes in CO2 emissions (e.g. Roberts and Grimes, 1997; Friedl and Getzner, 2003; Halicioglu, 2009; Ertugrul et al., 2016). Therefore, it seems reasonable to study to what extent the increasing globalisation has impacted in economic growth, energy consumption, CO2 emissions and, eventually, in world's environmental sustainability.

The aim of this paper is to analyse the relationship between economic growth and carbon dioxide emissions in 173 countries during the 1990–2014 period yet paying special attention to the influence of globalisation on it. To do so, we test the existence of spatial spillovers in the traditional CO2 EKC framework which, as far as we are concerned, have been largely overlooked and not sufficiently studied. Moreover, their inclusion may be crucial to overcome the misspecification issue, which has been previously highlighted as one of the major causes of disparity in final estimations (Stern, 2004, 2010). In addition to this, the omission of spatially lagged variables when they are relevant for the data generating process will lead to biased estimates (LeSage and Pace, 2009), which may explain why many studies on CO2 emissions have found extremely high and out of sample turning points (e.g., Holtz- Eakin and Selden, 1995; Galeotti and Lanza, 1999).

According to the foregoing, the question is how spatial models may contribute to estimate the impact of globalisation on the EKC. In this sense, trade profits are heavily influenced by distance costs (e.g., Hummels, 1999; Nitsch, 2000; Head and Mayer, 2002; Berthelon and Freund, 2008), thus one might suggest that international relationships are prone to be clustered around certain areas as long as trade and communication costs are sensitive to distance. In this regard, Beckerman (1956) states that developing countries are highly dependent on means of transport. Thus, as they close the distance between themselves and more-developed and important economies, their potential growth increases. Moreover, less-developed countries tend to generate a higher trade concentration than developed ones.

Given that distance is important for trade, the inclusion of spatial relationships allows us to test the pollution haven hypothesis (PHH) using new methodologies, as well as the existence of technological spillovers increasing energy efficiency. The PHH proposes that richer countries might present decreasing growth rates of pollution due to their export of environmentally harmful productive processes to poorer economies, leading to a situation where global net emissions do not decrease (Cole, 2004). Previous studies have tested the PHH for CO2 emissions relying only on the statistical significance of explanatory variables reflecting trade (trade openness, imports from developing countries, exports to developing countries), which did not account for pollution transfers among countries in the same state of development (Cole, 2004; Kearsley and Riddel, 2010). In this sense, we propose to overcome this shortcoming by considering spatial econometric models.

In contrast to previous spatial studies, which have mainly focused on the policy mimicry of environmental standards using spatial lags on the dependent variable, we study how neighbouring per capita income and other explanatory variables, such as energy intensity, can impact national per capita CO2 emissions. To this end, we estimate two types of EKC: a standard type, augmented by the share of renewable energy consumption over total energy consumption, the value added of the services sector over GDP and the energy intensity; and a “spatial EKC” (SEKC), which extends the previous one by using both spatially lagged per capita income and energy intensity.

The remainder of the paper is organised as follows. Section 3.2 contains a brief literature review for the EKC and its spatial approach. Section 3.3 describes both augmented and spatial EKC that will be estimated. Section 3.4 describes the data used in the empirical part of the paper. Section 3.5 presents the estimated models and discusses their results. Section 3.6 shows several forecasts for the EKC and SEKC. Section 3.7 presents conclusions and policy implications.

3.2 Literature Review

The origins of the “Kuznets-like” analysis for environmental quality can be traced back to the study of NAFTA’s effects on certain pollutant concentrations (Grossman and Krueger, 1991) and the World Bank report about the effects of economic development on the environment (IBRD, 1992). The pioneering works of Grossman and Krueger (1991, 1994) considered the idea that expanding economies might not always lead to greater environmental harm. The central thrust is that increasing trade may create new opportunities for environmentally friendly sectors (composition effect), as well as boost greener technical progress and productive efficiency (technique effect). Both effects should compensate, or even overcome, the impact of economic growth on pollution (scale effect). Nevertheless, it must be also highlighted that trade based on differences in production costs can account for migration of pollution from developed to developing countries, provided that in these latter there is a less stringent environmental regulation. Therefore, some sort of pollution displacement might occur between these types of countries (the pollution haven hypothesis), leading to a situation where global net pollution does not decrease. Despite this event might be crucial for understanding the evolution of global CO2 emissions, we have found few studies that have directly considered it. Additionally, none of them have taken into account how geographical space, and therefore spatial processes, may play a major role in pollution transfers. In this sense, we follow the hypothesis expressed by Wang et al. (2013) that not only "all the subjects that are related to environmental issues are inherently spatial" but there also exist spatial interactions between countries due to trade or technological diffusion.

The first category of empirical studies of EKC for CO2 was principally focused on the per capita income impact on per capita emissions, without taking into account other explanatory variables rather than national traits or time trends. Therefore, the 1990–2000's framework revolved around panel data estimations considering fixed effects for large sets of countries. Almost all these studies agree on the non-existence of an inverted U-shaped curve due to the excessive size of the estimated turning points (Shafik, 1994; Holtz-Eakin and Selden, 1995; Roberts and Grimes, 1997; Galeotti and Lanza, 1999), the finding of a monotonically increasing relationship (De Bruyn et al., 1998), the consideration of nonlinear dynamics as the major driver of polluting behaviours (Moomaw and Unruh, 1997) or the existence of heterogeneity in the estimated coefficients among countries (Dijkgraaf, Vollebergh, 1998). Some of them argued that the most developed countries were coming closer to a less steep trend of per capita emissions beyond a certain level of wealth rather than an inverted U-shape curve.

In essence, these preliminary works presented an important absence of explanatory capacity due to their focus on per capita income levels. As Moomaw and Unruh (1997) asserted, these initial results seemed to be more a by-product of the specification than a reflection of reality. These authors stressed the importance of market shocks in the longterm reduction of CO2 emissions, pointing out that the EKC in its initial reduced form is not a fair representation of structural changes. In this sense, Schmalensee et al. (1998) argued that there might be a misspecification problem. More precisely, the inclusion of explanatory variables reflecting shifts in the industrial composition or changes in environmental policy would better explain differences in pollution among industrialised and developing countries. In addition, De Bruyn et al. (1998) also pointed out the weakness of reduced forms for policy implications.

In order to overcome this misspecification problem, the second category of carbon-dioxide-EKC studies started to consider new explanatory variables on the basis of a deeper theoretical background and the reassessment of previously posed hypotheses. Nevertheless, the misleading results derived from the juxtaposition of countries in different development stages and the existence of heterogeneity among the estimated coefficients for every country (Dijkgraaf, Vollebergh, 1998), led to the study of time series instead of cross section or panel data. In this regard, the use of Error Correction models and autoregressive models became more popular in the carbon-dioxide-EKC framework for the late 1990's to the mid-2000's (Lim, 1997; Panayotou et al., 2000; Egli, 2002; Pauli, 2003; Friedl and Getzner, 2003; Cole, 2004).

A large part of these second-group studies tested the existence of the PHH by including some sort of trade-reflection variable (Panayotou et al., 2000; Egli, 2002; Friedl and Getzner, 2003; Cole, 2004). There was no consensus about the final results. However, most of them pointed towards the non-existence of this phenomenon, or at least, that it was not required to achieve a bell-shaped relationship. We stand out the comprehensive analysis carried out by Cole (2004) about the PHH. This study employed trade-paired data for the US, the UK and Japan in relation to their main undeveloped foreign markets and its results did not support the PHH for CO2 emissions. Nevertheless, the lack of a more representative sample for the industrialised world should be taken into account when interpreting its final results.

The other major focus of this second group was to test how structural changes may help to the EKC emergence (Panayotou et al., 2000; Friedl and Getzner, 2003; Cole, 2004). Again, estimations led to a stalemate in this matter. However, this may be a result derived from the quality of the explanatory variables used to capture this effect. Whilst in Panayotou et al. (2000) capital intensity is employed to test the structural change hypothesis, obtaining strong evidences of its existence, Friedl and Getzner (2003) include the share of the services sector over total GDP and find that it is very close to the statistical non-significance. Finally, Azomahou et al. (2006) rejected the structural change and EKC hypotheses using kernel regression methods.

A third category of studies was divided among those who used Autoregressive Distributed Lag (ARDL) models (e.g. Coondoo and Dinda, 2008; Halicioglu, 2009 or Narayan and Narayan, 2010), and those who continued testing complementary hypotheses to the EKC using traditional panel data or time series estimations (e.g. Kearsley and Riddel, 2010; Franklin and Ruth, 2012 or Zhang and Zhao, 2014).

On the whole, we may assert that the ARDL-cointegration studies do not achieve a unanimous result for the EKC hypothesis. For instance, Coondoo and Dinda (2008) analysed the impact of inter-country wealth inequalities on the income-pollution relationship, finding support only for the EKC in Europe. Halicioglu (2009) did not find strong evidence for the EKC in Turkey as well as an innocuous impact of trade openness on the evolution of carbon dioxide emissions. In this sense, Jalil and Mahmud (2009) also found that trade openness did not impact on Chinese emissions, but the EKC hypothesis was not rejected. For the European Union, Acaravci and Ozturk (2010) solely found a bell-shaped curve in Italy and Denmark.

Another set of ARDL-cointegration studies considered new explanatory variables, such as energy intensity and energy composition (Iwata et al., 2011; Baek and Kim, 2013; Bölük and Mert, 2014, 2015; Baek, 2015; Al-Mulali et al., 2016). In brief, their results were mixed, even though they found a positive impact of both nuclear and renewable energies on environmental sustainability. Additionally, Ertugrul et al. (2016) detected evidence of the existence of the PHH in Turkey, India, China and Indonesia. Besides, Lægreid and Povitkina (2018) estimated the impact of political institutions on carbon dioxide emissions for 154 countries, finding partial support to the EKC.

Among the standard panel data or time series estimations, some of them stand out due to their ground-breaking contributions to the CO2 EKC framework. To mention some examples, Kearsley and Riddel (2010) performed an extensive reanalysis of the PHH for several pollutants, taking also into consideration the structural change hypothesis. Their main results pointed towards a positive and monotonous relationship between income and carbon dioxide emissions due to the large sized turning points. As in Cole (2004), they did not find strong support for the existence of the PHH but rather the opposite outcome. Other researchers studied the impact of income inequality and structural changes on carbon dioxide emissions using long time series for the US (Franklin and Ruth, 2012) and panel data for Chinese provinces (Zhang and Zhao, 2014), finding opposite results in relation to their inclusion.

In summary, these previous studies have largely ignored the presence of spatial relationships, which indeed may be linked to the original idea of Grossman and Krueger (1991, 1994) of trade relationships changing pollution patterns among countries. As Wang et al. (2013) and Kang et al. (2016) asserted, spatial interactions may be a reflection of global integration processes, manifested in commerce, technological diffusion or capital inflows. In this sense, Rupasingha et al. (2004) were the first to consider spatial spillovers in the EKC framework. Subsequently, Maddison (2006) also analysed emissions of several pollutants employing three spatial models: the SLM (Spatial Lag Model), the SLX[1] (Spatial Lag of X) and the SEM (Spatial Error Model). Their results pointed towards the existence of spatial autocorrelation, in the form of policy mimicry and neighbouring income influences on national emissions.

To the best of our knowledge, the explicitly inclusion of spatial interactions in the analysis of the relationship between CO2 emissions and income has been mainly focused on China (Auffhammer and Carson, 2008; Chuai et al., 2012; Kang et al., 2016; Wang and Ye, 2016). Whilst none of these studies supported the EKC hypothesis, they detected statistically significant spatial autocorrelation among Chinese provinces.

A common element that must be pointed out from previous spatial EKC studies is the dominance of SLM and SEM estimations, leading to results that can barely be interpreted or used for policy making. Following the actual strand in the spatial econometric literature we will focus on the SLX and the Spatial Durbin Error (SDEM) models, which are suitable for testing the PHH and the existence of technology spillovers. The explicit consideration of spatial interactions through spatially lagged explanatory variables allows us to analyse influences among neighbouring countries. This will enable us to test whether some sort of indirect EKC exists, which may lead to a lower national turning point.

[1] The author did not explicitly use this denomination in their paper. Indeed, spatial regression model is the selected name by the author.

3.3 The EKC and the Spatial Econometrics

3.3.1 The Standard EKC

As mentioned above, many studies have employed several approaches to test the EKC hypothesis. However, we decided to estimate a log-linear EKC where we try to include the main drivers for CO2 emissions:

$$\ln e_{it} = \alpha_i + \gamma_t + \beta_1 \ln y_{it} + \beta_2 (\ln y_{it})^2 + \beta_3 RE_{it} + \beta_4 SVC_{it} + \beta_5 \ln EI_{it} + \varepsilon_{it} \quad (3.1)$$

where e_{it} is the per capita CO2 emissions; y_{it} is the per capita income; RE_{it} is the share of renewable energy consumption in total final energy consumption; SVC_{it} is the value added of the services sector over GDP; and EI_{it} represents the energy intensity, which can be understood as a proxy for technological progress associated to energy consumption. ln stands for natural logarithms, α_i represents individual fixed effects, γ_t is the time fixed effects and ε_{it} represents the error term. This equation tries to reflect the four major drivers of pollution dynamics (Grossman and Krueger, 1991, 1994; Stern, 2004; Dinda, 2004; Kaika and Zervas, 2013a): the scale effect and the income elasticity of environmental quality demand ($\ln y_{it}$ and $(\ln y_{it})^2$), the composition effect (RE_{it} and SVC_{it}) and the technological effect ($\ln EI_{it}$). We do not include a cubic term for income because an N-shaped curve would prove to be more a result of data fitting to the polynomial function rather than a true image of reality (Moomaw and Unruh, 1997).[2]

The expected signs for the major drivers' coefficients are:

(i) $\beta_1 > 0$ and $\beta_2 < 0$

It is expected that an increase in per capita production will increase per capita emissions. Conversely, if we consider that the economic agent must choose between two relevant products (consumption goods vs. environmental quality), as income grows and the population starts to satisfy its basic needs, the marginal utility of consumption starts to fall, whereas the marginal utility of environmental quality rises. After a turning point is reached, per capita emissions will present a negative growth rate as per capita income increases.

(ii) $\beta_3 < 0$

If economies change their input mix from non-renewable to renewable energies, it is expected that per capita emissions will be reduced when a new good or service is produced. Richmond and Kaufmann (2006) find the inclusion of fuel consumption shares determinant for supporting the EKC and the size of the estimated turning points. In addition, measuring the impacts of the energy mix on CO2 emissions will prove very useful for policymaking in the long-run.

(iii) $\beta_4 < 0$

[2] Moreover, the estimated turning points will present unreachable magnitudes, apart from the risk of obtaining imaginary roots.

The dominant sector of an economy will also determine the amount of CO2 generated by each unit of product. Historically, the first stages of development are based on the agricultural sector, where production generates only a small amount of pollution. As economies start to become industrialised, most of the production comes from the secondary sector, where manufacturing is highly polluting. Finally, the third stage of development will be based on services, which are supposedly less polluting.

(iv) $\beta_5 > 0$

As economies boost their technological progress, their productive processes become more efficient and cleaner. This means that industries will require smaller amounts of polluting energy to make a new unit of output. We use the amount of energy used per unit of GDP as a proxy for energy efficiency.

3.3.2 The Spatial EKC

As mentioned in Section 3.2, the standard EKC hypothesis for CO2 emissions has been studied using different methodologies and samples, leading to inconclusive results. According to Dinda (2004) and Stern (2004), the omission of relevant variables may explain this disparity of results. Thus, considering spatial relationships may help solve the issue of omitted relevant variables.

Perrings and Hannon (2001) state that the relationship between economic growth and pollution depends on the timing and location of the environmental effects. Therefore, the geographic distance between CO2 emitters and regions where climate change has greater impacts, might determine the formation of polluting clusters. Observing the average per capita CO2 emissions in 173 countries, for the 1990–2014 period, it is possible to observe a World that, in terms of pollution is roughly divided between the Northern and the Southern Hemispheres (Fig. 3.1). Most of the Northern countries and Oceania present emissions of more than 6 t per capita (e.g., the US, Canada, Europe, Russia, the Arabian Peninsula). The more environmentally friendly Southern Hemisphere, including Southern Africa, South America and Southeastern Asia, presents emissions lower than 2 t per capita. More homogeneous clusters can be found on a smaller scale, such as for Canada-US, the former Soviet Union, the Hindustan Peninsula, and Sub-Saharan Africa.

Supposing that spatial relationships exist for CO2 emissions, the correct spatial specification must be selected. According to Halleck Vega and Elhorst (2015), seven spatial models have been considered in the literature that differ according to whether spatial spillovers are global or local. LeSage (2014) states that the existence of endogeneity in the spatial relationships will determine the type of spatial spillover. The local effects are purely exogenous, which means that changes in neighbouring explanatory variables will directly impact the national dependent variable. By contrast, when endogenous spatial effects exist, a feedback effect will arise. This feedback effect means that changes in one nation will impact neighbouring countries, and these will subsequently

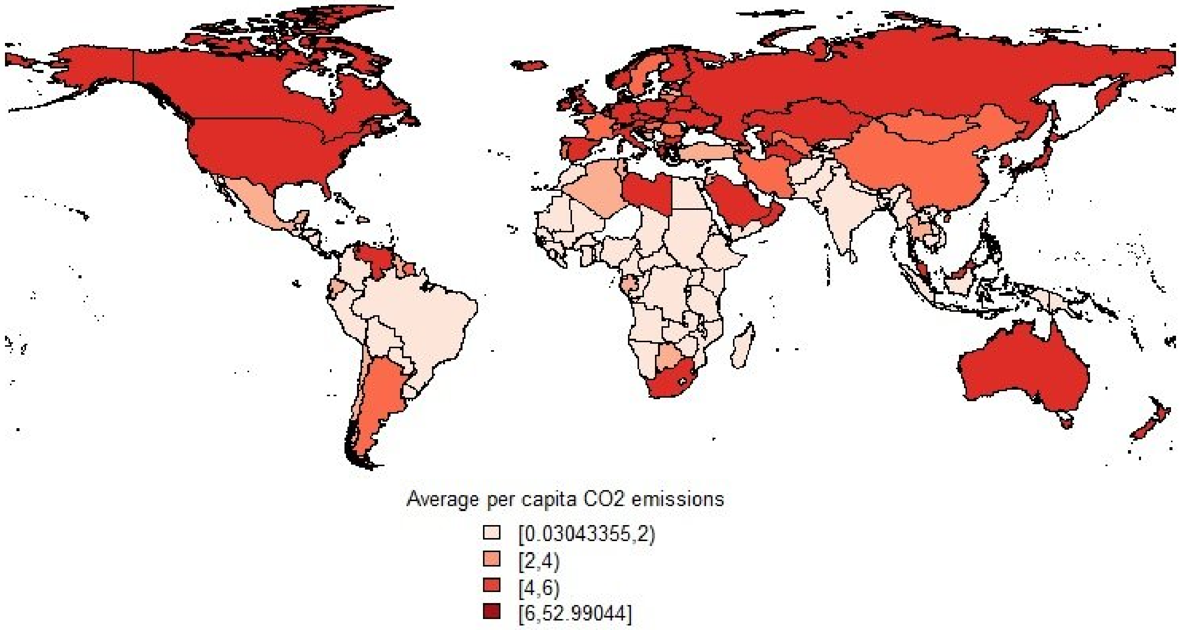

Figure 3.1: CO2 emissions (tonnes per capita) in the World. (1990–2014). Source: Data from World Development Indicators, The World Bank. Prepared by the authors.

transfer part of the impact to their neighbours, and so on. Finally, these changes will return to the national dependent variable. Thus, the relevant issue is to detect what type of spatial spillover effect is arising from the relationship between the environment and economic growth.

Maddison (2006, 2007) argues that the PHH could be a type of local spillover. Moreover, if technology is related to trade -and therefore to distance- clean technology diffusion may also be measured as a local spillover. Reppelin-Hill (1999) found that the adoption of cleaner technology in the steel industry may be distorted by trade openness. For global spillovers, Maddison (2006) suggests that the competition among governments in terms of capital or trade attraction will lead to changes in the environmental policy. Moreover, he states that "politicians constantly assess policy against those of their neighbours in order to legitimate their actions and to reduce the costs of decisionmaking, resulting in similar environmental standards". This policy mimicking can occur swiftly and at a global level due to the lower barriers to communication and travel (Shipan and Volden, 2012). Nevertheless, we will only focus on the local spillovers due to two major reasons: the significance of global spillovers may only be determined by the omission of other spatially lagged explanatory variables (Corrado and Fingleton, 2012); and imposing the condition that each country is affected by all other countries' emissions seems implausible for a global sample.

There are three spatial models which only account for exogenous spatial spillovers: the SDEM (Spatial Durbin Error Model), which includes spatial lags for the explanatory variables and the error term, and therefore nests the following models; the SLX (Spatial Lag of X), which only includes spatially lagged explanatory variables and whose estimated parameters should be unbiased despite the SDEM being the true model, since spatial dependence in the disturbances represents only an efficiency problem (LeSage, 2014); and the SEM (Spatial Error Model), which only takes the spatially lagged error term into consideration. We follow the stepwise backward elimination procedure as in Jiang et al. (2014) with the aim of choosing the explanatory variables, starting with the SDEM and testing whether it could be simplified to one of its nested models (SLX or SEM). This will allow us to compare which exogenous spatial model better fits the data in order to avoid the misspecification problems that commonly appear in EKC studies. Our final EKC regression will take the following form:[3]

$$\begin{aligned} \ln e_{it} &= \alpha_i + \gamma_t + \beta_1 \ln y_{it} + \beta_2 (\ln y_{it})^2 + \beta_3 RE_{it} + \beta_4 SVC_{it} + \beta_5 \ln EI_{it} \\ &+\theta_1 \sum_{j=1}^{N} w_{ij} \ln y_{jt} + \theta_2 \sum_{j=1}^{N} w_{ij} (\ln y_{jt})^2 + \theta_3 \sum_{j=1}^{N} w_{ij} \ln EI_{jt} + \lambda \sum_{j=1}^{N} w_{ij} u_{it} + \varepsilon_{it} \end{aligned} \tag{3.2}$$

where $\sum_{j=1}^{N} w_{ij} \ln y_{jt}$ and $\sum_{j=1}^{N} w_{ij} (\ln y_{jt})^2$ measure the exogenous interaction effects among per capita income of all the j neighbours to country i; $\sum_{j=1}^{N} w_{ij} \ln EI_{jt}$ the exogenous interaction effects among the energy intensity of all j neighbours to country i; θ_p the spillover effects for the p spatially lagged variables; $\sum_{j=1}^{N} w_{ij} u_{it}$ the interaction effects among the disturbance terms of the different observations; and λ the strength of dependence between error terms. The expected signs for the new estimated coefficients are:

(i) $\theta_1 > 0$ and $\theta_2 < 0$ if the PHH is supported in the short term.

It is expected that an increase in neighbouring per capita production will increase countries' trade and investment capacities. Then, national per capita emissions will rise via greater inflows of foreign polluting capital. A turning point will be reached when the neighbouring marginal benefit related to polluting capital exports is exceeded by the marginal cost of climate change. From this point onwards, inflows of foreign investment will shift from polluting to environmentally friendly capital.

(ii) $\theta_1 > 0$ and $\theta_2 \geq 0$ if the PHH is supported in the long term.

This is the same as above, except that national emissions will follow a positive trend adopting a slope that may become steeper as neighbouring per capita income grows. This will reflect a constant transfer of polluting capital between neighbouring countries at a constant rate ($\theta_2 = 0$) or an increasing rate ($\theta_2 > 0$).

(iii) $\theta_1 \leq 0$ and $\theta_2 \leq 0$ if the PHH is rejected.

[3]We have not spatially lagged RE_{it} in order to avoid double accounting (it measures final consumption, then it already considers imported energy). Regarding to SVC_{it}, we do not expect that neighbouring output composition will be relevant for national carbon emissions. Moreover, we tested the significance of both coefficients for the world as a whole, leading to statistical rejection at a 5% level of significance.

(iv) $\theta_3 > 0$

The existence and relevance of technology spillovers have been proved by previous researchers (Branstetter, 2001; Coe et al., 2009). Moreover, distances reduce their impact (Bottazzi and Peri, 2003; Funke and Niebuhr, 2005). Therefore, we expect that as neighbouring energy efficiency is increased, national industries will mimic neighbouring productive processes to sustain international competitiveness. Consequently, national emissions will fall.

3.4 Database

We employ a panel data set composed of 173 countries[4] for the 1990–2014 period to analyse the existence of a spatial EKC for CO2 emissions. All data belong to the World Bank Development Indicators Database. All variables (Table 3.1), except for the share of renewable energy in total final energy consumption and the value added of services over GDP, are transformed into logarithms for two reasons: firstly, because the final results will be interpreted in percentage terms for all variables (for the log-log estimations, there will be elasticities, while for the log-linear estimations, there will be semi-elasticities). Secondly, we want to avoid heteroskedasticity in the data.

Table 3.1: Dependent and explanatory variables.

	Description
e	Per capita carbon dioxide emissions (tonnes of CO_2)
y	Per capita GDP, in purchasing parity power (constant 2011 international US$)
POP	Total population. All residents regardless of legal status or citizenship.
RE	Share of renewable energy in total final energy consumption. (%)
SVC	Value added of services over GDP (ISIC divisions 50-99) (%)
EI	Energy intensity level of primary energy (MJ/$2011 PPP GDP)

Source: Data from World Development Indicators, The World Bank. Prepared by the authors

In line with previous literature, we define neighbourhood relationships using the maximum distance observed between all pairs of closest neighbouring countries. The objective is to ensure one neighbour for each country (Maddison, 2006; Hao et al., 2016). The spatial weights matrix is created using the inverse distance between country centroids.

3.5 Results and Discussion

In this section, we firstly perform the joint significance LR tests for all areas in order to select which fixed effect specification better fits the data. Subsequently, we estimate both standard and spatially lagged EKCs as well as study if the SDEM model can be reduced to the SLX. Finally, we compare and discuss the obtained results.

[4] See Appendix A for sample statistics. Appendix B presents a list of countries.

Table 3.2 shows the results of the LR tests for joint significance. For the 173 countries representing most of the World, Europe, South America and Africa, the null hypothesis of non-significant individual effects is rejected at a 5% significance level. The null hypothesis for time effects is not rejected, so their estimations will only include individual effects. In North America, Asia and Oceania, both hypotheses are rejected at the same significance level, so their estimations will include both individual and time fixed effects.

Table 3.2: LR-tests for joint significance.

Area/degrees of freedom (indiv. FE)	**LR-test joint significance individual fixed effects**	**LR-test joint significance time fixed effects**
World/173	6810.964*** (p = 0.000)	36.790* (p = 0.060)
Europe/36	1893.534*** (p = 0.000)	24.203 (p = 0.507)
North America/22	688.721*** (p = 0.000)	76.070*** (p = 0.000)
South America/12	441.913*** (p = 0.000)	15.885 (p = 0.918)
Asia/44	1387.917*** (p = 0.000)	45.793*** (p = 0.006)
Oceania/10	333.161*** (p = 0.000)	144.115*** (p = 0.000)
Africa/49	1961.127*** (p = 0.000)	31.789 (p = 0.164)

Source: Prepared by the authors.
Notes: The degrees of freedom for the LR time effect tests are equal to 25 in all cases. ***, ** and * are significance levels of 1%, 5% and 10%, respectively.

Table 3.3 presents the OLS estimations for the non-spatial EKC. At a 1% level of significance, all areas except for Oceania support the EKC hypothesis. In all cases, the estimated coefficient for the per capita income ($\ln y$) is positive and for the quadratic term ($(\ln y)^2$) is negative. The other explanatory variables, except for the relative weight of the services sector (SVC), seem to present robustness in their results for the regions analysed.

The relative consumption of renewable energy (RE) and energy intensity ($\ln EI$) are significant at a 1% level for all estimates. Moreover, their estimated signs are constant among the areas, negative for the first one and positive for the second one. These results coincide with our expectations. As economies shift their energy consumption from nonrenewable and polluting sources to renewable sources, per capita CO2 emissions will decrease. The energy intensity reflects the inefficiency of productive processes in terms of energy use, so reductions in the energy employed per unit of good and service produced will reduce the emissions. On the other hand, the output composition (SVC), measured as the degree of tertiarisation, is not significant for explaining changes in per capita CO2 emissions in the areas of North America, South America and Asia. To conclude the standard EKC analysis, the estimated turning points in all areas, except for Asia, are extremely high, similar to what occurred in previous studies. No country in the sample reaches or even comes close to the estimated point for the World as a whole. Hence, we will focus on the spatial EKC results, expecting that its estimates will shed more light on the underlying dynamics of income and pollution.

Table 3.3: Non-spatial estimations for logarithmic per capita CO2 emissions.

Determinants	**World (Individual FE)**	**Europe (Individual FE)**	**North America (Two-Way FE)**	**South America (Individual FE)**	**Asia (Two-Way FE)**	**Oceania (Two-Way FE)**	**Africa (Individual FE)**
N	173	36	22	12	44	10	49
lny	2.607*** (30.159)	2.152*** (17.297)	1.918*** (7.847)	2.332*** (3.931)	3.081*** (18.842)	0.894*** (3.960)	1.895*** (8.481)
$(\text{lny})^2$	-0.095*** (-19.841)	-0.070*** (-10.500)	-0.057*** (-4.457)	-0.074** (-2.315)	-0.123*** (-13.393)	-0.019 (-1.506)	-0.057*** (-4.360)
RE	-0.014*** (-33.231)	-0.014*** (-21.696)	-0.010*** (-19.937)	-0.009*** (-6.361)	-0.007*** (-7.645)	-0.016*** (-30.555)	-0.016*** (-15.825)
SVC	-0.002*** (-4.167)	-0.004*** (-6.534)	0.000 (-0.185)	0.000 (-0.022)	0.001 (1.355)	-0.002** (-2.138)	-0.005*** (-4.614)
lnEI	0.710*** (45.667)	0.773*** (32.324)	0.965*** (49.976)	1.029*** (20.179)	0.821*** (28.768)	0.843*** (34.815)	0.459*** (11.723)
R^2 (Adjusted)	0.698	0.772	0.882	0.803	0.656	0.898	0.659
σ^2	0.024	0.006	0.002	0.006	0.027	0.002	0.047
lnL	1877.5	1006	834.229	341.2782	412.724	420.122	137.072
Durbin-Watson	1.943	1.868	2.223	2.015	2.118	2.155	1.839
Turning Point (US$)	926,226.9	5,137,116.408	18,038,762.24	7,463,721.176	270,026.7	10,521,646,923	15,033,135.4

Source: Prepared by the authors.

Notes: lny, RE, SVC and lnEI are the logarithms of per capita GDP, renewable energy consumption over the total energy consumption, weight of the tertiary sector over the GDP and the logarithm of energy intensity. The t statistics for the estimated coefficients are in parenthesis. ***, ** and * are significance levels of 1%, 5% and 10%, respectively.

As noted in Section 3.3, we decided to use both SDEM and SLX specifications because they are the only spatial models which allow us to model local spatial spillovers (LeSage, 2014; Halleck Vega and Elhorst, 2015). In addition, the spatial EKC will allow us to test the existence of the PHH and technological spillovers. If the PHH is supported, then three turning points (y^*) will be estimated: the direct turning point, which is estimated only taking into account the national income elasticity ($y^*_D = -\frac{\beta_1}{2\beta_2}$), as it was carried out using the non-spatial EKC; the indirect turning point, which is estimated by only taking into account the changes in neighbouring per capita income ($y^*_I = -\frac{\theta_1}{2\theta_2}$); and the total turning point, which is obtained by considering both national and neighbouring changes ($y^*_T = -\frac{\beta_1+\theta_1}{2(\beta_2+\theta_2)}$).

Table 3.4 presents the spatial EKC estimations for both SDEM and SLX models. First of all, we study the LR tests in order to determine whether the SDEM can be reduced to a nested form. The LR SLX test poses a null hypothesis where the spatial lag of the error term (λ) is equal to zero, which is clearly not rejected in all areas; whilst the LR SEM test poses a null hypothesis where the spatial lag of all the explanatory variables (θ_p) is equal to zero, which is clearly rejected for the world as whole and almost all areas. Therefore, we will focus our discussion on the SLX results. Starting with the national income elasticity to per capita CO2 emissions ($\ln y$ and $(\ln y)^2$), in all cases except for Oceania, the EKC hypothesis is supported again at a 1% significance level. Comparing both standard and spatial regressions, the differences in size of the estimated coefficients are small. Moreover, their signs and statistical significance remain unaltered. Only North America and South America present increases in the non-squared term (from 1.918% to 2.058%, and 2.332–3.119%, respectively) and decreases in the squared terms (-0.057% to -0.065%, and -0.074% to -0.121%, respectively), whilst the remaining areas show the opposite change. Obviously, these changes have impacted the estimated direct turning points. The North and South American cases present reductions in their turning points (their sizes are reduced by 56% and 94%, respectively), whilst the other areas show increases ranging from 5% (Asia) to 1,533,209% (Oceania) compared to the non-spatial estimation.

Focusing on the magnitude of the coefficients, Oceania presents the lowest national income elasticity (0.815%), but the non-significance of the squared term seems to indicate that emissions will increase monotonically as income increases. South America presents the most responsive per capita CO2 emissions to changes in national income (3.119%, regardless of the squared term), closely followed by Asia (2.707%). Even though South America's direct turning point (402,125.361 US$) is more feasible than that estimated for Oceania, the richest South American country is still too far away from it (Chile, with 22,226.452 US$ in 2014, represents roughly 5% of the direct turning point). In the Asian case, Macau (130,750.166 US$) and Qatar (120,860.068 US$) presented the closest per capita incomes in the year 2014, representing less than 47% of the Asian direct turning point (283,740.932 US$). Finally, the World as a whole presents the third highest income elasticity (2.448%, regardless of the squared term), although the direct turning point seems to be more unreachable compared to the South American and Asian cases.

Table 3.4: Spatial estimations for logarithmic per capita CO2 emissions.

Determ	World (Individual FE)		Europe (Individual FE)		North America (Two-Way FE)		South America (Individual FE)		Asia (Two-Way FE)		Oceania (Two-Way FE)		Africa (Individual FE)	
	SLX	SDEM	SLX	SDEM	SLX	SDEM	SLX	SDEM	SLX	SDEM	SLX	SDEM	SLX	SDEM
lny	2.448***	2.442***	1.593***	1.566***	2.058***	2.106***	3.119***	3.102***	2.707***	2.698***	0.815***	0.794***	1.797***	1.786***
	(26.086)	(25.697)	(10.036)	(9.777)	(7.461)	(7.245)	(4.976)	(4.904)	(15.617)	(15.257)	(3.492)	(3.259)	(7.953)	(7.761)
(lny)^2	-0.086***	-0.086***	-0.035***	-0.033***	-0.065***	-0.067***	-0.121***	-0.120***	-0.108***	-0.107***	-0.012 (-	-0.011	-0.051***	-0.050***
	(-16.167)	(-15.911)	(-3.812)	(-3.595)	(-4.455)	(-4.388)	(-3.523)	(-3.464)	(-11.247)	(-10.972)	0.927)	(-0.806)	(-3.817)	(-3.693)
RE	-0.013***	-0.013***	-0.012***	-0.012***	-0.010***	-0.011***	-0.007***	-0.007***	-0.007***	-0.007***	-0.016***	-0.016***	-0.017***	-0.017***
	(-30.500)	(-29.952)	(-16.815)	(-16.692)	(-19.751)	(-19.341)	(-4.873)	(-4.938)	(-6.977)	(-6.891)	(-29.095)	(-27.311)	(-15.849)	(-15.511)
SVC	-0.002***	-0.002***	-0.002***	-0.002***	0.000	-0.001	0.000	-0.001	0.000	0.001	-0.001* (-	-0.001*	-0.006***	-0.006***
	(-4.126)	(-4.101)	(-3.230)	(-3.072)	(-0.275)	(-0.163)	(-0.050)	(-0.131)	(0.426)	(0.607)	1.659)	(-1.712)	(-4.910)	(-4.858)
lnEI	0.702***	0.701***	0.785***	0.784***	0.968***	0.969***	1.012***	1.011***	0.826***	0.823***	0.857***	0.856***	0.492***	0.492***
	(44.614)	(43.896)	(33.226)	(32.675)	(46.164)	(44.145)	(19.972)	(19.784)	(29.530)	(28.746)	(35.103)	(33.430)	(12.406)	(12.189)
Wlny	0.960***	0.979***	0.995***	1.033***	-0.541	-0.763*	-0.673	-0.718	1.089***	1.109***	-1.762**	-1.720**	0.121	0.087
	(5.088)	(4.942)	(3.118)	(3.065)	(-1.198)	(-1.716)	(-1.047)	(–1.111)	(4.203)	(4.121)	(-2.227)	(-2.058)	(0.204)	(0.143)
W(lny)^2	-0.049***	-0.051**	-0.045***	-0.047***	0.026	0.037	0.047	0.049	-0.042***	-0.044***	0.121**	0.118**	-0.023	-0.021
	(-4.610)	(-4.523)	(-2.679)	(-2.654)	(1.116)	(1.610)	(1.305)	(1.362)	(-2.916)	(-2.926)	(2.389)	(2.201)	(-0.691)	(-0.618)
WlnEI	0.108***	0.097**	0.351***	0.359***	0.008	0.020	0.188***	0.184***	0.056	0.057	0.060	0.064*	-0.363***	-0.373***
	(2.615)	(2.216)	(5.606)	(5.403)	(0.194)	(0.523)	(3.106)	(3.007)	(1.145)	(1.107)	(1.647)	(1.659)	(-3.413)	(-3.412)
Wu		0.075**		0.085		-0.088		-0.023		0.085**		0.055		0.032
		(2.299)		(1.196)		(-1.373)		(-0.416)		(2.372)		(0.827)		(0.673)
R^2 (Adj.)	0.701	0.701	0.785	0.786	0.882	0.883	0.810	0.815	0.673	0.675	0.901	0.903	0.665	0.667
σ^2	0.024	0.025	0.006	0.006	0.003	0.003	0.006	0.006	0.026	0.028	0.002	0.002	0.046	0.048
lnL	1893.7	1894.244	1031.900	1032.154	835.053	837.676	347.809	347.769	441.244	442.173	424.630	425.012	148.560	148.236
DW	1.932		1.886		2.212		1.969		2.011		2.142		1.852	
LR SLX		1.403 (p = 0.924)		0.4780 (p = 0.993)		5.247 (p = 0.387)		-0.080 (p = 0.999)		1.858 (p = 0.868)		0.762 (p = 0.979)		-0.647 (p = 0.999)
LR SEM		30.002*** (p = 0.001)		52.922*** (p = 0.001)		3.412 (p = 0.637)		12.178** (p = 0.032)		52.705*** (p = 0.001)		8.579 (p = 0.127)		23.108 (p = 0.001)
Turning P. (Direct)	1,427.410		7,860,786.1		7,918.663		402.125		283.740		161,329x10^6		49,849.999	
Turning P. (Indir.)	17.587		64.849		36.125		1.328		398.480		1.448		0.013	
Turning P. (Total)	290.259		10,893.476		279,656.175		14,893.450		312.202		0.078		441.493	

Source: Prepared by the authors.
Notes: Same as in Table 3. W is the spatial weights matrix. We only show the estimated turning points for the SLX, expressed in constant 2011 international US$, thousands.

The national coefficients for renewable energy consumption (RE) and energy intensity ($\ln EI$) are statistically significant, and their signs remain identical to the non-spatial estimation. As in previous research, increases in renewable energy consumption will improve environmental quality (Marrero, 2010; Ben Jebli, Ben Youssef, 2015), and its inclusion may support the existence of the EKC (Sulaiman et al., 2013; López-Menéndez et al., 2014; Bölük and Mert, 2015). Nevertheless, an increase of 1% in the share of renewable energy will reduce per capita CO2 emissions by barely -0.007% in the worst case (South America and Asia) to -0.017% in the best case (Africa). On the other hand, increases in energy intensity worsen environmental quality, which agrees with the results of previous research (Cole and Neumayer, 2004; Poumanyvong and Kaneko, 2010; Du et al., 2012; Liu et al., 2015; Wang et al., 2017). The estimated elasticity is very close to 1% in most areas, which emphasises the importance of energy efficiency in reducing carbon dioxide emissions. Notwithstanding, we cannot conclude that the value added of services over GDP (SVC) is relevant for explaining changes in emissions. As revealed in the non-spatial estimations, the degree of tertiarisation in North America, South America, and Asia is not statistically significant. Furthermore, in those areas where it is indeed significant, the estimated magnitude is quite close to 0%. Previous studies have found differing conclusions with respect to the impact of output structural changes on pollution. Lindmark (2002) find that services are not significant for explaining changes in Swedish CO2 emissions. Moreover, Kaika and Zervas (2013b) have pointed out how the use of value-added data may give a false impression of changes in real GDP composition due to changes in prices.

Table 3.4 also presents the estimations for neighbouring per capita income and energy intensity ($W \ln y$, $W(\ln y)^2$ and $W \ln EI$). The World as a whole, Europe, Asia and Oceania support the existence of an indirect EKC at a 5% level of significance, i.e., the neighbouring per capita income apparently impacts national per capita emissions, probably through polluting capital transfers. However, the PHH is supported in different ways among these four geographical areas. Oceania presents a U-shaped curve for the indirect EKC. This means that as Oceanian countries become richer in the first stages of development, they will reduce neighbouring per capita emissions at a decreasing rate until a turning point equal to 1448.936 US$ is reached. However, the minimum value in the Oceanian sample is 1466.336 US$ (see Appendix A), which corresponds to the Solomon Islands and exceeds the estimated point. Therefore, further economic growth of Oceanian countries will increase neighbouring per capita CO2 emissions at a growing rate. This seems to support the existence of a long-term PHH in Oceania. The remaining three areas that support the indirect EKC show a short-term dynamic on pollution displacement. Then, as their economies grow, the polluting capital could be displaced to neighbouring countries until a turning point is reached. This point can be explained by the marginal benefit of exporting polluting capital being exceeded by the marginal cost of neighbouring pollution (thus, we suppose that at some stage, individuals internalise the effects of neighbouring pollution). From this point onwards, populations from richer countries will start to import goods based on low-carbon processes and will export more environmentally friendly capital and carbon sequestration goods at increasing rates. In these three areas, the neighbouring income elasticity of national per capita CO2 emissions is approximately 1%, regardless of the squared term.

The existence of technological spillovers ($W \ln EI$) is supported in Europe, South America, Africa and the World as a whole. It seems remarkable that only Africa shows a negative estimated coefficient (-0.363%). This means that as African countries improve their productive processes in terms of energy efficiency (lower $\ln EI$), their neighbours become more inefficient. Therefore, one could say that African countries may be following a spiral of diffusion of non-environmentally friendly technologies. Nevertheless, the total impact (that is, the addition of the average direct impact to the average indirect impact, equal to 0.129%) presents a positive influence, so national efforts are more influential than neighbouring changes for energy efficiency, therefore leading to decreases in national emissions. For the other areas, technological diffusion must be boosted in order to accelerate environmental improvements. Specifically, European countries show the largest indirect impact for technology spillovers (0.351%), probably due to the existence of an integration process and due to the relatively small size of the European states compared with other continents.

In summary, there seems to exist strong support for the direct EKC for both standard and spatial specifications in all areas except Oceania. In addition, there seems to only be a robust indirect EKC for the World as a whole, Europe and Asia, probably due to the way in which the spatial matrices have been specified. Nevertheless, the inclusion of spatially lagged variables does not seem to disrupt the standard estimates, but the estimated total turning points certainly suffer important changes when neighbouring influence is considered. Specifically, the estimate for the World presents a significant reduction in its total turning point compared to the standard estimate (a decrease of more than 68%, from 926,226.9 US$ to 290,259.573 US$). However, the total turning point is still out of the sample (the closest countries to it were Macau, with 130,750.166 US$, and Qatar, with 120,860.068 US$, in 2014).

3.6 Emission Forecasts

As previous researchers have noted, if estimated turning points are far from the data, the income elasticity of per capita carbon dioxide emissions may tend to zero instead of becoming negative as income grows (Holtz-Eakin and Selden, 1995; Kearsley and Riddel, 2010). Therefore, we perform several forecasts of annual CO2 emissions from 2015 to 2100 in order to assess whether considering spillover impacts agrees with the aforementioned conclusion.

Two per capita GDP growth rates are estimated: the first follows Holtz-Eakin and Selden's (1995) method,[5] whilst the second considers the existence of a spatial process.[6] We also create a faster GDP growth rate by adding 0.005 to the estimates and exogenous

[5] $\ln y_{it+1} - \ln y_{it} = \alpha_i + 0.083965 \ln y_{it} - 0.004258 (\ln y_{it})^2$

[6] $\ln y_{it+1} - \ln y_{it} = \alpha_i + 0.091364 \ln y_{it} - 0.005124 (\ln y_{it})^2 + 0.014467 \sum_{j=1}^{N} w_{ij} \ln y_{jt}$

Table 3.5: Global emissions forecasts. Annual CO2 emissions (gigatons of carbon dioxide).

Year	**2015**	**2030**	**2045**	**2060**	**2075**	**2100**
Standard EKC						
Base g_y	35.210	49.889	66.362	81.565	93.701	107.909
Base g_y (W)	35.883	51.825	70.231	88.325	104.243	125.199
Base g_y (W)/gRE= 1%, gEI= -1%	35.381	41.390	45.535	46.724	45.590	46.356
Base g_y (W)/gRE= 2.5%, gEI= -2.5%	33.555	19.322	12.530	12.312	13.296	14.910
Base g_y (W)/gRE= 5%, gEI= -5%	32.249	9.958	7.399	5.533	3.899	1.986
Faster g_y	35.968	53.558	73.839	92.949	108.533	127.124
Faster g_y (W)	36.011	54.603	76.793	99.121	118.958	144.750
Faster g_y (W)/gRE= 1%, gEI= -1%	35.508	43.608	49.797	52.478	52.164	54.055
Faster g_y (W)/gRE= 2.5%, gEI= -2.5%	33.675	20.359	13.735	13.895	15.294	17.425
Faster g_y (W)/gRE= 5%, gEI= -5%	32.364	10.502	8.110	6.235	4.475	2.315
Spatial EKC						
Base g_y	36.121	52.235	70.616	87.350	99.681	103.746
Base g_y (W)	36.172	52.660	72.544	90.275	103.679	113.909
Base g_y (W)/gRE= 1%, gEI= -1%	35.689	42.486	47.933	48.862	46.248	41.627
Base g_y (W)/gRE= 2.5%, gEI= -2.5%	33.755	19.182	12.500	11.800	12.107	11.901
Base g_y (W)/gRE= 5%, gEI= -5%	32.448	9.772	6.845	4.629	2.902	1.148
Faster g_y	36.258	55.163	77.328	97.756	112.726	116.250
Faster g_y (W)	36.309	56.386	80.453	103.319	120.798	136.532
Faster g_y (W)/gRE= 1%, gEI= -1%	35.825	45.497	53.215	56.337	55.136	53.987
Faster g_y (W)/gRE= 2.5%, gEI= -2.5%	33.883	20.527	13.907	13.761	14.539	15.179
Faster g_y (W)/gRE= 5%, gEI= -5%	32.571	10.495	7.646	5.417	3.512	1.492

Source: Prepared by the authors.

Notes: gy is the estimated per capita GDP growth rate. gy (W) includes the spatially lagged per capita GDP. gRE and gEI are the exogenous growth rates for the share of renewable energy in total final energy consumption and energy intensity respectively. The faster rates are obtained by adding 0.005 to the base growth rates.

Table 3.6: Global concentrations forecasts. Annual CO2 concentrations (ppm).

Year	**2015**	**2030**	**2045**	**2060**	**2075**	**2100**
Standard EKC						
Base g_y	402.076	439.939	491.809	557.899	635.997	785.848
Base g_y (W)	402.116	441.128	495.562	566.359	652.173	822.795
Base g_y (W)/gRE= 1%, gEI= -1%	402.087	436.304	475.061	516.130	557.028	624.183
Base g_y (W)/gRE= 2.5%, gEI= -2.5%	401.979	424.187	437.620	448.260	459.611	480.471
Base g_y (W)/gRE= 5%, gEI= -5%	401.902	417.820	425.157	430.815	434.913	439.072
Faster g_y	402.121	441.940	498.812	573.382	663.219	838.516
Faster g_y (W)	402.124	442.402	501.014	579.617	676.872	873.194
Faster g_y (W)/gRE= 1%, gEI= -1%	402.094	437.392	479.101	524.700	571.116	648.836
Faster g_y (W)/gRE= 2.5%, gEI= -2.5%	401.986	424.832	439.275	451.135	464.088	488.320
Faster g_y (W)/gRE= 5%, gEI= -5%	401.909	418.245	426.147	432.443	437.108	441.921
Spatial EKC						
Base g_y	402.130	441.425	496.259	566.902	650.336	803.666
Base g_y (W)	402.133	441.479	497.359	570.006	656.587	819.028
Base g_y (W)/gRE= 1%, gEI= -1%	402.105	436.813	477.191	520.237	562.446	626.850
Base g_y (W)/gRE= 2.5%, gEI= -2.5%	401.991	424.072	437.450	447.814	458.418	476.223
Base g_y (W)/gRE= 5%, gEI= -5%	401.914	417.710	424.715	429.674	432.917	435.691
Faster g_y	402.138	442.774	501.943	580.319	674.299	847.567
Faster g_y (W)	402.141	443.319	504.417	586.685	686.776	878.853
Faster g_y (W)/gRE= 1%, gEI= -1%	402.113	438.400	482.546	531.483	580.972	660.950
Faster g_y (W)/gRE= 2.5%, gEI= -2.5%	401.998	424.982	439.588	451.488	464.048	486.075
Faster g_y (W)/gRE= 5%, gEI= -5%	401.921	418.327	426.014	431.719	435.576	439.035

Source: Prepared by the authors.
Notes: Same as in Table 6.

growth rates for the share of renewable energy consumption and energy intensity in order to assess their effectiveness. The share of the services sector over GDP will be kept constant over time at the same levels as 2014, and the population forecasts will correspond to the medium fertility variant of the "UN World Population Prospects: The 2017 Revision".

The results presented in Tables 3.5, 3.6 and Figure 3.2 point towards rejecting the EKC hypothesis in the long term. Although global CO2 emissions seem to grow at a decreasing rate between 2015 and 2100, only two forecasts based on economic growth reach a turning point before the end of the XXI century (base and faster gy for the SEKC). These results coincide with the estimates of Section 3.5, where it was shown that the spatial EKC will reach an earlier turning point because the displacement of polluting industries cannot be held in the long term.

However, their turning points are reached in 2090 and 2089, respectively, which implies that the average global temperature would have already increased. According to Sachs (2015), approximately 46% of carbon dioxide emissions remain in the atmosphere, and of this 46%, each 7800 million tonnes of CO2 creates 1 ppm (ppm) CO2 concentration. In 2014, the atmospheric concentrations of CO2 were close to 400 ppm; thus, for 2046, the CO2 concentrations will exceed 500 ppm if we consider the base gy for the spatial EKC. This implies a total increase in average global temperature of 2 °C since the nineteenth century. The conclusions for the remaining scenarios are similar or even worse (Figure 3.2).

The only solution to accelerated climate change may be to invest in renewable energy and increase energy efficiency. Specifically, when we impose a growth rate of renewable energy consumption over total energy consumption equal to 1% and for energy intensity equal to -1%, we obtain more-environmentally friendly results, but they are still not enough (now, the 500 ppm mark will be reached around 2050 for both standard and spatial EKC). When a growth rate near 2.5% is imposed, we can affirm that environmental sustainability will be achieved (in 2100, the CO2 atmospheric concentrations will be roughly equal to 488 ppm in the worst scenario "Faster $gy(W)/gRE = 2.5\%$, $gEI = -2.5\%$" for the standard EKC). However, if income grows at a sufficiently high rate, it may hamper the improvements achieved through greater consumption of renewable energy or increases in energy efficiency ($\downarrow EI$), as can be observed in Tables 3.5, 3.6 for the cases of "Faster $gy(W)/gRE$ and gEI" (three last rows for the standard and spatial EKC forecasts). Moreover, some researchers have noted that investments in renewable energy may also boost economic growth (Chien and Hu, 2008; Apergis and Payne, 2010, 2012), which could lead to greater concentrations before 2100.

3.7 Conclusions and Policy Implications

We analysed the determinants of CO2 emissions over the period 1990–2014 for a sample of 173 countries. In addition, forecasts for global carbon dioxide emissions were conducted. We took the EKC hypothesis as our theoretical framework and augmented it

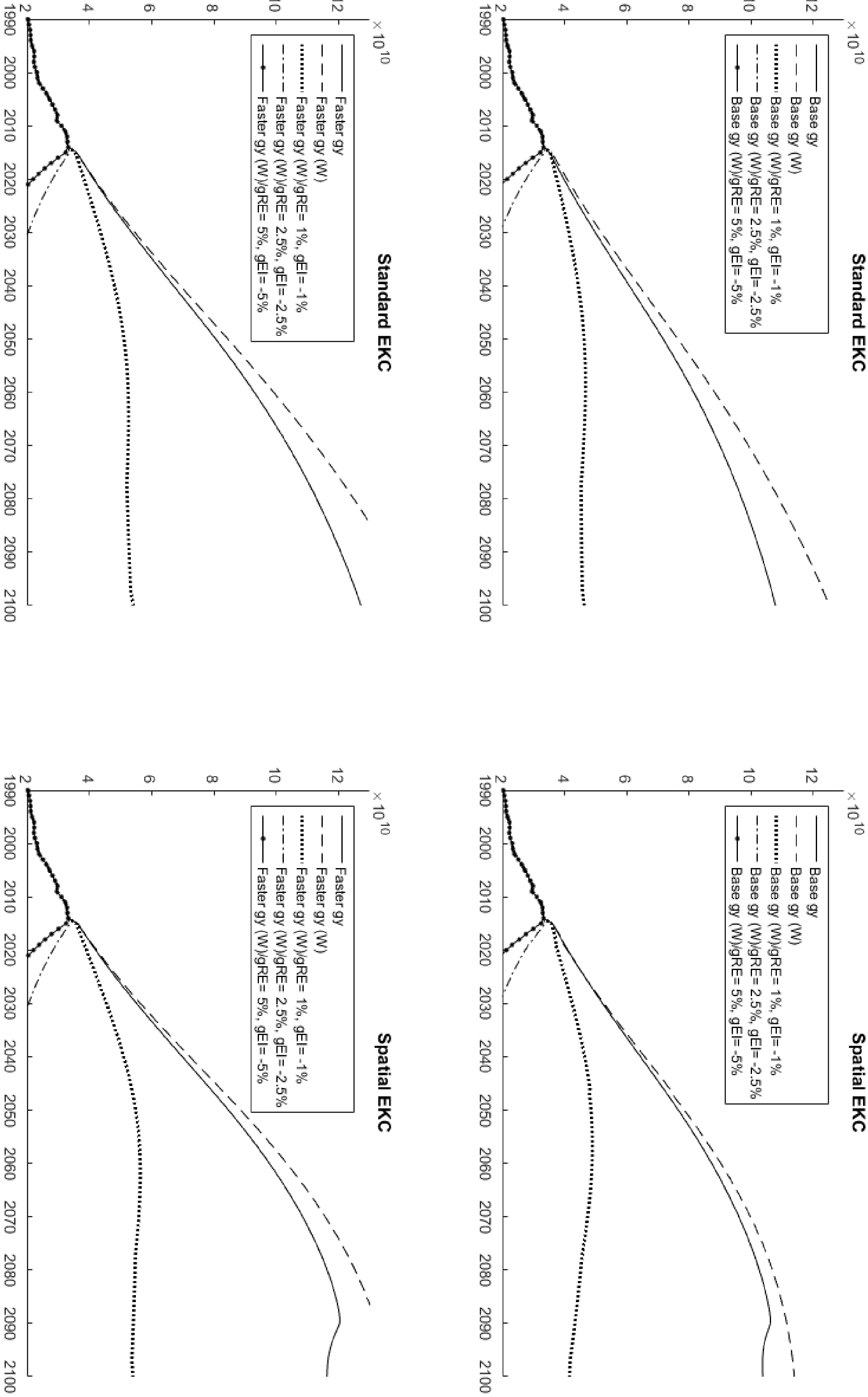

Figure 3.2: Global emissions forecasts. Source: Prepared by the authors.

by incorporating spatial relationships. Two models were estimated: a standard EKC that includes the share of renewable energy consumption and the share of the services sector in GDP with the purpose of reflecting the composition effect; with energy intensity as a proxy of technological progress; and a spatial EKC including the previous specification and both spatially lagged income and energy intensity. Neighbouring income serves to test the pollution haven hypothesis; and neighbouring energy intensity is used as a proxy for technological spillovers.

The results show that the direct EKC (changes in national nonsquared and squared income) is strongly supported for all areas, except for Oceania, whose emissions increase monotonically with national per capita income. An indirect EKC (changes in neighbouring non-squared and squared income) is strongly supported for the World as a whole and for Europe and Asia. Hence, as neighbouring per capita income increases, national emissions will rise at a decreasing rate until a turning point is reached. From then onwards, further increases in neighbouring per capita income will reduce national emissions. The continent of Oceania shows the inverse relationship, an indirect U-shaped curve. We conclude that when spillover impacts are taken into account for the World as a whole, the estimated final turning point will be lower than the standard one due to long-term neighbouring influences.

The policy implications of our research can be summarised in the following five points:

(i) Economic growth by its own will not guarantee environmental sustainability. Our forecasts predict that boosting only per capita income will result in an increase of global average temperature of 2 °C by around the year 2050. Therefore, countries must allocate a substantive part of their growth to environmentally friendly sectors.

(ii) Technology related to energy efficiency, must be improved in a large extent due to its impact not only in each nation, but also on their neighbouring countries. Our estimations reveal that the second largest elasticity of carbon dioxide emissions is respect to energy intensity, regardless to the elasticity related to technological spillovers.

(iii) The share of renewable energy over total energy consumption has also been proved to be relevant to reduce CO2 emissions. Nevertheless, its impact is dimmer than the related to energy efficiency. According to our forecasts, a sustained decrease of energy intensity close to 2.5%, along with greater relative consumption of renewable energy, may guarantee environmental sustainability prior to 2100.

(iv) Finally, the degree of tertiarisation seems to be non-significant for explaining changes in CO2 emissions in most areas.

Table 3.7: Appendix A. Sample Statistics

	Min.	Max.	Average	Median	Standard Dev.
e (World)	0.011	70.136	4.524	2.102	6.459
y (World)	247.437	135318.809	15160.898	8099.462	18491.413
POP (World)	40834	1364270000	35194183.079	6524283	130779963.201
RE (World)	0	98.343	33.820	24.544	31.598
SVC (World)	4.141	100	55.439	56.526	15.641
EI (World)	0.426	57.988	7.000	5.206	5.644
e (Europe)	0.490	27.431	7.613	7.030	3.615
y (Europe)	1246.959	97864.195	27694.786	26456.737	16187.834
POP (Europe)	254826	82534176	15893809.001	7548227.500	21000360.120
RE (Europe)	0	77.359	16.025	10.226	15.816
SVC (Europe)	15.898	87.647	64.894	65.931	10.097
EI (Europe)	2.318	47.106	6.557	5.152	4.480
e (NA)	0.473	36.093	5.046	2.285	6.515
y (NA)	2806.602	60675.982	15827.448	10525.588	13010.000
POP (NA)	40834	318563456	21552444.205	1889367.500	62091460.412
RE (NA)	0	74.965	21.236	13.031	20.475
SVC (NA)	33.402	93.363	68.088	69.069	10.981
EI (NA)	1.757	21.148	5.054	3.980	3.462
e (SA)	0.494	7.608	2.562	1.927	1.602
y (SA)	2837.362	22226.452	10488.120	10313.325	4441.481
POP (SA)	407472	204213133	29766038.100	14472694	47219840.905
RE (SA)	7.610	79.150	31.935	30.683	15.718
SVC (SA)	26.124	72.854	54.693	55.222	8.813
EI (SA)	2.343	11.584	4.532	4.215	1.625
e (Asia)	0.034	70.136	6.366	3.057	9.781
y (Asia)	728.032	135318.809	18983.878	6961.430	26212.933
POP (Asia)	218000	1364270000	87047835.541	13999235	244991236.029
RE (Asia)	0	95.920	24.900	6.077	29.937
SVC (Asia)	16.560	94.240	49.621	47.305	15.040
EI (Asia)	0.426	38.335	7.711	5.597	6.154
e (Oceania)	0.222	18.200	3.135	1.002	5.021
y (Oceania)	1466.336	43395.571	9141.407	3191.057	12102.595
POP (Oceania)	47298	23460694	3156161.088	285345	5942375.586
RE (Oceania)	0	70.798	25.696	14.555	25.323
SVC (Oceania)	20.440	83.343	61.022	65.256	14.243
EI (Oceania)	2.484	13.189	5.665	5.353	2.189
e (Africa)	0.011	10.044	1.131	0.311	2.014
y (Africa)	247.437	40015.819	4593.003	2107.822	5883.730
POP (Africa)	69507	176460502	16804162.126	8680346	24401012.760
RE (Africa)	0	98.343	62.674	76.955	30.608
SVC (Africa)	4.141	100	47.083	47.462	15.082
EI (Africa)	1.492	57.988	8.438	5.786	7.112

Source: Data from World Development Indicators, The World Bank. Prepared by the authors.

Table 3.8: Appendix B1. List of Countries

List of countries	
[1] Antigua and Barbuda	[34] Chad
[2] Algeria	[35] Colombia
[3] Azerbaijan	[36] Costa Rica
[4] Albania	[37] Central African Republic
[5] Armenia	[38] Cape Verde
[6] Angola	[39] Cyprus
[7] Argentina	[40] Denmark
[8] Australia	[41] Djibouti
[9] Bahrain	[42] Dominica
[10] Barbados	[43] Dominican Republic
[11] Bermuda	[44] Ecuador
[12] Bahamas	[45] Egypt
[13] Bangladesh	[46] Ireland
[14] Belize	[47] Equatorial Guinea
[15] Bosnia and Herzegovina	[48] Estonia
[16] Bolivia	[49] Eritrea
[17] Burma	[50] El Salvador
[18] Benin	[51] Ethiopia
[19] Solomon Islands	[52] Austria
[20] Brazil	[53] Czech Republic
[21] Bulgaria	[54] Finland
[22] Brunei Darussalam	[55] Fiji
[23] Canada	[56] Micronesia, Federated States of
[24] Cambodia	[57] France
[25] Sri Lanka	[58] Gambia
[26] Congo	[59] Gabon
[27] Democratic Republic of the Congo	[60] Georgia
[28] Burundi	[61] Ghana
[29] China	[62] Grenada
[30] Afghanistan	[63] Germany
[31] Bhutan	[64] Greece
[32] Chile	[65] Guatemala
[33] Cameroon	[66] Guinea

Table 3.9: Appendix B2. List of Countries

List of countries (cont.)	
[67] Guyana	[100] Oman
[68] Honduras	[101] Maldives
[69] Croatia	[102] Mexico
[70] Hungary	[103] Malaysia
[71] Iceland	[104] Mozambique
[72] India	[105] Malawi
[73] Iran (Islamic Republic of)	[106] Belgium
[74] Italy	[107] Hong Kong
[75] Japan	[108] Luxembourg
[76] Jamaica	[109] Macau
[77] Jordan	[110] Vanuatu
[78] Kenya	[111] Nigeria
[79] Kyrgyzstan	[112] Netherlands
[80] Kiribati	[113] Norway
[81] Korea, Republic of	[114] Nepal
[82] Kuwait	[115] Suriname
[83] Kazakhstan	[116] Nicaragua
[84] Lao People's Democratic Republic	[117] New Zealand
[85] Lebanon	[118] Paraguay
[86] Latvia	[119] Peru
[87] Belarus	[120] Pakistan
[88] Lithuania	[121] Poland
[89] Liberia	[122] Panama
[90] Slovakia	[123] Portugal
[91] Libyan Arab Jamahiriya	[124] Papua New Guinea
[92] Madagascar	[125] Guinea-Bissau
[93] Mongolia	[126] Qatar
[94] The former Yugoslav Rep. of Macedonia	[127] Romania
[95] Mali	[128] Philippines
[96] Morocco	[129] Russia
[97] Mauritius	[130] Rwanda
[98] Mauritania	[131] Saudi Arabia
[99] Malta	[132] Saint Kitts and Nevis

Table 3.10: Appendix B3. List of Countries

List of countries (cont.)	
[133] Seychelles	[154] Turkmenistan
[134] South Africa	[155] United Republic of Tanzania
[135] Lesotho	[156] Uganda
[136] Botswana	[157] United Kingdom
[137] Senegal	[158] Ukraine
[138] Slovenia	[159] United States
[139] Sierra Leone	[160] Burkina Faso
[140] Singapore	[161] Uruguay
[141] Spain	[162] Uzbekistan
[142] Saint Lucia	[163] Saint Vincent and the Grenadines
[143] Sudan	[164] Venezuela
[144] Sweden	[165] Viet Nam
[145] Switzerland	[166] Namibia
[146] Trinidad and Tobago	[167] Swaziland
[147] Thailand	[168] Yemen
[148] Tajikistan	[169] Zambia
[149] Tonga	[170] Zimbabwe
[150] Togo	[171] Indonesia
[151] Sao Tome and Principe	[172] Timor-Leste
[152] Tunisia	[173] Marshall Islands
[153] Turkey	

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4 New Insights into the World's Energy Intensity Convergence: A Neoclassical Approach Considering Spatial Spillovers

4.1 Introduction

To achieve the objective of net zero CO2 emissions related to energy consumption, two possibilities emerge: substitution by nonpolluting sources and improvements in energy efficiency levels. At an aggregate level, the latter measures technical innovations in the quality of energy flows and/or measures in other sectors more efficient production processes that lead to lower gross energy consumption. Moreover, endogenous changes in productivity can be linked to shifts in the demand for substitute goods, and vice versa, as posed by models such as those of "directed technical change" (e.g. Acemoglu, 2002; Eriksson, 2018), thus studying the evolution of energy intensity (a proxy for energy efficiency) is very likely to explain the long-term sustainability of modern economies. In addition, previous works have also found a strong and positive correlation between levels of energy intensity and CO2 emissions (Cole and Neumayer, 2004; Poumanyvong and Kaneko, 2010; Du et al., 2012; Liu et al., 2015; Wang et al., 2017; Balado-Naves et al., 2018; Danish et al., 2020).

According to the available data from the World Development Indicators Database (World Bank, 2021), the 1990-2014 period was marked by a steady decrease in worldwide energy intensity levels. Knowing whether this pattern is driven only by "clubs" of countries is important for long-term sustainability and supranational policies, such as the EU Emissions Trading System, given that it might be reverted as less developed countries intensify their energy consumption due to strong industrializing processes. Herrerias (2012), for instance, stresses the importance of achieving international agreements between developing and developed countries that will foster environmentally friendly institutions and technological diffusion.

Moreover, as commented in Mielnik and Goldemberg (2000), the existence of convergent paths in energy intensity levels allows for using energy intensity growth as a proxy variable of how well the world as a whole is dealing with climate change. In this sense, Duro et al. (2010) also find strong evidence that energy intensity convergence drives energy consumption convergence for OECD countries. Therefore, if countries converge in their patterns of energy consumption, forecasts on the effect of new regulation or public policies directed to control excessive consumption will gain superior accuracy. For all these reasons, the study of worldwide energy intensity convergence is crucial for policy-making aimed at environmental sustainability.

Previous literature on the country-level convergence in energy intensity, can be divided into two major branches. The first, or traditional branch, studies the existence of both β- and σ-convergence by employing the techniques of economic growth literature that started with Barro (1991) and Barro and Sala-i-Martin (1992). Among these studies, the first approach corresponds to Miketa and Mulder (2005), who study the existence of convergence in energy intensity for 56 developed and developing countries during the period 1971-1995. In addition to analysing the evolution of standard deviations and finding significant σ-convergence, their methodology follows a direct adaptation of the β-convergence specification from the neoclassical growth model for 10 different manufacturing sectors, finding evidence in favour of conditional convergence after controlling for country fixed effects and explanatory variables such as energy prices, saving rates or the share of different energy sources in the energy mix.

An immediate successor of this work can be find in Mulder and de Groot (2007), where the dataset is reduced to 11 OECD countries for the period 1970-1997. The analysis is performed at an aggregate and sectoral level, considering 14 sectors covering the entire economy, instead of just manufacturing industries. They find that the standard deviation of energy intensity leads to σ-divergence at an aggregate level, or persistent differences in energy intensity, driven by the manufacturing sector, which is justified by a significant conditional β-convergence controlled by the share of each sector with respect to GDP. Other control variables, such as labour wages or trade openness are statistically insignificant in most cases. Mulder and de Groot (2012) expand the analysis to 18 OECD countries, with a more consistent database for 1970 to 2005 and at a more disaggregated level (50 sectors). They find that σ-convergence in energy intensity starts from 1995 onwards, caused by convergence within the manufacturing sector, while convergence in the services sector slows it down. Regarding β-convergence tests, they find absolute convergence at a rate of 1.8%, as well as conditional convergence at higher rates after controlling for country fixed effects. Additionally, they carry out a sectoral decomposition analysis, finding that structural changes have hindered conditional β-convergence after 1995 due to a more dominant and energy-intensive services sector.

The study of Markandya et al. (2006) focuses on β-convergence in terms of energy intensity and income per capita for 12 Eastern European transition countries and Turkey with respect to the average levels of the EU15 between 1992 and 2002. They control for country and time effects, and test for correlations between the estimated speeds of convergence and institutional variables such as privatization or price liberalization. Moreover, they also consider the influence of differences in per capita income on energy intensity gaps. Their estimations reveal statistically significant β-convergence in energy intensity for 11 countries, but not sufficient evidence in favour of per capita income convergence as one of its sources. Additionally, they find that most of the included institutional variables are strongly correlated with the estimated speed of convergence, implying that better institutional quality leads to faster convergence in energy intensity.

Liddle (2012) studies the σ, γ and β-convergences for 28 OECD countries over the period 1960-2006. σ-convergence is studied by means of a trend analysis of the coefficient of variation and the shape of the distribution with kernel estimators, with results pointing towards significant reductions in dispersion and a unimodal distribution, thus clubs of convergence seem to be absent. Without taking into account any control variables, for testing the β-convergence hypothesis, cross-sectional regressions are used, the results of which cannot reject the existence of absolute β-convergence. However, the analysis of γ-convergence by employing an index of rank of concordance, which yields scarce intradistribution mobility, and the estimation of an ergodic distribution of OECD energy intensity levels do not support the existence of absolute but do support conditional convergence for the given period. For a representative sample of the world as a whole, using 111 countries between 1971-2006 and 134 countries for the 1990-2006 period, Liddle (2010) again analyses the existence of σ, γ and β-convergence. The study of σ-convergence finds strong support for worldwide convergence. Moreover, a deeper analysis of intradistribution mobility and a consideration of disaggregated subareas reveals different rates of convergence between groups of countries, as well as constant or increasing divergence between clubs of convergence. In addition, the author finds that the existence of σ-convergence is very susceptible to absent data from countries such as Iraq or the former Soviet countries, while the study of β-convergence again follows a simple cross-sectional regression for the two sets of countries, with no control variables, finding evidence in favour of absolute convergence in all cases.

Through a simple cross-sectional regression and without taking into account any variable of control, Voigt et al. (2014) only study the existence of β-convergence for 40 major economies between 1995 and 2007. Their results confirm the existence of cross-country convergence, but not at a sectoral level. Moreover, their decomposition analysis of energy intensity patterns shows that although global production has moved towards more energy intensive countries, sustained and widespread technical developments and domestic structural changes towards more efficient industries have led to a sustained decrease in global energy intensity levels.

Finally, Csereklyei et al. (2016) analyse both σ- and β-convergence parameters for 99 developed and developing countries during the 1971-2010 period. Convergence is measured in terms of both energy consumed per unit of GDP and per unit of capital stock, and conditional β-convergence only accounts for individual and time fixed effects, without considering any explanatory variable besides the time lag of energy intensity or energy per unit of capital stock. Their results yield strong support in favour of both absolute and conditional β-convergence, as well as σ-convergence, which implies a global convergence for the last four decades mainly driven by developing countries imitating the energy-intensive patterns of developed countries.

The second branch, on the contrary, avoids standard econometric methods and focuses on σ-convergence and nonparametric techniques aimed at tackling Galton's Fallacy, which is likely to emerge in β-convergence analyses given the expected emergence of multimodal distributions, as it is emphasized in Quah (1993; 1996). The seminal works of Nielsson (1993) and Goldemberg (1996) are mainly focused on descriptive techniques. Both authors analyse trends of energy intensity in 31 developing and developed countries for the period 1950-1988, finding the existence of convergence towards 0.4 toe/US$1000 of GDP (1980 dollars). In a later work, Mielnik and Goldemberg (2000) show the importance of measuring energy intensity levels in terms of constant PPP GDP to detect the true pattern in energy saving techniques for cross-country analyses. More precisely, they use data from 41 countries for the period 1971-1992, detecting the existence of σ-convergence due to the developing countries increasing their energy intensity levels, while developed countries were following the opposite evolution.

In Ezcurra (2007), the cross-country distribution of energy intensity levels for 98 countries during the period 1971-2001 is analysed by means of kernel density estimators and Markov chains. The results point towards the existence of convergence in energy intensity as well as a decrease in world average levels. Duro et al. (2010) study the evolution of the Theil index of energy intensity levels for 30 OECD countries between 1980 and 2006, finding evidence for convergence. Moreover, a further decomposition analysis of the variance in energy intensity reveals that agreggate technical progress drove convergence, while sectoral specialization along with energy allocation in less efficient sectors increased differences in energy intensity.

Le Pen and Sévi (2010) and Kiran (2013) employ cointegration methods. Le Pen and Sévi (2010) consider a pairwise approach for 97 countries between 1971 and 2003, concluding that there is no convergence for the entire set of countries, while it cannot be rejected for the Middle East and OECD subsets. Kiran (2013) tests for fractional cointegration for 21 OECD countries for the period 1980-2010, finding convergence with respect to the OECD mean for 9 countries such as Germany or Denmark. Herrerias (2012) analyses the cross-sectional distribution dynamics of energy intensity in 83 countries between 1971 and 2008 by modelling a stochastic process, and studies the external shape of the distribution by means of a kernel estimator to detect the existence of convergence. Moreover, the author studies convergence considering different sources of energy and weights the convergence process by population. Their results support the existence of convergence towards two different clubs divided between developing and developed countries.

However, most of these studies rely upon convenient approximations or direct adaptations of the standard β-convergence equation that can be found in Barro and Sala-i-Martin (1992), with no attempt to connect the neoclassical model of growth with the evolution of energy intensity as we do in the present work. To the best of our knowledge, only Mulder and de Groot (2007) attempted to link neoclassical theory with energy consumption to justify the employment of convergence analyses at energy intensity levels. Ezcurra (2007) and Liddle (2012) point out the need to study the true determinants behind convergence in energy efficiency levels and patterns of energy use. In this sense, our work addresses the aforementioned issue by providing a simple, but more consistent, theoretical framework and by controlling for a wide range of explanatory variables related to the steady states of economies at the time of estimating energy intensity growth rates. Some of these variables, such as saving rates or average institutional quality, have not yet been employed for such a large number of countries.

Moreover, Miketa and Mulder (2005) comment on the need to explore worldwide technical diffusion since technological change is a major source of energy-productivity growth, while Liddle (2010) detects geographical barriers determining convergence in energy intensity within clubs of countries. In this sense, we have only found three works of energy intensity convergence controlling for spatial spillovers. Yu (2012) and Jiang et al. (2018) focus their analysis on Chinese provinces, finding strong evidence in favour of spatial correlation. Mulder et al. (2011) is the only study employing a cross-country dataset of 102 countries between 1971 and 2001 and taking into account spatial dependence. They also find significant spatial correlation across countries, but their estimated speeds of convergence present null differences compared to their OLS estimations. Additionally, they limit their estimations to the spatial autoregressive and error specifications, without considering spatially lagged exogenous variables. This gap in the empirical literature on worldwide energy intensity convergence is also filled in the present paper.

The remainder of this paper is organized as follows. Section 4.2 introduces the neoclassical theoretical framework justifying the estimation of β-convergence regressions for energy intensity convergence and its relationship with σ-convergence. Section 4.3 presents the methods of study, the specifications for regressions and data. Section 4.4 features the results from the σ- and β-convergence analyses. Section 4.5 concludes and introduces some policy recommendations.

4.2 Theoretical Framework

4.2.1 Economic growth, energy and the beta convergence

Assume GDP comes from combining M intermediate goods x_v with raw labor L_Y according to the following constant returns to scale production function (the growth models with “rising product quality" can be found in Grossman and Helpman (1991) and Aghion and Howitt (1992). Moreover, the present Neoclassical-Schumpeterian general equilibrium model mainly draws from Howitt and Aghion (1998))

$$Y = L_Y^{1-\eta} \sum_{v=1}^{M} Q_v X_v^{\eta} \tag{4.1}$$

with Q_v as the quality level associated to each intermediate good X_v and $0 < \eta < 1$. Assume that intermediate goods take the following constant returns to scale production function

$$X_v = \frac{B_v}{Q_v} L_{Xv}^{1-\gamma} K_v^{\gamma} \tag{4.2}$$

where $\frac{B_v}{Q_v}$ represents the effective technical factor, which increases in the efficiency of the transformation process B_v, and decreases with the quality of the intermediate good Q_v. This specification allows for increasing marginal costs in quality levels Q_v, and decreasing marginal costs in production techniques B_v. Additionally, $0 < \gamma < 1$. Using (2) in (1), and solving the general equilibrium model assuming intermediate firms have market power yields the standard Neoclassical production function for GDP

$$Y = (AL)^{1-\alpha} K^{\alpha} \tag{4.3}$$

with $A = \left((1-\mu_X)^{1-\eta} \mu_X^{\eta(1-\gamma)} \left(\sum_{v=1}^{M} Q_v B_v^{\frac{\eta}{1-\eta}} \right)^{1-\eta} \right)^{\frac{1}{1-\alpha}}$ as the productivity factor of aggregate gross labor, with $\mu_X = \sum_{v=1}^{M} L_{Xv}/L$ and $\alpha = \eta\gamma$. Dividing (2) by (3), we obtain intensity levels of each intermediate good and service respect to aggregate gross output $\hat{X}_v = X_v/Y$

$$\hat{X}_v = \phi_v \frac{B_v}{Q_v} \left(\frac{\mu_X}{A} \right)^{1-\gamma} \tilde{k}^{(1-\eta)\gamma} \tag{4.4}$$

where $\phi_v = Y_v/Y = \left(A_v/A\right)^{1-\alpha}$ is the share of the gross value of each final good v respect to aggregate GDP, and $\tilde{k} = K/(AL)$ is the value of gross capital stock per effective worker. Since (3) is the same production function as in the Cobb-Douglas version of the the Ramsey-Cass-Koopmans model, the log-linearization of the model and its solution around the steady state leads to (see Barro and Sala-i-Martin (1992, 2004); Islam (1995))

$$\frac{\ln \tilde{k}_T - \ln \tilde{k}_0}{T} = \frac{1-e^{-\beta T}}{T} \left(\ln \tilde{k}^* - \ln \tilde{k}_0 \right) \tag{4.5}$$

Using (5) in the growth rate of (4) in discrete terms for interval T yields (recall that $\phi_v = \left(A_v/A\right)^{1-\alpha}$)

$$\frac{\ln \hat{X}_{vT} - \ln \hat{X}_{v0}}{T} = a_v - \frac{1-e^{-\beta T}}{T} \ln \hat{X}_{v0} \tag{4.6}$$

where $a_v = \eta \tilde{g}_v - \left(2 - \gamma(1+\eta)\right) g_A + \frac{1-e^{-\beta T}}{T} \left((1-\eta)\gamma \ln \tilde{k}^* + \ln \Omega_0 \right)$, $\tilde{g}_v = \frac{1+\eta}{\eta} g_{Bv} - g_{Qv}$ is the growth rate of the v intermediate good/service per effective worker $A^\gamma L$, and $\Omega_0 = \phi_{v0} \frac{B_{v0}}{Q_{v0}} \left(\frac{\mu_X}{A_0} \right)^{1-\gamma}$. Restating (6) for energy intensity $\hat{E} = E/Y$ and discrete periods of time of one year we have

$$\ln \left(\hat{E}_{it} / \hat{E}_{it-1} \right) = a_{\hat{E}i} + b \ln \hat{E}_{it-1} + u_{it} \tag{4.7}$$

where $b = -\left(1 - e^{-\beta}\right)$ is the coefficient containing the implicit speed of convergence, $i = 1, ..., N$ represents the analyzed country from the dataset, u_{it} is the idiosyncratic error term, and $a_{\hat{E}i} = a_{\hat{E}} \left(g_{Ai}, g_{Li}, s_i, \delta_i, \bar{NX}_i, ... \right)$ measures for country fixed effects and the economic steady state affecting energy intensity through variables such as technical progress g_{Ai}, population growth g_{Li}, saving rates s_i, depreciation rates δ_i or trade openness $\bar{NX}_i$.

4.2.2 Beta convergence as necessary condition for sigma convergence

The cross-country variance $\sigma^2_{\hat{E}t} = Var\left(\ln \hat{E}_{it}\right)$ for the set of countries N equals

$$\sigma^2_{\hat{E}t} = \frac{1}{N} \sum_{i=1}^{N} \left(\ln \hat{E}_{it} - \mu_{\hat{E}t} \right)^2 \tag{4.8}$$

where $\mu_{\hat{E}t} = e^{-\beta}\mu_{\hat{E}t-1} + \mu_a$ is the mean at time t of the natural logarithm of energy intensity. Rearranging (7), and substituting in (8) we have (assume $\sigma^2_{ut} = \sigma^2_u$)

$$\sigma^2_{\hat{E}t} = e^{-2\beta}\sigma^2_{\hat{E}t-1} + \sigma^2_a + \sigma^2_u \tag{4.9}$$

Solution to this first order equation in differences equals

$$\sigma^2_{\hat{E}t} = e^{-2\beta t}\left(\sigma^2_{\hat{E}0} - \frac{\sigma^2_a + \sigma^2_u}{1 - e^{-2\beta}}\right) + \frac{\sigma^2_a + \sigma^2_u}{1 - e^{-2\beta}} \tag{4.10}$$

- Absolute convergence: this type of convergence assumes each i country faces the same set of variables determining long-term evolution of logarithm of energy intensity $\ln \hat{E}_{it}$, that is $a_{\hat{E}i} = a_{\hat{E}j} = \mu_a$, where $i \neq j$. This modifies (10) into

$$\sigma^2_{\hat{E}t} = e^{-2\beta t}\left(\sigma^2_{\hat{E}0} - \frac{\sigma^2_u}{1 - e^{-2\beta}}\right) + \frac{\sigma^2_u}{1 - e^{-2\beta}} \tag{4.11}$$

  For the existence of absolute convergence, we require $\beta > 0$, thus $\lim_{t\to\infty} \sigma^2_{\hat{E}t} = \frac{\sigma^2_u}{1-e^{-2\beta}}$. That is, the population variance of the logarithm of energy intensity must asymptotically approach to the variance of unobserved determinants and exogenous shocks common to all countries.

- Conditional convergence: in this case, we do not assume the existence of common steady states. Therefore, (10) remains valid to analyze the evolution of dispersion in the distribution of energy intensity. The existence of convergence conditioned to each steady state $a_{\hat{E}i}$ requires again $\beta > 0$, which for $t \to \infty$ implies (assume that $Cov(x, y) = 0$)

$$\lim_{t\to\infty} \sigma^2_{\hat{E}t} = \frac{d_1^2\sigma^2_{g_{\tilde{g}}} + d_2^2\sigma^2_{g_A} + d_3^2\sigma^2_{\ln \tilde{k}^*} + b^2\sigma^2_{\ln \Omega_0} + \sigma^2_u}{1 - e^{-2\beta}} \tag{4.12}$$

  where $d_1 = \eta$, $d_2 = -(2 - \gamma(1 + \eta))$, $d_3 = b(1 - \eta)\gamma$.

Therefore, the present Neoclassical model considering energy as an intermediate input leads to the conclusion of $b < 0$ or $\beta > 0$ as a necessary condition for convergence in terms of energy intensity, whether this is in absolute or conditional terms.

4.3 Methods and Data

4.3.1 σ-convergence assessment

To evaluate the existence of σ-convergence we study the standard deviation constructed in (8) for the world as a whole and 4 continental subareas. To confirm these results, we also analyze the density function of the natural logarithm of energy intensity through the kernel density estimator

$$\hat{f}_{ht}(\ln EI_t) = \frac{1}{Nh}\sum_{r=1}^{N} W\left(\frac{\ln EI_t - \ln EI_{rt}}{h}\right) \tag{4.13}$$

where N is the cross-country sample size at time t, h the bandwith, W(.) is the kernel smoothing function, and $\ln EI_{rt}$ are random samples from an unknown distribution.

4.3.2 β-convergence regressions

From Section 4.2, the "stylized" equation for further cross-sectional regressions takes the form

$$\frac{\ln\left(EI_{iT}/EI_{i0}\right)}{T} = a + b\ln EI_{i-1} + \sum_{v=1}^{K}\phi_v x_{iv} + \sum_{v=1}^{K}\sum_{j=1}^{N}\theta_v w_{ij}x_{jv} + u_i \tag{4.14}$$

where a is the intercept term; $b = \frac{1-e^{-\beta T}}{T}$ is the coefficient associated to the speed of convergence β between time 0 and T; $\ln EI_{i-1}$ is the lagged natural logarithm of energy intensity; ϕ_v are the coefficients associated to the x_{iv} explanatory variables controlling for the steady state of the economy and technical progress; θ_v are the coefficients associated to the $w_{ij}x_{jv}$ spatially lagged explanatory variables, with w_{ij} as the spatial weights; and $u_i = \lambda\sum_{j=1}^{N} w_{ij}u_j + \varepsilon_i$, where residuals u_i are spatially correlated according to parameter λ and ε_i represents the idiosyncratic random error term. In the case of panel data estimations, (14) turns into

$$\frac{\ln\left(EI_{iT_t}/EI_{i0_t}\right)}{T_t} = \tilde{a}_i + \tilde{b}\ln EI_{i0_t-1} + \sum_{v=1}^{K}\tilde{\phi}_v x_{ivt} + \sum_{v=1}^{K}\sum_{j=1}^{N}\tilde{\theta}_v w_{ij}x_{jvt} + u_{it} \tag{4.15}$$

with $t = 1, ..., S$ sub-intervals of identical extension T_t, hence $S\cdot T_t = T$, and individual fixed effects a_i. Since estimations are for sub-intervals of extension $T_t < T$, the approximated speed of convergence for T comes from $\beta = -\frac{\ln\left(1+\tilde{b}T_t\right)}{T}$.[7] Therefore, under the assumption of Cobb-Douglas production functions, the existence of convergence requires in both cases $b < 0$ and $\tilde{b} < 0$. Previous equations correspond to the Spatial Durbin Error Model (SDEM) specification with individual fixed effects, which nests the Spatial Lag of X (SLX) specification where spatial dependence is exogenous through $\sum_{v=1}^{K}\sum_{j=1}^{N}\theta_v w_{ijt}x_{jvt}$, as well as considers absent spatially lagged control variables contained in the spatially autocorrelated error term $u_{it} = \lambda\sum_{j=1}^{N} w_{ij}u_{jt} + \varepsilon_{it}$.

Our focus on the SDEM and spatial exogeneity is based on previous research that points towards the existence of local rather than global spatial spillovers in variables, such as technical diffusion (Keller, 2002; 2004); that is, geographical space is still a relevant determinant for technology adoption or goods trade, acting as a strong discount factor on neighbourhood relationships. Previous analyses of energy intensity convergence, such as Liddle (2010), have also observed the existence of geographical barriers in the validation and speed of convergence, and Mulder et al. (2011) and Jiang et al. (2018) have found strong evidences in favour of local spillovers in the context of energy intensity convergence. Moreover, Corrado and Fingleton (2012) and Vega and Elhorst (2015) encourage the

[7] Assume that $\ln\left(EI_{T_t}/EI_{0_t}\right) \approx \ln\left(EI_T/EI_0\right)$, hence $g_{EI}\left(T,0\right) \approx \frac{T_t}{T}g_{EI}\left(T_t, 0_t\right)$.

employment of the SLX or SDEM models including more spatially lagged explanatory variables if global spillovers are statistically significant but cannot be theoretically or empirically defended.

4.3.3 Data Sources

Table 4.1: Main Statistics

Variable	Mean	SD	Min	Max
gEI	0.0163	0.0961	-0.4520	1.8703
EI	7.3057	5.9577	0.7049	57.9882
gy	0.0223	0.0642	-0.4781	1.4050
gL	-0.0148	0.0146	-0.1507	0.1319
y	14436.7308	17810.2559	247.4365	119723.1007
RE	0.3426	0.3207	0.0010	0.9834
SVC	0.5474	0.1561	0.0414	0.9896
s	0.1933	0.1085	0.0061	0.8890
delta	0.0424	0.0167	0.0177	0.1027
instquality	0.5123	0.1953	0.0363	0.9522
NX/Y	-0.0339	0.1534	-1.2070	0.7501

Source: Elaborated by the authors.

According to data availability, the data span the period from 1990 to 2010. Data for energy intensity levels, per capita GDP, population, share of renewable energy over aggregate energy consumption and the added value of the services sector with respect to gross GDP are obtained from the *World Development Indicators Database* (World Bank, 2021). Data for the share of gross capital formation, the average depreciation rates of capital stock, and the shares of merchandise imports and exports come from the *Penn World Table 9.0 Database* (Feenstra et al., 2015). Data for absolute political, legal and economic institutional quality levels are available from Kuncic's *Institutional Quality Dataset* (Kuncic, 2014).[8]

4.3.4 Explanatory Variables of Conditional Convergence

According to (13), testing the existence of conditional convergence for energy intensity levels requires the employment of explanatory variables reflecting both the steady state of the economy, and the long-term direction of technical progress devoted to energy production. Given the availability of data, we approximate these determinants for the large dataset of 173 countries with the growth rates of per capita GDP and the population,

[8] We construct a simple average with these institutional quality indicators to reflect the average institutional quality in a given country and avoid some empty data reducing the sample of countries. For instance, if a country does not present data for the quality of legal institutions, the average institutional quality is only computed considering economic and political institutions, and so on.

as well as through the natural logarithm of per capita GDP, the share of renewable energy over aggregate energy consumption and the added value of the services sector with respect to gross GDP. For the small dataset of 130 countries, we employ more accurate variables representing the neoclassical steady state of the economy, which are the saving and depreciation rates, the share of net exports over gross GDP, and the institutional quality levels of each country. Moreover, the spatial lags of these variables are considered to control for spatial autocorrelation.

To capture long-term or steady-state behaviour of the explanatory variables, we employ time averages from each of them. Therefore, in the case of cross-sectional estimations, the average will be for the entire period 1990-2010, while for panel data estimations, averages will correspond to each 5-year interval. The 5-year interval was elected because seems to be sufficient to eliminate business cycle fluctuations and serial correlation from the error term (Islam, 1995; Petterson et al., 2013).

Per capita GDP growth rate

The lack of data regarding new patent registration or R&D expenditure for large datasets imposes the need to approximate technical progress through the average growth rate of per capita GDP. Assuming a neoclassical aggregate production function and economies close to or at the steady state, this variable should reflect the evolution of aggregate productivity rather well (e.g. Barro and Sala-i-Martin, 2004). Additionally, if we assume aggregate technical progress as a composite of different innovations at a micro level, as is assumed in models of endogenous growth (e.g. Romer 1990; Howitt and Aghion, 1998), both aggregate and disaggregated technical progress should be correlated, hence it must also serve as a proxy for the role of quality and process innovations among energy producers.

According to this, the expected signs of this variable are: i) positive, when the marginal costs of energy producers improve faster than the quality of energy flows and the marginal costs of other intermediate goods, increasing thus the relative demand of gross energy; ii) negative, when the quality of energy and/or the marginal costs of other intermediate goods improve faster than the marginal costs of energy producers, increasing thus the demand of effective energy services faster than that of gross energy; and iii) null, when both effects offset each other. Works such as Csereklyei et al. (2016) have found a strong negative relationship between average growth rates of energy intensity and per capita GDP, therefore the option of growth based on energy-saving techniques is more likely to emerge.

Population growth rate

According to the neoclassical model of growth, populations presenting long-term faster rates of growth will lead to a lower steady-state ratio of capital stock per effective worker (Solow, 1956), thus lowering the generation of gross energy per unit of output. Additionally, Herrerias (2012) finds that energy intensity convergence is more significant after controlling for population. According to (6) and (7), we should expect a negative impact of population growth on growth rates of energy intensity.

Per capita GDP

The natural logarithm of average per capita GDP is first included to control for the nonobserved variables of the neoclassical steady state, such as saving and depreciation rates. Second, previous studies has detected a positive, and even an inverse-U relationship between energy intensity and income in developing countries (Zilberfarb and Adams, 1981; Ang, 1987; Medlock and Soligo, 2001). However, Csereklyei et al. (2016) find that, although there exists a negative relationship between energy intensity and per capita GDP for a 1971-2010 panel dataset of 99 countries, the average growth rates of energy intensity are not correlated to levels of per capita GDP. Therefore, we must expect that, if this variable were significantly different than zero, then according to our neoclassical model, it should present a positive sign, since it serves as a proxy for steady state of the economy (assuming null technical progress, economies with higher saving rates are expected to capitalize faster in gross terms, thus increasing their production of energy flows for constant elasticities of substitution).

Share of renewable energy

Changes in the energy mix have been previously observed to be a strong determinant for reductions in energy intensity levels (Cleveland et al., 2000; Kaufmann, 2004). Moreover, Miketa and Mulder (2005) employ this factor as a control variable to test the existence of conditional β-convergence in energy intensity for manufacturing industries, finding contradictory results in terms of the sign and statistical significance for a few sectors. Therefore, we include this variable to test whether technical change in the energy sector has been embodied in a process of input substitution for world energy intensity convergence. If this were true, the expected sign should be negative.

Share of the services sector

According to Schäfer (2005), the net contribution of sectoral shifts to changes in worldwide energy intensity levels accounts for a scarce 5%. Nevertheless, it is still significant and negative as economies progress towards the tertiary sector. Therefore we include the share of added value of the services sector with respect to GDP as a likely control variable for β-convergence regressions. On the other hand, Mulder and de Groot (2012) find strong evidence in OECD countries of the manufacturing sector experiencing sustained decreases in energy intensity levels, while the services sector does so at a slower pace. Jiang et al. (2018) consider the role of the secondary sector for their analysis of β-convergence in 29 Chinese provinces, finding a positive and significant relationship with energy intensity growth rates. We therefore can expect that both positive and negative signs may emerge.

Saving rates

As in Miketa and Mulder (2005) and Mulder and de Groot (2007), the share of gross investment over aggregate GDP is included to test the *embodiment hypothesis*, which poses that the role of technical progress is partially considered in the value of new vintages of capital stock. According to Mulder et al. (2003), the long-term evolution of energy intensity due to capital accumulation will depend on the size of the arrival rate of energy-saving techniques compared to the improvement in the cost of producing new vintages of capital stock and their degree of substitution. In contrast, our simple theoretical framework points towards a direct relationship between energy intensity growth and saving rates; that is, saving rates increase the size of capital stock per effective worker in the steady state, which leads to a lower marginal costs of energy production, thus increasing the production of gross energy flows for the maximization of net profits.

Depreciation rates

This variable follows the same logic of population growth rates, given that a faster decay of capital stock leads to lower steady-state levels of accumulated capital per effective worker. We expect a negative sign, assuming the neoclassical model of growth is correct.

Average institutional quality

Recent developments in economic growth modelling have hypothesised the importance of efficient institutional frameworks (inclusive political and economic rules) in the long-term accumulation of capital stock per effective worker as well as in the generation of new ideas and techniques (e.g. Acemoglu, 2005; 2006). Nevertheless, among empirical researchers (e.g. Gyimah-Brempong and Dapaah, 1996; Acemoglu et al., 2001 and Knutsen, 2013), there is no strong consensus that supports the existence of the aforementioned negative correlation. Glaeser et al. (2004) find this relationship weak, as well as likely causality in the opposite direction). Regarding studies of β-convergence in energy intensity, we have only found that the work of Markandya et al. (2006) takes into consideration the role of institutions. More precisely, they analyse the correlation between the estimated speed of convergence of European transition countries with respect to the EU average, and institutional variables such as the quality of the competition policy enforced to markets or the degree of privatization among firms. Their results point towards a positive and statistically significant relationship; thus, better institutions should imply faster convergence given that transition countries will also converge in terms of steady-state variables. We therefore expect a positive sign in the estimated variable if better institutions lead to a larger accumulation of capital stock per effective worker and a negative sign when incentives for R&D push faster aggregate technical progress.

Share of trade balance

Mulder and de Groot (2007) consider the sum of exports and imports with respect to GDP as a control variable for conditional β-convergence regressions on energy intensity for 14 OECD countries. They argue that the degree of openness of a given economy or sector should be positively correlated with productivity growth due to stronger market competition. Nevertheless, their findings point towards nonsignificant coefficients in most economic sectors. In this sense, we also account for trade openness as an explanatory variable to test how robust their results are considering a much larger set of countries. Moreover, we employ the difference between exports and imports relative to GDP; thus, we can also check whether net importers improve their energy efficiency through the acquisition of more productive foreign capital goods. Therefore, a positive estimated coefficient is required to emerge for net importers presenting lower rates of growth in energy intensity levels thanks to the diffusion of energy-saving techniques.

Spatially lagged variables

The inclusion of spatial lags in all variables from the regressions controlling for steady states finds its justification in assuming that neighbouring countries with higher steady-state capital per effective worker are more likely to depend on raw capital instead of technological advancements; thus, their economies are less efficient in terms of energy and create clusters of low technical diffusion mainly due to exports of capital nonintensive in knowledge and to low capabilities of technical imitation. The idea of technical diffusion is strongly linked to foreign direct investment, which has been observed to be a major driver of the transmission of energy-saving techniques among developing countries (Mielnik and Goldemberg, 2002; Hübler and Keller, 2010).

4.4 Results and Discussion

4.4.1 σ-convergence

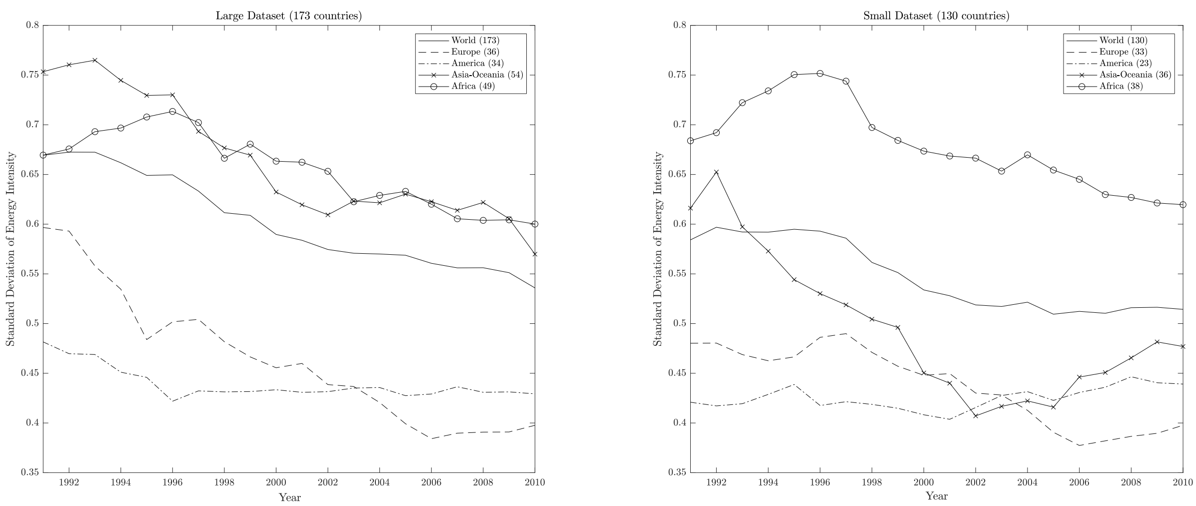

Figure 4.1: Standard deviations of lnEI by area (1990-2010). Elaborated by the authors.

As a preliminary study we present in Figure 4.1 the results of σ-convergence analysis. The left-hand panel shows the evolution of the standard deviations of the natural logarithm of energy intensity levels for the 1990-2010 period for 5 differentiated areas of 173 countries: one for the world as a whole; 4 large continental areas combining Asia and Oceania as a joint group; and South and North America as another group. The right-hand panel shows the evolution for the small dataset of 130 countries. At first glance and considering the change in standard deviations between the initial and final years, we can affirm that both datasets and all areas, except for America in the short dataset, have converged in terms of energy intensity, similarly to the results obtained in Csereklyei et al. (2016) for 99 countries between 1971 and 2010. More precisely, in the large dataset the world as a whole faced an average decrease in the standard deviation of energy intensity of 1.1%, while in the short dataset, decreased by 0.6%. Assuming these rates will remain constant in the future, the worldwide differences in energy intensity levels will halve between 63 and 116 years (the half-life of convergence).

Regarding continental subareas, we find that, in the large dataset, Europe presents the fastest decrease of 2%, with a half-life of 25 years; while Africa and America present the slowest decreases, accounting for 0.5% and a half-life of 139 years. Voigt et al. (2014) also find that worldwide convergence is also dominated by European countries, with Eastern European economies among the highest initial levels of energy intensity and reductions of energy intensity, while Western and Central European countries present the opposite combination for the 1995-2007 period. In the short dataset, the combined region of Asia and Oceania presents the highest convergence rate, with a value of 1.2% (similar to the rate from the large dataset rate of 1.3%, with half-lives of 58 and 53 years respectively), while Africa presents the slowest convergence rate with 0.4% (similar to that of the large dataset).

In the case of America, after eliminating from the large dataset 11 Caribbean countries such as Jamaica or Suriname, convergence turns into divergence, with an average rate of 0.2% and 347 years before differences across American countries double. These results are similar to those of Liddle (2010), who finds limited or null convergence among Latin American and Caribbean countries, or North African and Subsaharian economies. The author, as we do, also finds strong σ-convergence among Asian and European countries. The reasons provided are the volatility in oil prices and economic growth rates among developing countries, as well as institutional differences regarding the OECD or EU. Finally, a simple linear regression on the observed values of standard deviations for the world as a whole with respect to those of each area confirms a dominant influence of Asian and Oceanian economies on worldwide convergence, followed by Africa, with estimated average elasticities of 44% and 43.5% respectively.[9]

Moreover, the elasticities of the worldwide standard deviation with respect to those of the mostly divergent or nonconvergent areas of America and Africa have presented a positive evolution over time, while those of Europe and Asia-Oceania have decreased. Therefore, the current results supporting worldwide convergence can be reverted in the future if

[9] The estimated regression line equals $\sigma_{Wt} = 0.153\sigma_{Et} + 0.161\sigma_{Amt} + 0.406\sigma_{AOt} + 0.298\sigma_{Aft}$, with $R^2 = 0.99$ and DW=2.43. W: the world as a whole; E: Europe; Am: North, Central and South America; AO: Asia and Oceania; Af: Africa. Elasticities are computed as $\varepsilon_{it} = \hat{b}\frac{\sigma_{it}}{\sigma_{Wt}}$.

America and Africa continue to follow nonconvergent paths.

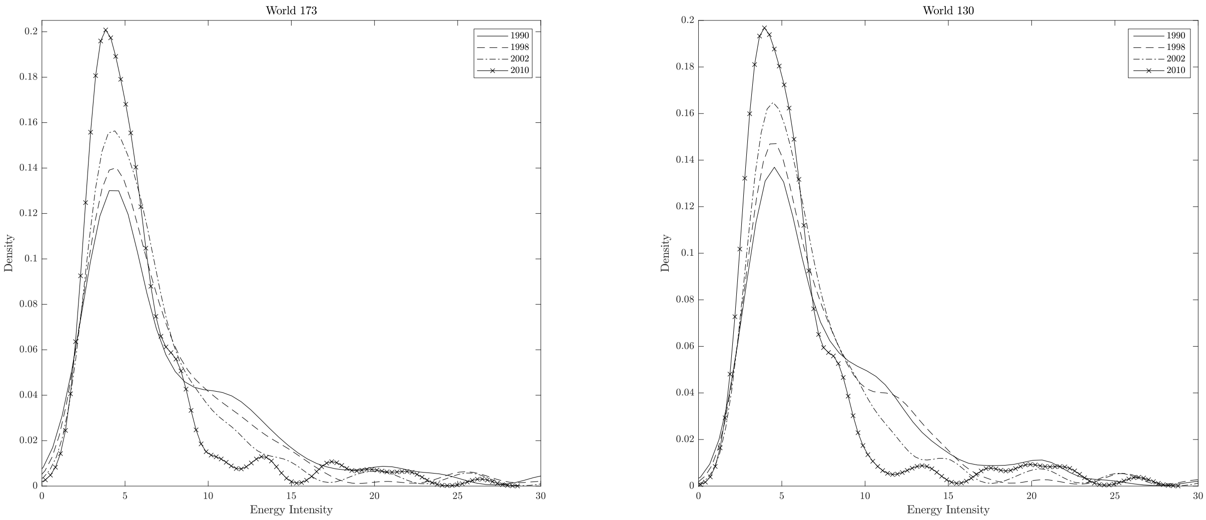

Figure 4.2: Estimated kernel density for worldwide energy intensity, 1990, 1998, 2002, 2010. Elaborated by the authors.

As a complementary analysis to the assessment of standard deviations, estimated kernel density distributions over time are studied. In Figure 4.2, the world as a whole, irrespective of the chosen dataset and year, presents a right-skewed unimodal distribution. The time evolution of each distribution shows a clear pattern towards higher cross-country concentration around the mode (from 13/14% observations in 1990 to 20% in 2010), as well as a significant reduction in the right tail area. This serves as further evidence in support of the worldwide σ-convergence previously detected. The direction of σ-convergence points towards more efficient economies in terms of energy usage, given that the most frequent level of energy intensity diminishes from 4.3 to 3.83 for the large dataset, and from 4.55 to 4 for the short dataset. Global means also diminish from $\bar{EI}_{1990} = 8.30$ to $\bar{EI}_{2010} = 6.05$, and $\bar{EI}_{1990} = 8.08$ to $\bar{EI}_{2010} = 6.16$ respectively.

Regarding continental subareas, the same pattern in the shape of the distribution can be observed except for the short set of American countries (see Figure 4.3 and Figure 4.4), where there is practically no change in the density value (approximately 24%) associated with a mode accounting for 4.22 units of primary energy supplied with respect to real GDP. These results are also in line with the initial analysis of standard deviations; thus, we can affirm that irrespective of the employed dataset during the period 1990-2010, there exists strong evidence in favour of σ-convergence in energy intensity levels for the world as a whole, Europe, Asia-Oceania, and Africa. In the case of America, there only seems to exist an initial slight σ-convergence in the first decade for the large dataset. However, we also detect that the worldwide improvement in energy efficiency is led by European economies, where the mode and the mean of energy intensity levels decreased by 1.5% (5.31 to 3.88) and 2.7% (9.09 to 5.28), respectively, for the large dataset, and by 1.3% (5.23 to 3.98) and 1.9% (7.62 to 5.14), respectively, for the 130-country dataset.

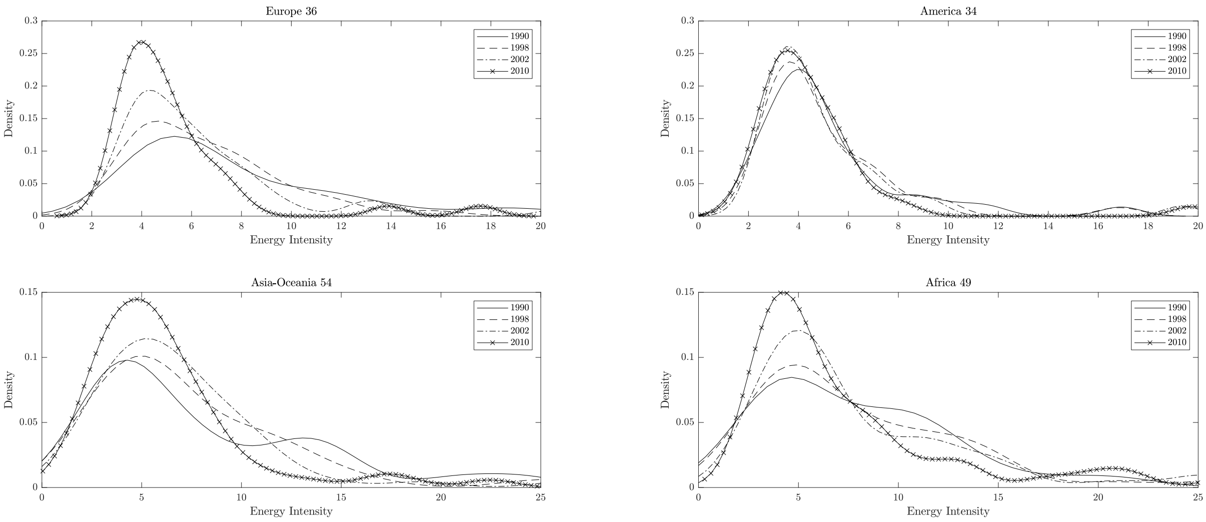

Figure 4.3: Estimated kernel density for each area energy intensity, 1990, 1994, 1998, 2002, 2006, 2010 (173 countries). Elaborated by the authors.

In contrast, the areas of Asia and Oceania moved in the opposite direction, where the most frequent value of energy intensity increased between 1990 and 2010 from 1.43 to 1.56 in the large dataset, and from 1.652 to 1.654 in the short dataset. The African area, which also contains a large number of developing countries, presented a minimal decrease of 0.2%, irrespective of the sample. This result differs from initial studies, where worldwide convergence in energy intensity has been observed to be mainly driven by developing countries adopting energy-saving techniques due to technical diffusion (Goldemberg, 1996; Mielnik and Goldemberg, 2000; Ezcurra, 2007). Csereklyei et al. (2016) conclude that the slight negative slope that can be observed for worldwide energy intensity evolution is a consequence of developing countries enriching themselves and adopting the energy patterns of developed countries.

Therefore, worldwide energy intensity convergence seems to be based on increasing efficiency among developed countries; at the same time, the developing economies are adopting more inefficient ways of production. In this sense, Duro et al. (2010) and Voigt et al. (2014) show that cross-country structural changes and sectoral specialization have contributed to increased differences in energy intensity levels and to the worsening of worldwide levels of energy intensity, while the role of widespread technical innovations increasing energy efficiency seems to be the major factor driving convergence and the improvement of energy intensity levels.

4.4.2 β-convergence

The strategy for the β-convergence analysis will be the following: i) Moran's I tests will be performed to detect the existence of spatial autocorrelation according to eight different spatial weights matrices for the world as a whole and each continental region (Europe, America, Asia-Oceania and Africa); ii) estimations will only include the spatial weight

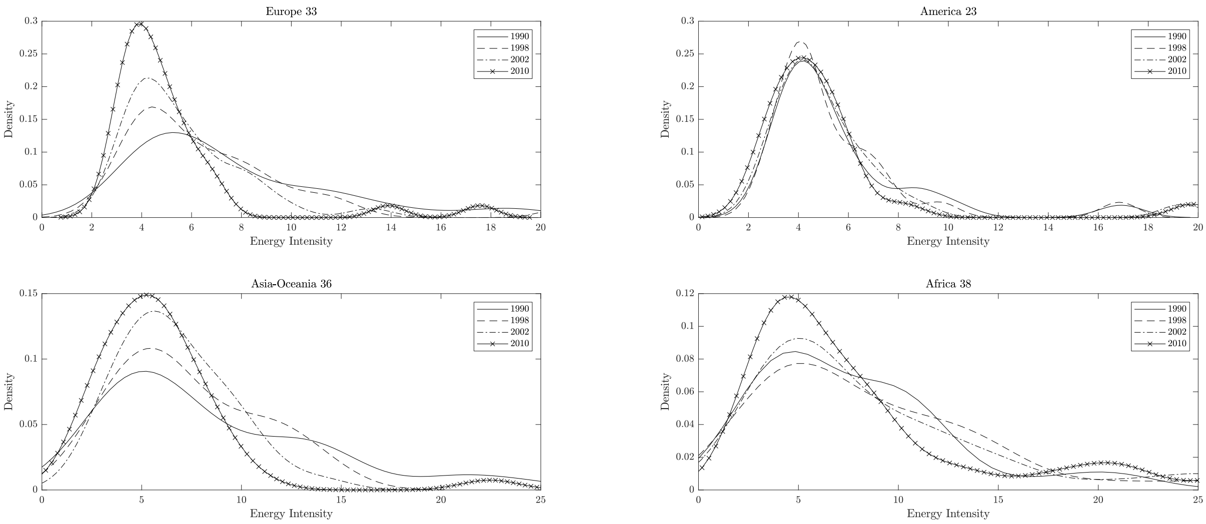

Figure 4.4: Estimated kernel density for each area energy intensity, 1990, 1994, 1998, 2002, 2006, 2010 (130 countries). Elaborated by the authors.

matrices that show the strongest spatial dependence as well as yield the highest coefficient of determination and log likelihood; iii) speeds of convergence $\hat{\beta}$ will be estimated and presented for both datasets, considering absolute and conditional specifications, as well as cross-sectional and panel data estimators; iv) for the analysis of the estimated coefficients in the control variables, we perform ex-post forecasts of standard deviations and choose the best specification on the basis of the minimization of the sum of the squared residuals from the corresponding simulation; v) to analyze the influence of previous control variables on energy intensity convergence we also carry out panel data estimations of the SDEM specification considering as dependent variable the differences of domestic energy intensity with respect to the cross-country mean.

The eight spatial weight matrices considered to test the existence of spatial correlation are constructed according to the following criteria of neighbourhood: the maximum distance observed between all pairs of closest neighbouring countries to ensure at least one neighbour for each country; half of that maximum distance; the five closest neighbouring countries; all countries are neighbours; the relative levels of economic development (differences in average per capita income, as in Jiang et al., 2018); and the relative levels of economic development weighted by geographical distances. All weights are constructed as the inverse of the distances between neighbours; and for the case of all countries as neighbours, as well as the relative levels of economic development weighted by geographical distances, we employ both linear and squared distances.

The results from the Moran's I tests performed for the average, initial and final values of the growth rate of energy intensity considering both large and short datasets for the world as a whole show that all spatial weight matrices, except for those of standard economic distances and quadratic economic distances weighted by geographical distances, yield significant spatial autocorrelation. The estimated Moran's I significantly different than

Model - Speeds of Convergence (Betas)	World	Europe	America	Asia-Oceania	Africa
Absolute Convergence (Cross section 173)	0.023*** (-9.85)	0.034*** (-6.60)	0.013*** (-2.94)	0.027*** (-6.23)	0.020*** (-3.87)
Conditional Convergence (Cross section 173)	0.019*** (-8.05)	0.008** (-2.54)	0.013** (-2.41)	0.022*** (-4.52)	0.007 (-1.42)
Conditional Convergence SLX (Cross section 173)	0.017*** (-7.11)	0.004 (-1.48)	0.016** (-2.81)	0.022*** (-4.33)	0.006 (-1.06)
Conditional Convergence SDEM (Cross section 173)	0.015*** (-7.22)	0.003 (-1.62)	0.016*** (-3.59)	0.022*** (-5.30)	0.011*** (-2.70)
Absolute Convergence (Panel 5-year 173)	0.004*** (-8.53)	0.009*** (-6.57)	0.002** (-2.27)	0.005*** (-5.38)	0.004*** (-3.38)
Conditional Convergence No Control (Panel 5-year 173)	0.025*** (-13.33)	0.025*** (-8.73)	0.025*** (-5.35)	0.013*** (-3.76)	0.035*** (-9.19)
Conditional Convergence (Panel 5-year 173)	0.041*** (-16.10)	0.123*** (-11.62)	0.026*** (-5.48)	0.052*** (-8.62)	0.021*** (-6.17)
Conditional Convergence SLX (Panel 5-year 173)	0.036*** (-16.38)	0.117*** (-10.55)	0.028*** (-5.25)	0.051*** (-8.02)	0.023*** (-6.48)
Conditional Convergence SDEM (Panel 5-year 173)	0.036*** (-14.29)	0.098*** (-9.25)	0.036*** (-5.66)	0.050*** (-7.10)	0.023*** (-5.78)
Absolute Convergence (Cross section 130)	0.019*** (-6.53)	0.020*** (-3.80)	0.002 (-0.55)	0.030*** (-4.86)	0.016*** (-3.05)
Conditional Convergence (Cross section 130)	0.013*** (-4.57)	0.005 (-1.42)	0.006* (-1.84)	0.028*** (-3.51)	0.002 (-0.38)
Conditional Convergence SLX (Cross section 130)	0.011*** (-3.87)	0.003 (-0.92)	0.022** (-3.71)	0.041*** (-3.55)	-0.002 (0.33)
Conditional Convergence SDEM (Cross section 130)	0.012*** (-5.40)	0.002 (-1.15)	0.009 (-0.82)	0.017*** (-2.89)	0.004 (-0.93)
Absolute Convergence (Panel 5-year 130)	0.003*** (-5.71)	0.004*** (-3.95)	0.001 (-0.10)	0.006*** (-5.00)	0.002** (-2.54)
Conditional Convergence No Control (Panel 5-year 130)	0.017*** (-8.44)	0.008*** (-3.07)	0.026*** (-4.32)	0.014*** (-4.04)	0.029*** (-5.65)
Conditional Convergence (Panel 5-year 130)	0.037*** (-12.96)	0.049*** (-7.20)	0.047*** (-6.38)	0.047*** (-7.20)	0.015*** (-3.15)
Conditional Convergence SLX (Panel 5-year 130)	0.037*** (-13.01)	0.042*** (-6.30)	0.049*** (-5.93)	0.042*** (-6.24)	0.016*** (-3.40)
Conditional Convergence SDEM (Panel 5-year 130)	0.037*** (-11.53)	0.033*** (-5.09)	0.051*** (-5.95)	0.039*** (-5.52)	0.016*** (-3.19)

Source: Elaborated by the authors. Speed of convergence follows the same formula as in the theoretical background (considering length of sub-intervals for panel data). Except for Asia-Oceania, all areas consider the spatial weight matrix of inverse linear distances. Asia-Oceania employ the relative-development spatial weight matrix. t-statistics appear between brackets. ***, ** and * are for p-values lower than 1%, 5% and 10% respectively.

Table 4.2: Estimated Betas.

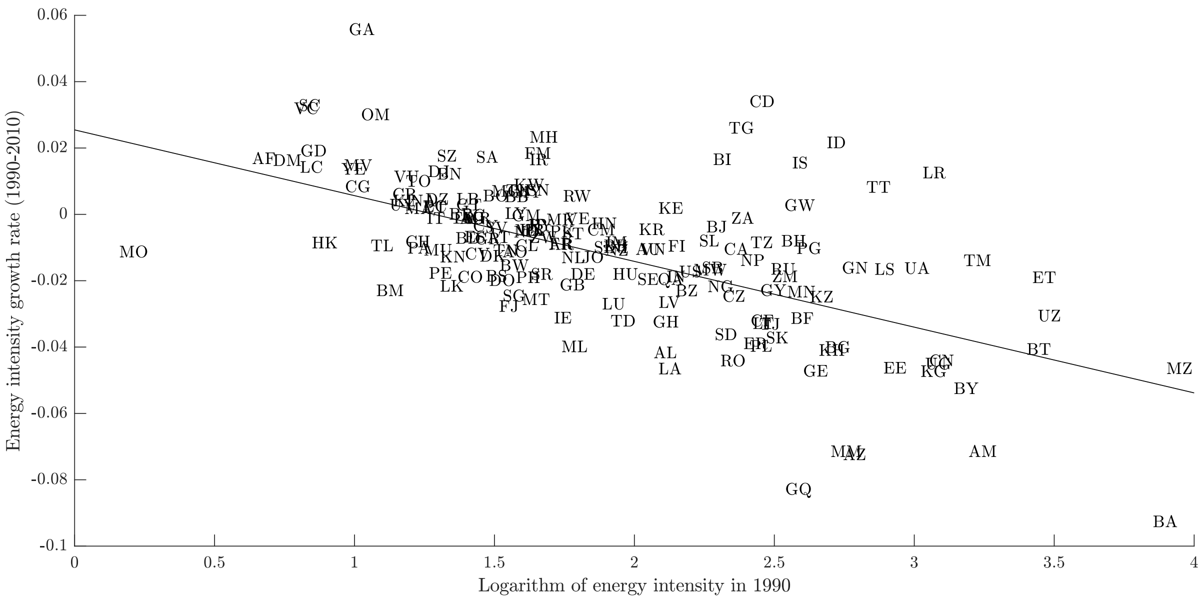

Figure 4.5: Convergence of energy intensity across the world: 1990 energy intensity and 1990-2010 average energy intensity growth. Elaborated by the authors

zero are in the interval $\hat{I}:[0.084, 1.060]$, where the lowest value of spatial autocorrelation corresponds to the maximum distance spatial weights matrix, and the highest value corresponds to the linear economic distance matrix weighted by geographical distances with a statistical significance of $p = 0.000$ and $p = 0.003$ respectively. The positive values point towards the existence of positive spatial autocorrelation; that is, the domestic growth rates of energy intensity tend to increase with foreign growth rates. These results are in line with Mulder et al. (2011), who also detect positive spatial autocorrelation for a shorter dataset of 109 countries between 1971 and 2001. Having said that, after we ran several regressions employing each significant spatial matrix, the best and chosen one for the β-convergence analysis in terms of data fitting was that of linear distances among all countries. Regarding the continental areas, the estimated significant Moran's I values are $\hat{I}:[0.044^{*}, 0.302^{***}]$ for Europe (asterisks are for levels of significance, where $*$ is for 10%, $**$ 5% and $***$ 1%), $\hat{I}:[0.097^{*}, 1.208^{***}]$ for America, and $\hat{I}:[0.121^{**}, 0.407^{***}]$ for Africa, with the best spatial weight matrices denoted by those of linear distances among all countries of the corresponding subset. In the case of Asia-Oceania, Moran's I ranges between $\hat{I}:[0.670^{***}, 0.948^{***}]$, and the best spatial weights matrix is that of relative development measured by the differences in the average levels of per capita income.

Table 4.2 presents the results of the both cross-sectional and panel data estimations of the speeds of convergence for both datasets and for each subset of countries. In the case of panel data estimations, we only employ time fixed effects when absolute convergence is tested. When conditional convergence is analysed, we only consider individual fixed effects, given that for a large and diverse set of countries, it is hard to justify the inclusion of common exogenous time effects. To avoid likely problems of endogeneity, at the same time we retain the shape of the steady state, the averages of the control variables are computed omitting the first and last values of the entire period or in the case of panel data estimations, the relevant sub-interval.

Commencing with the results for the world as a whole, we find strong evidence in favour of β-convergence, whether in terms of absolute or conditional convergence, and irrespective of the chosen dataset. Figure 4.5 also serves to reinforce this result, where the negative relationship between the average growth rates of energy intensity and time lagged energy intensity is quite obvious. At a lower level of aggregation, we only find robust estimations in favour of absolute and conditional β-convergence for Asia and Oceania as a joint group, considering both datasets, and for America only in the 173-country dataset. In the case of Europe and Africa, we only find strong support for β-convergence after controlling for country effects with panel data estimations.

Regarding the estimated speeds of convergence, we find five relevant patterns: first, when cross-sectional data are employed, the estimated speeds of convergence diminish when we move from absolute to conditional convergence; second, when panel data are used, the speeds of convergence increase as we shift from absolute to conditional convergence; third, changing from cross-sectional to panel data yields faster rates of conditional convergence; fourth, for regressions considering conditional convergence and explanatory variables, as we control more for spatial spillovers, the size of the estimated betas decrease; and fifth, for estimations of conditional convergence considering panel data, regressions only accounting for country fixed effects without control variables and spatial spillovers always lead to lower rates of convergence. The third point is a common finding in works of economic growth convergence (Islam, 1995; 2003; Barro and Sala-i-Martin, 2004), a consequence of controlling for the unobserved heterogeneity lying in productivity factors (Islam, 2003; Abreu et al., 2005), which determine each country's steady state towards which energy intensity levels are converging. In this sense Shioji (1997) proves how rates of convergence are no longer overestimated in panel data estimation when intervals are constructed for sufficiently larger periods of time, a solution that would require us to collect data from a larger span of time which is currently unavailable for the chosen set of countries and control variables.

According to Table 4.2, for the world as a whole and 173 countries, the statistically significant rates of convergence are in the interval $\hat{\beta} : [0.004^{***}, 0.036^{***}]$, where the lower limit corresponds to the absolute convergence with time fixed effects specification, and the upper limit comes from the panel data estimations with SLX and SDEM specifications. In the case of 130 countries, the interval changes to $\hat{\beta} : [0.003^{***}, 0.037^{***}]$, with the lower limit representing absolute convergence, and the upper limit for the panel data estimation of the SLX specification. A comparison with previous works is problematic due to differences in the chosen sample of countries as well as the studied time period. Nevertheless, employing a spatial autoregressive model and cross-sectional data, Mulder et al. (2011) find a significant speed of absolute convergence of $\hat{\beta} = 0.015$ for 109 countries between 1986 and 2001, which is similar to our results. Csereklyei et al. (2016) also find similar values for their cross-sectional $\hat{\beta} = 0.014$, and panel data estimations $\hat{\beta} = 0.040$

Model / Sum of Squared Residuals from Simulations	World	Europe	America	Asia-Oceania	Africa
Absolute Convergence (Cross section / 173)	0.065	0.014 (II)	0.006 (II)	0.118	0.185
Conditional Convergence (Cross section / 173)	0.024 (III)	0.246	0.006 (I)	0.047	0.016 (III)
Conditional Convergence SLX (Cross section / 173)	0.011 (II)	3.290	0.081	0.039 (III)	0.014 (I)
Conditional Convergence SDEM (Cross section / 173)	0.003 (I)	2.832	0.849	0.038 (II)	0.030
Absolute Convergence (Panel 5-year / 173)	0.074	0.207 (III)	0.042 (III)	0.113	0.015 (II)
Conditional Convergence No Control (Panel 5-year 173)	0.088	0.013 (I)	0.069	0.012 (I)	0.566
Conditional Convergence (Panel 5-year / 173)	0.382	1.004	0.077	0.682	0.198
Conditional Convergence SLX (Panel 5-year / 173)	0.271	0.491	0.078	0.582	0.225
Conditional Convergence SDEM (Panel 5-year / 173)	0.271	0.225	1.437	0.531	0.224
Absolute Convergence (Cross section / 130)	0.056	0.021 (II)	0.002 (II)	0.042 (III)	0.151
Conditional Convergence (Cross section / 130)	0.012 (III)	0.040	0.008 (III)	0.034 (I)	0.031 (III)
Conditional Convergence SLX (Cross section / 130)	0.007 (II)	11.430	7.124	2.318	0.115
Conditional Convergence SDEM (Cross section / 130)	0.005 (I)	6.595	14.144	1.397	0.031 (II)
Absolute Convergence (Panel 5-year / 130)	0.034	0.046	0.002 (I)	0.246	0.030 (I)
Conditional Convergence No Control (Panel 5-year 130)	0.036	0.019 (I)	0.175	0.097	0.474
Conditional Convergence (Panel 5-year / 130)	0.307	0.286	0.426	0.155	0.128
Conditional Convergence SLX (Panel 5-year / 130)	0.199	0.033 (III)	0.077	0.041 (II)	0.138
Conditional Convergence SDEM (Panel 5-year / 130)	0.233	0.042	0.039	0.047	0.131

Source: Elaborated by the authors. Simulations of standard deviations follow equation (10), employing speeds of convergence and coefficients of each control variable from estimated regressions. Variances for each control variable are assumed to be constant throughout time, which are measured as the sample variance of time average values of explanatory variables. Variance of the error term is approximated by the variance of residuals from beta-convergence regressions. (I), (II) and (III) refer to the three first least sums of squared residuals.

Table 4.3: Simulation Residuals.

for 99 countries during the period 1971-2010. Moreover, Liddle (2010) estimates a speed of convergence of $\hat{\beta} = 0.016$ for 134 countries between 1990 and 2006, while Mulder and de Groot (2012) detect a speed of convergence of $\hat{\beta} = 0.018$ for OECD countries between 1980 and 2005.

For continental subareas, we find the intervals of significant estimated speeds of convergence are as follows: $\hat{\beta} : [0.008^{**}, 0.123^{***}]$ for 36 European countries and $\hat{\beta} : [0.004^{**}, 0.049^{***}]$ for 33 European countries; $\hat{\beta} : [0.002^{**}, 0.036^{***}]$ for 34 American countries and $\hat{\beta} : [0.006^{*}, 0.051^{***}]$ for 23 American countries; $\hat{\beta} : [0.005^{***}, 0.052^{***}]$ for 54 Asian and Oceanian countries and $\hat{\beta} : [0.006^{***}, 0.047^{***}]$ for 36 Asian and Oceanian countries; and $\hat{\beta} : [0.004^{***}, 0.035^{***}]$ for 49 African countries and $\hat{\beta} : [0.002^{**}, 0.029^{***}]$ for 38 African countries. For comparison purposes, only Markandya et al. (2006) performed β-convergence estimations of energy intensity for one of these continental subareas. More precisely, they find that with respect to the EU15, the average rate of convergence for 12 transition countries of Central and Eastern Europe equals $\hat{\beta} = 0.79$, with a half-life of convergence of approximately one year, which is far higher than those obtained in our analysis. The reason might reside in the employed methodology, given that our study uses a neoclassical model and theirs use a non-microfounded approximation. Moreover, their data are for a reduced span of time of 11 years (1992-2002) and focused on transition countries; thus, their results are not comparable with ours.

Having said that, since we have already commented the existence of β-convergence is a necessary condition of σ-convergence, a non-biased estimation of β or the speed of convergence must therefore yield an accurate ex-post forecast on the evolution of standard deviations. Table 4.3 presents the sums of the squared residuals from each simulation or ex-post forecast respect to the real standard deviation. We again find three interesting patterns. First, for both datasets and almost all geographical areas, the cross-section estimations tend to yield the best simulations of the standard deviation of energy intensity. Second, we cannot detect a clear preference of spatial specifications over standard regressions, but for the world as whole the inclusion of spatial spillovers always lead to the first two best simulations. Third, the long dataset is the only sample that unequivocally favors the conditional β-convergence irrespective of the area. Moreover, after comparing results from Table 4.2 with Table 4.3 and those from the σ-convergence assessment, we can conclude there exists strong support to the existence of conditional β-convergence for the period 1990-2010 in all areas and samples except for America and Africa, where absolute convergence seems to be the most plausible situation in the short dataset and conditional specifications in the long dataset yields non-significant rates of convergence. Comparing the size of estimated betas for results with those of Subsection 4.4.1, we also find the estimated speeds of convergence tend to be a bit faster than those of the computed growth rates of standard deviations. For instance, the world as a whole presents speeds of convergence of 1.5/1.2% for the large and short datasets respectively, while their standard deviations decreased at rates 1.1/0.6%. These differences are not a proof of biased estimations, since according to (10), the growth rate of the standard deviation of energy intensity converges to zero as the size of the analyzed period of time increases, therefore $|g_\sigma| \leq |\beta|$.[10]

Assuming stable convergence rates, as well as standard deviations from control variables and residuals, we can expect that worldwide convergence in terms of energy productivity will halt around a standard deviation ranging between 0.197 and 0.276 with a half-life of convergence between 46 and 58 years. For the continental subareas, we should see in Europe convergence towards $\sigma^* = [0.147, 0.257]$ with half-life $\hat{H} = [28, 87]$; in Asia-Oceania $\sigma^* = [0.154, 0.202]$ with $\hat{H} = [25, 53]$; and in Africa $\sigma^* = [0.399, 0.500]$ with $\hat{H} = [116, 347]$. Therefore, worldwide convergence seems to be driven by Asia and Oceania, whether in terms of lower steady-state standard deviations or faster rates of convergence. In the case of America, as it was commented in Subsection 4.4.1, the large dataset including Caribbean economies shows a brief initial period of σ-convergence followed by 14 years of stagnation, and the short dataset shows σ-divergence for the last 10 years. This evidence, alongside results from Table 4.2 and 4.3, leads to rejection of convergence in energy intensity for this area, or at least, the large dataset seems to have reached the steady-state value of standard deviation in the natural logarithm of energy intensity.

Another important contribution of the present paper is the inclusion of several control variables capturing the steady state of economies and that have not yet been tested in the context of energy intensity convergence with a large dataset of countries. Due to space limitations, we will be focused on estimates from conditional β-convergence regressions that yield the best simulations. Table 4.4 and Table 4.5 present the best β-conditional estimations for the long and short datasets respectively. They show that domestic technical progress, approximated through per capita GDP growth gy, seems to be the most robust variable across regressions and samples. The estimated coefficient is always negative, as in Csereklyei et al. (2016), and ranges between -0.064 and -0.768, depending on the chosen regression. That is, faster domestic technical progress leads to further improvements in energy productivity. Nevertheless, this result does not allow us to distinguish whether this is due to gains in aggregate productivity throughout different industries across the economy, or due to an improvement in the quality of energy flows. In this sense, Voigt et al. (2014) show that sustained global decreases in energy intensity for 40 major economies between 1995 and 2007 were driven by more efficient industries in terms of energy consumption, which seems to support the first hypothesis on technical progress and energy intensity growth. Liddle (2012) also supports the idea of energy end-use improvements leading to reductions in energy intensity, but he also comments that electricity conversion (an improvement in the quality of energy supply) is a likely determinant of energy efficiency growth.

On the other hand, most of the remaining control variables tend not to be statistically significant across specifications. This problem also emerges in Mulder and de Groot

[10] Assuming steady states rather constant throughout time, the growth rate of the standard deviation of energy intensity can be read as $g_\sigma = -\frac{e^{-2\beta T}\left(\sigma^2_{\hat{E}0} - \frac{\sigma^2_a + \sigma^2_u}{1-e^{-2\beta}}\right)}{\sigma^2}\beta$, where $\lim_{T\to 0} g_\sigma = -\beta$ and $\lim_{T\to\infty} g_\sigma = 0$.

Determinants	**World (SDEM CS)**	**Europe (SDEM PD)**	**America (Conditional CS)**	**Asia/Oceania (SDEM CS)**	**Africa (SLX CS)**
lnEI (-1)	-0.013*** (-7.22)	-0.043*** (-9.25)	-0.012** (-2.41)	-0.018*** (-5.30)	-0.006 (-1.06)
gy	-0.402*** (-8.31)	-0.064** (-2.54)	-0.016 (-0.88)	-0.257** (-2.16)	-0.458*** (-4.26)
gL	-0.029 (-0.20)	0.302 (1.37)	-0.48 (-1.39)	0.162 (0.77)	0.420 (0.78)
lny	0.001 (0.06)	-0.010* (-1.99)	-0.005 (-1.16)	0.002* (1.94)	0.004 (0.79)
RE	-0.010 (-1.60)	-0.022 (-1.40)	-0.018 (-1.25)	-0.011 (-1.10)	-0.024 (-1.38)
SVC	-0.007 (-0.68)	-0.006 (-0.51)	-0.020 (-0.73)	-0.004 (-0.25)	0.011 (0.54)
Wgy	0.102 (1.21)	0.054 (1.29)		-2.710 (-0.67)	0.325 (1.09)
WgL	0.509*** (2.96)	0.399 (0.94)		-11.556 (-1.25)	-0.277 (-0.26)
Wlny	0.001 (0.38)	-0.006* (-1.84)		0.040 (1.31)	-0.002 (-0.64)
WRE	0.010 (1.38)	-0.063* (-1.76)		-0.097 (-0.33)	0.036 (1.44)
WSVC	0.019 (1.33)	0.008 (0.47)		0.222 (0.74)	0.013 (0.26)
lambda	0.220*** (2.82)	0.494*** (12.52)		0.990 (0.65)	
Obs.	173	144	34	54	49
R^2 (Adjusted)	0.584	0.780	0.231	0.490	0.561
σ^2	0.001	0.001	0.001	0.001	0.001
lnL	554.310	392.618	107.245	166.952	141.019
Speed of Convergence	0.015	0.098	0.013	0.022	0.006

Source: Elaborated by the authors. Speed of convergence follows the same formula as in the theoretical background (considering length of sub-intervals for panel data). Except for Asia-Oceania, all areas consider the spatial weight matrix of inverse linear distances. Asia-Oceania employ the relative-development spatial weight matrix. CS and PD are for cross-section and panel data estimations. t-statistics appear between brackets. ***, ** and * are for p-values lower than 1%, 5% and 10% respectively.

Table 4.4: Estimation Growth Rates Energy Intensity (173 countries).

Determinants	**World (SDEM CS)**	**Europe (SLX PD)**	**America (Conditional CS)**	**Asia/Oceania (Conditional CS)**	**Africa (SDEM CS)**
lnEI (-1)	-0.011*** (-5.40)	-0.028*** (-6.30)	-0.006* (-1.84)	-0.022*** (-3.51)	-0.004 (-0.93)
gy	-0.378*** (-4.71)	-0.096*** (3.94)	-0.421** (-2.78)	-0.273 (-1.54)	-0.768*** (-4.09)
gL	0.097 (0.47)	-0.157 (-0.93)	-1.116*** (-3.26)	-0.049 (-0.18)	0.570 (1.07)
lny	0.002 (1.59)	-0.012*** (-2.71)	-0.007 (-1.50)	-0.007 (-1.15)	0.002 (0.80)
RE	-0.007 (-1.01)	0.007 (0.54)	-0.004 (-0.39)	-0.018 (-1.19)	-0.037** (-2.16)
SVC	0.000 (0.00)	0.002 (0.27)	-0.049** (-2.27)	-0.028 (-0.78)	0.022 (0.66)
s	0.009 (0.36)	0.032*** (2.86)	-0.046 (-1.04)	0.088 (1.50)	-0.042 (-0.95)
delta	-0.073 (-0.58)	0.248* (1.80)	0.631** (2.82)	-0.282 (-1.04)	0.170 (0.53)
instquality	-0.004 (-0.33)	-0.015 (-1.63)	0.034 (1.51)	0.019 (0.55)	-0.024 (-0.83)
NX/Y	0.020 (1.28)	0.003 (0.41)	0.055** (2.79)	0.074* (1.72)	0.008 (0.24)
Wgy	0.118 (0.76)	-0.026 (-0.61)			-0.626 (-0.87)
WgL	0.197 (0.75)	0.092 (0.25)			-1.749 (-1.36)
Wlny	-0.001 (-0.32)	-0.006* (-1.74)			0.004 (0.48)
WRE	0.010 (1.25)	-0.013 (-0.45)			0.050* (1.94)
WSVC	-0.024 (-0.58)	0.016 (0.91)			0.056 (0.49)
Ws	-0.015 (-0.31)	0.009 (0.50)			-0.053 (-0.27)
Wdelta	-0.001 (-0.00)	0.253 (0.84)			-1.502 (-1.09)
Winstquality	0.026 (0.92)	0.019 (0.91)			0.076 (0.76)
W(NX/Y)	-0.036 (-1.09)	0.027 (1.30)			0.035 (0.31)
lambda	-0.287* (-1.90)				-0.753*** (-3.33)
Obs.	130	132	23	36	38
R^2 (Adjusted)	0.460	0.726	0.617	0.469	0.406
σ^2	0.001	0.001	0.001	0.001	0.001
lnL	423.146	392.723	93.447	103.037	127.045
Speed of Convergence	0.012	0.042	0.006	0.028	0.004

Source: Elaborated by the authors. Speed of convergence follows the same formula as in the theoretical background (considering length of sub-intervals for panel data). Except for Asia-Oceania, all areas consider the spatial weight matrix of inverse linear distances. Asia-Oceania employ the relative-development spatial weight matrix. CS and PD are for cross-section and panel data estimations. t-statistics appear between brackets. ***, ** and * are for p-values lower than 1%, 5% and 10% respectively.

Table 4.5: Estimation Growth Rates Energy Intensity (130 countries).

(2007), who find that most regressions point towards joint rejection of explanatory variables and a limited contribution of these variables to estimates when they are not jointly rejected. Must be said that, when we control for cross-country heterogeneity considering country fixed effects, many control variables emerge as significantly different than zero (see Table 4.8 and 4.9 in Appendix), but recall these specifications lead to worse ex-post forecasts and the estimated coefficients are more likely to capture the behavior of the business cycle given that fixed effects estimations are carried out for 5-year interval panel data, thus we cannot reject the null hypothesis of statistically insignificant explanatory variables except for the natural logarithm of lagged energy intensity $\ln EI(-1)$ and growth rates of per capita GDP gy. In addition, for the world as whole, the coefficient of spatial autocorrelation is significantly different than zero taking values $\hat{\lambda} : \{0.220^{***}, -0.287^{*}\}$ for the large and short datasets respectively. Therefore, worldwide estimations on energy intensity growth rates and implicit β-convergence rates are expected to improve after including new spatially lagged variables. Since local technical diffusion has been argued to be a major driver of energy productivity convergence within clubs of countries (Mielnik and Goldemberg, 2000; Miketa and Mulder, 2005; Ezcurra, 2007; Mulder and de Groot, 2007; Duro et al., 2010; Liddle, 2010; Voigt et al., 2014), variables such as the relative expenditure in R&D or the number of registered patents from neighbouring countries, which as far as we know are not currently available for a long set of countries, may control for significant worldwide spatial autocorrelation.

We now proceed to the last step of our analysis, where we construct a new dependent variable measuring for each country's relative distance to the mean $D_{it} = \frac{|\ln \hat{E}_{it} - \mu_t|}{\mu_t}$. Since the SDEM is the specification that nests the SLX and the OLS models, we present in Table 4.6 and Table 4.7 regressions for D_{it} subject to the control variables employed in the β-convergence regressions and the SDEM specification.[11] First of all, we find the SDEM regressions fits quite well the data, with adjusted coefficients of determination higher than 0.8 for all areas and samples. Moreover, the LR tests of joint significance do not reject the SDEM specification as the best model for most areas in the large sample and the world as whole in the short one, while continental subareas in the short dataset tend to favor the SLX specification with minimal differences respect to the SDEM regressions. Therefore, spatial spillovers are relevant in the process of energy intensity convergence, and it seems the inclusion of the spatially lagged variables from the short dataset are sufficient to control for spatial autocorrelation in most cases. However, this is not sufficient for the world as a whole, hence new spatially lagged variables must be considered to establish the causes behind worldwide convergence in energy intensity.

We find the most robust and significant variables explaining country differences in energy intensity across samples are the natural logarithm of per capita GDP lny, the share of renewables over aggregate energy consumption RE and the share of net exports over aggregate GDP NX/Y. The first variable, lny, measuring for the state of

[11] Markandya et al. (2006) take a similar approach by regressing estimated speeds of convergence respect to institutional variables.

Determinants	World	Europe	America	Asia/Oceania	Africa
gy	-0.072*** (-2.81)	-0.222*** (-4.05)	0.051 (0.69)	-0.167*** (-3.08)	0.008 (0.20)
gL	0.010 (0.06)	2.044*** (4.16)	0.547 (0.58)	0.768*** (3.31)	-1.877*** (-5.58)
lny	-0.093*** (-10.98)	-0.181*** (-9.69)	0.080*** (3.32)	-0.165*** (-8.86)	-0.016 (-1.17)
RE	-0.197*** (-7.74)	-0.001 (-0.01)	-0.269*** (-3.98)	-0.236*** (-5.31)	-0.140*** (-3.08)
SVC	0.022 (0.74)	0.335*** (5.50)	-0.185*** (-2.90)	-0.072 (-1.33)	0.182*** (3.20)
Wgy	-0.115*** (-3.10)	0.014 (0.41)	-0.139* (-1.80)	-0.195** (-2.15)	-0.008 (-0.14)
WgL	-0.030 (-0.12)	-0.450 (-0.81)	-3.769*** (-2.78)	-0.331 (-0.85)	-1.256** (-2.28)
Wlny	-0.041*** (-3.72)	0.044*** (3.85)	-0.020 (-0.98)	0.017 (0.73)	-0.075*** (-2.72)
WRE	0.027 (0.76)	-0.064 (-1.10)	0.251*** (2.77)	-0.150 (-1.50)	-0.114 (-1.61)
WSVC	-0.053 (-1.12)	-0.218*** (-3.77)	0.097 (0.78)	-0.226* (-1.87)	-0.243*** (-2.97)
lambda	0.143*** (7.942)	-0.119*** (-2.62)	0.087*** (3.09)	0.228*** (7.24)	-0.163*** (-3.20)
Obs.	3460	720	680	1080	980
R^2 (Adjusted)	0.847	0.838	0.895	0.867	0.803
σ^2	0.006	0.004	0.003	0.007	0.007
lnL	3781.001	980.154	945.941	1161.106	1025.663
LR SLX	58.278*** (p = 0.000)	5.059** (p = 0.024)	1.964 (p = 0.157)	8.948*** (p = 0.002)	7.091*** (p = 0.007)
LR SEM	32.718*** (p = 0.000)	25.981*** (p = 0.000)	30.743*** (p = 0.000)	19.312*** (p = 0.001)	23.471*** (p = 0.000)
LR OLS	94.334*** (p = 0.000)	25.771*** (p = 0.000)	65.430*** (p = 0.000)	34.153*** (p = 0.000)	29.981*** (p = 0.000)

Source: Elaborated by the authors. Except for Asia-Oceania, all areas consider the spatial weight matrix of inverse linear distances. Asia-Oceania employ the relative-development spatial weight matrix. t-statistics appear between brackets. ***, ** and * are for p-values lower than 1%, 5% and 10% respectively.

Table 4.6: Estimation Relative Distances (173 countries).

economic development of economies through aggregate productivity levels and capital deepening, shows a negative coefficient in all areas except for America, where economic development seems to be fostering energy productivity divergence. Since saving rates s are also significantly different than zero and positive for Europe, Asia-Oceania and Africa, which represent most of the world, it is very likely the negative impact of lny on worldwide differences is driven through accumulated technical progress, but not through accumulation of capital stock.

Regarding the share of renewable energy RE, we tend to find a strong negative correlation with respect to differences in energy intensity except for Europe. According to models of "*directed technical change*" (e.g. Acemoglu, 2002; Eriksson, 2018), substitution between inputs is governed by changes in relative prices directing technical improvements. Therefore, it seems that increases in stock of knowledge relative to renewable energy production is also promoting convergence for the world as whole. Alongside the estimated effects of lny and RE, we also find per capita GDP growth rates gy are significantly different than zero for the world as whole and Asia-Oceania, with an estimated negative sign, thus we may conclude the role of technical progress is crucial for closing the gap of energy productivity across countries, whether in terms of past improvements or new discoveries, especially among the Asian-Oceanian economies.

The role of the share of net exports NX/Y is also important for convergence in energy productivity, with significant and positive coefficients for all areas except for Asia and Oceania, which contradicts the results of Mulder and de Groot (2007) for OECD countries. That is, net importers reduce differences respect to the cross-country average due to technological adoption. The relationship between trade and technical diffusion has been previously proven for different samples of countries, justified through importation of more productive capital goods or imitation and acquisition of foreign patents (Xu and Chiang, 2005; Coe et al., 2009). In this sense, we also observe the spatial lag of saving rates Ws and relative net exports $W(NX/Y)$ are significantly different than zero and negative for the world as a whole and Asia-Oceania, while the spatial lag of per capita GDP growth rates Wgy is not robust across estimations, reinforcing the idea of foreign direct investment and trade in capital goods is the major driver of technical diffusion in terms of energy productivity.

Finally, we highlight the importance of average institutional quality for convergence in the world as a whole and Europe. We observe that domestic improvements in the set of constraints $instquality$, or more inclusive institutions, increases individual differences respect to average levels of energy intensity, while improvements in neighbouring countries $Winstquality$ drive convergence. The first result seems to be related to better domestic institutions fostering national capital deepening, as it is argued in models of growth and institutional quality (e.g. Acemoglu, 2005), and the relationship with capital accumulation and divergence in energy productivity as it has been already shown. The second result points towards the need of groups of neighbouring countries moving in the same direction through institutional mimicry or adoption to achieve convergent paths in energy intensity. This might be a consequence of better institutions leading to economic

Determinants	World	Europe	America	Asia/Oceania	Africa
gy	-0.081*** (-2.67)	0.004 (0.06)	0.040 (0.54)	-0.381*** (-5.76)	-0.065* (-1.68)
gL	-0.770*** (-4.51)	0.810* (1.85)	-0.818 (-0.71)	-0.281 (-1.11)	-1.851*** (-6.41)
lny	-0.135*** (-11.61)	-0.057** (-2.35)	0.067*** (2.77)	-0.150*** (-7.55)	-0.304*** (-16.81)
RE	-0.061** (-2.31)	0.167*** (2.84)	-0.177** (-2.39)	-0.101** (-2.02)	-0.119*** (-3.36)
SVC	0.195*** (5.77)	0.318*** (5.74)	-0.063 (-0.81)	0.128 (1.62)	-0.052 (-1.06)
s	0.044 (1.26)	0.205*** (3.01)	-0.121 (-1.27)	0.125** (2.03)	0.352*** (7.11)
delta	-0.318 (-0.99)	-0.725 (-0.88)	0.428 (0.68)	-1.411** (-1.99)	-3.656*** (-8.99)
instquality	0.057* (1.81)	0.113** (1.98)	-0.036 (-0.76)	-0.043 (-0.64)	0.012 (0.24)
NX/Y	0.050** (2.15)	0.207*** (4.24)	0.099* (1.84)	-0.050 (-1.23)	0.088** (2.44)
Wgy	-0.019 (-0.42)	-0.117** (-2.07)	0.163 (1.02)	-0.116 (-0.84)	0.056 (0.72)
WgL	-0.852*** (-2.66)	-0.402 (-0.58)	-4.493 (-1.43)	-0.858 (-1.58)	-0.165 (-0.35)
Wlny	0.092*** (5.91)	0.011 (0.47)	0.197*** (3.44)	0.384*** (7.22)	0.212*** (5.06)
WRE	-0.213*** (-4.58)	-0.208** (-2.43)	0.849*** (6.80)	0.367** (2.14)	-0.077 (-1.10)
WSVC	-0.277*** (-3.83)	-0.042 (-0.47)	0.460* (1.68)	-1.119*** (-5.23)	-0.101 (-0.94)
Ws	-0.290*** (-4.33)	-0.150 (-1.41)	0.131 (0.59)	-0.644*** (-4.03)	0.022 (0.16)
Wdelta	-0.999 (-1.37)	-0.614 (-0.41)	5.254*** (3.16)	-5.117*** (-2.58)	-1.171 (-1.19)
Winstquality	-0.132*** (-2.84)	-0.109* (-1.92)	-0.112 (-0.79)	-0.187 (-1.40)	-0.082 (-0.79)
W(NX/Y)	-0.187*** (-3.97)	0.067 (0.71)	-0.020 (-0.14)	-0.361*** (-4.02)	0.061 (0.75)
lambda	0.121*** (5.65)	0.048 (1.23)	-0.065 (-0.75)	-0.117 (-1.58)	-0.105* (-1.68)
Obs.	2600	660	460	720	760
R^2 (Adjusted)	0.859	0.883	0.937	0.811	0.967
σ^2	0.005	0.002	0.002	0.005	0.003
lnL	3292.448	1028.059	775.795	907.975	1052.135
LR SLX	16.666*** (p = 0.000)	-0.084 (p = 0.999)	-0.217 (p = 0.999)	1.015 (p = 0.314)	0.866 (p = 0.352)
LR SEM	76.422*** (p = 0.000)	47.847*** (p = 0.000)	59.620*** (p = 0.000)	77.603*** (p = 0.000)	45.262*** (p = 0.000)
LR OLS	85.198*** (p = 0.000)	48.607*** (p = 0.000)	70.402*** (p = 0.000)	81.68*** (p = 0.000)	49.946*** (p = 0.000)

Source: Elaborated by the authors. Except for Asia-Oceania, all areas consider the spatial weight matrix of inverse linear distances. Asia-Oceania employ the relative-development spatial weight matrix. t-statistics appear between brackets. ***, ** and * are for p-values lower than 1%, 5% and 10% respectively.

Table 4.7: Estimation Relative Distances (130 countries).

convergence (Knack, 1996). Moreover, our results are similar to those of Markandya et al. (2006), where the adoption of Western and Central European institutions by Eastern European transitioning countries tend to increase the speed of convergence in energy intensity.

4.5 Conclusions and policy implications

We analysed the convergence of cross-country energy intensity over the period 1990–2010 for two samples of 130 and 173 countries, considering four continental subdivisions and spatial spillovers. In addition, we proposed a simple theoretical model that justifies the relationship between β-convergence in energy intensity and steady states of economies, as well as studied the likely determinants of individual deviations with respect to the cross-country mean in terms of energy intensity. The hypothesis of convergence is tested through two approaches: a nonparametric assessment of kernel density estimators and cross-sectional as well as panel data estimations of different β-convergence specifications. The σ-convergence analysis studies the time evolution of standard deviations and estimated kernel density functions. β-convergence regressions are carried out for OLS, fixed effects, spatial lag of X and spatial Durbin error models, employing a large set of explanatory variables. We also regress on cross-country deviations in energy intensity with respect to the mean considering the same control variables and spatial correlation; thus, we can test for the approximate determinants of convergence in energy intensity.

The results can be summarized as follows:

i) Worldwide differences in energy productivity diminished between 1990 and 2010, moving towards lower average levels of energy intensity. According to estimations of kernel density functions for different continental areas, the trend is marked by movements towards unimodal distributions, thus we cannot reject from a descriptive perspective the existence of absolute convergence.

ii) Depending on the sample, the worldwide average levels of energy intensity have only decreased by 1.58% and 1.35% for the entire period, while the mode diminished by 0.6%. If this trend persists, the average energy intensity will be halved only after 2055. If there is no fast shift from fossil to alternative and nonpolluting fuels, global energy policies must toughen to tackle climate change through energy productivity.

iii) σ-convergence has been mainly led by European and Asian-Oceanian countries, with observed convergence rates ranging between 1% and 2% depending on the area and the sample. Additionally, the European convergence process has been marked by sustained reductions in average and most frequent values of energy intensity, while the Asian-Oceanian path has presented a worsening in energy productivity.

iv) In the cases of America and Africa, divergent or practically nonconvergent paths have been observed. Moreover, the elasticity of the worldwide standard deviation in energy intensity with respect to deviations in those areas increased during the period. Therefore, worldwide convergence could be reverted in the future if Africa and America continue to follow divergent paths.

v) According to the estimations of β-convergence and under the criterion of best ex-post predictors of standard deviations, the results tend to support the existence of conditional β-convergence favouring cross-sectional before panel data. However, most control variables tend to be statistically insignificant and nonrobust across regressions and geographical areas. In this sense, we have only found the domestic average growth rate of per capita GDP (a proxy for long-term technical progress) as the more stable and significant variable of control presenting a negative coefficient. Moreover, Africa is the most sensitive area with respect to changes in domestic technical progress.

vi) Regressions on country differences in energy intensity with respect to the same control variables point towards three major drivers of convergence: domestic technical progress, technical diffusion and diffusion of better institutional quality. The impact of domestic technical progress is mainly explained by changes in the natural logarithm of per capita GDP and the share of renewable energy, while the impact of technical diffusion by the share of net exports respect with aggregate GDP, where net importers reduce their gap with respect the cross-country mean of energy intensity. Finally, diffusion and adoption of better institutional quality by clusters of neighbouring countries is only relevant for the world as a whole and Europe, hence it seems this variable is closely related to processes of economic integration such as the European Union.

Based on these conclusions, we suggest the following policy recommendations. First, domestic public intervention supporting faster technical progress through R&D subsidies and low taxation on innovative firms is mandatory for fast convergence and improvements in worldwide energy intensity levels. Moreover, technical progress directed to faster transitions to production based on renewable energy consumption will lead not only to worldwide reductions in differences in energy productivity, but also to more sustainable paths of growth in terms of CO_2 emissions. Second, a deeper world economic integration fostering technology imitation and adoption must be carried out by means of larger international patent markets, increased foreign direct investment from energy-efficient firms and international trade prioritising the exchange of energy-saving capital goods. Third, the adoption of more inclusive or efficient institutions by clubs of neighbouring countries, similar to the process of political integration of the European Union, must be supported to accelerate worldwide convergence in energy productivity. Furthermore, if technical progress is proven to be positively correlated with levels of institutional quality, the worldwide adoption of more inclusive institutions should indirectly accelerate the transition to more energy-efficient domestic economies.

Determinants	World (SDEM PD)	Europe (SDEM CS)	America (Conditional PD)	Asia/Oceania (SDEM PD)	Africa (SLX PD)
lnEI (-1)	-0.026*** (-14.29)	-0.004 (-1.62)	-0.020*** (-5.48)	-0.031*** (-7.10)	-0.019*** (-6.48)
gy	-0.099*** (-10.43)	-0.596*** (-8.56)	-0.050** (-2.24)	-0.086*** (-5.28)	-0.143*** (-12.11)
gL	-0.129*** (-2.91)	0.854*** (3.67)	0.058 (0.30)	-0.167** (-2.42)	-0.108 (-1.53)
lny	-0.009*** (-4.68)	-0.006*** (-3.96)	-0.003 (-1.30)	-0.020*** (-4.93)	-0.007*** (-2.63)
RE	-0.010* (-1.84)	0.046*** (6.56)	0.005 (0.58)	-0.032** (-2.39)	-0.016** (-2.16)
SVC	-0.003 (-0.65)	0.092*** (4.48)	-0.001 (-0.20)	-0.019 (-1.46)	-0.013 (-1.49)
Wgy	0.002 (0.23)	0.798*** (4.16)		0.133 (0.43)	-0.025 (-1.36)
WgL	-0.001 (-0.02)	0.608 (1.13)		-9.373* (-1.82)	0.013 (0.11)
Wlny	-0.003 (-1.46)	-0.012*** (-2.84)		0.054 (0.71)	0.004 (0.82)
WRE	-0.018** (-2.36)	0.006 (0.29)		0.231 (0.63)	-0.005 (-0.44)
WSVC	-0.008 (-0.92)	0.147** (2.48)		-0.203 (-0.89)	-0.033** (-2.32)
lambda	-0.014 (-0.352)	-0.337 (-1.47)		0.989 (1.31)	
Obs.	692	36	136	216	196
R^2 (Adjusted)	0.628	0.901	0.454	0.557	0.750
σ^2	0.001	0.001	0.001	0.001	0.001
lnL	1606.286	149.735	369.631	471.683	463.056
Speed of Convergence	0.036	0.003	0.026	0.050	0.023

Source: Elaborated by the authors. Speed of convergence follows the same formula as in the theoretical background (considering length of sub-intervals for panel data). Except for Asia-Oceania, all areas consider the spatial weight matrix of inverse linear distances. Asia-Oceania employ the relative-development spatial weight matrix. CS and PD are for cross-section and panel data estimations. t-statistics appear between brackets. ***, ** and * are for p-values lower than 1%, 5% and 10% respectively.

Table 4.8: Estimated Betas.

Determinants	World (SDEM PD)	Europe (SLX CS)	America (Conditional PD)	Asia/Oceania (Conditional PD)	Africa (SDEM PD)
lnEI (-1)	-0.026*** (-11.53)	-0.003 (-0.92)	-0.030*** (-6.38)	-0.030*** (-7.20)	-0.014*** (-3.19)
gy	-0.072*** (-7.81)	-0.715*** (-3.81)	-0.047** (-2.05)	0.008 (0.47)	-0.135*** (-8.74)
gL	-0.175*** (-3.62)	1.592** (2.21)	0.154 (0.66)	-0.270*** (-4.11)	-0.124 (-1.40)
lny	-0.013*** (-5.36)	-0.011 (-0.69)	-0.015*** (-3.79)	-0.013*** (-3.70)	-0.013** (-2.48)
RE	-0.005 (-0.92)	0.065*** (3.24)	-0.002 (-0.18)	-0.046*** (-3.12)	-0.015* (-1.73)
SVC	-0.014** (-2.19)	0.105 (1.70)	-0.012 (-0.84)	-0.081*** (-5.13)	-0.009 (-0.85)
s	0.030*** (4.14)	-0.013 (-0.16)	0.085*** (3.73)	0.020* (1.67)	0.022* (1.88)
delta	-0.162** (-2.55)	-0.023 (-0.05)	0.311*** (2.94)	-0.479*** (-3.82)	-0.192** (-2.04)
instquality	-0.000 (-0.03)	-0.012 (-0.35)	0.002 (0.24)	0.002 (0.16)	-0.000 (-0.01)
NX/Y	0.013*** (2.58)	-0.032 (-0.82)	0.017* (1.67)	0.017** (2.06)	0.013 (1.36)
Wgy	-0.002 (-0.20)	1.211** (2.24)			-0.001 (-0.05)
WgL	-0.040 (-0.50)	2.204 (1.35)			-0.046 (-0.34)
Wlny	0.002 (1.16)	-0.027 (-1.46)			-0.002 (-0.20)
WRE	0.002 (0.33)	0.077 (1.29)			-0.009 (-0.55)
WSVC	-0.011 (-0.87)	0.253 (1.36)			-0.045* (-1.74)
Ws	-0.026*** (-2.67)	0.010 (0.04)			0.035 (0.95)
Wdelta	0.261** (2.16)	0.295 (0.18)			0.014 (0.05)
Winstquality	-0.002 (-0.30)	0.080 (0.72)			-0.025 (-0.89)
W(NX/Y)	-0.007 (-0.91)	-0.195 (-1.29)			-0.009 (-0.35)
lambda	-0.212*** (-2.88)				-0.189 (-1.33)
Obs.	520	33	92	144	152
R^2 (Adjusted)	0.610	0.784	0.546	0.619	0.759
σ^2	0.001	0.001	0.001	0.001	0.001
lnL	1296.306	132.402	274.437	352.832	380.097
Speed of Convergence	0.037	0.003	0.047	0.047	0.016

Source: Elaborated by the authors. Speed of convergence follows the same formula as in the theoretical background (considering length of sub-intervals for panel data). Except for Asia-Oceania, all areas consider the spatial weight matrix of inverse linear distances. Asia-Oceania employ the relative-development spatial weight matrix. CS and PD are for cross-section and panel data estimations. t-statistics appear between brackets. ***, ** and * are for p-values lower than 1%, 5% and 10% respectively.

Table 4.9: Estimated Betas.

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5 The Role of Institutional Efficiency in Energy Intensity and the Climate Change: An Endogenous Growth Model

5.1 Introduction

Paths for decarbonized economies with no losses in overall welfare and unchanged consumption patterns require fast and selective technical progress, that is, improvements in energy efficiency levels, cheaper non-polluting energy sources, and better systems for carbon capture and storage. Empirical data from the last 30 years point towards energy efficiency as the most significant and successful factor, with worldwide energy intensity levels decreasing at an average rate of 1.3% during 1990-2012, while the share of renewable energy consumption has remained at approximately 17.5% for the same period, only showing a positive trend from 2007 onwards at a rate of 0.7% (elabourated by the authors with data from the WDI database (World Bank, 2021)). Therefore, further efforts to understand the linkages between economic activities and pollution are required to achieve net-zero emissions in 2050.

Regarding energy efficiency and shifts in the energy mix, we must focus on what shapes, drives, and constrains technical progress. Seminal works such as North (1991) and North and Weingast (1989) posed economic and political institutions[12] as crucial determinants for long-term economic growth. Progressively, economic growth theories integrated this vision, leading to endogenous technical change models where incentives for private research and development (R&D) activities played the main role in determining the rate of arrival and direction of innovations (e.g. Romer, 1990; Aghion and Howitt, 1992; Acemoglu, 2002). Acemoglu and Robinson (2019) define inclusive economic institutions as those rules “which create broad-based economic incentives and opportunities" and foster static and dynamic economic efficiency. The authors also pose, as North and Weingast (1989) and North (1991) do, that political institutions define formal economic institutions, such as secure property rights. Moreover, inclusive political institutions understood as those humanly devised constraints that lead to a “broad distribution of political power and a strong (or effective or capable) state", are required for the emergence of inclusive economic institutions and thus more efficient economic growth.

A recent strand of both theoretical and empirical literature has shown an increasing interest in how institutions shape climate change through economic variables. Mu (2018), for instance, studies how Chinese political institutions determine economic institutions related to environmental policies. The author poses that the 1989 environmental target policy (ETP) for pollution control has required several updates to be rather effective due

[12] For institutions, we refer to “humanly devised constraints that structure political, economic and social interaction. (...) Institutions provide the incentive structure of an economy; as that structure evolves, it shapes the direction of economic change towards growth, stagnation, or decline." (North, 1991).

to three major political institutions constraining Chinese economic policies: fiscal semi-decentralization, administrative semi-authoritarianism, and a political personnel system. Works such as Cheng et al. (2020) show the emergence of an inverted-U curve between fiscal decentralization and CO_2 emissions in China. Additionally, Khan et al. (2021) propose that this relationship is reinforced with institutional quality indexes containing other institutions, such as corruption control or the effectiveness of government.

Having said that, economic modelling is absent considering endogenous economic institutions in the environment-growth nexus. Some recent works, such as Riekhof et al. (2019), have introduced the role of exogenous economic institutions in determining property rules over natural resources and their influence on sustainable exploitation and fast economic growth. However, they lack an endogenous mechanism determining the shift between both regimes due to political conflict between population subsets, which leaves a gap that must be filled for accurate forecasts and effective policy-making. This is one of the major tasks of the present model: First, we seek to set a general and tractable framework based on the Neoclassical-Schumpeterian approach to make explicit market determinants for a clean energy transition and improvements in energy intensity levels. Second, we want to extend this model considering the role of political and economic institutions in shaping the incentives mentioned above for sustainable economic growth. The endogenization of economic institutions through political struggles and excessive pollution levels will improve the analytical quality of the present model, and yield more realistic simulations.

Besides this, and in contrast to previous works, our model will allow for two ways to attain a successful clean energy transition, which will depend on the relative R&D expenditure devoted to each type of technique: one led by relatively faster improvements in quality levels of polluting energy sources, which in exchange increase marginal costs of polluting energy production; and one led by more efficient forms of capital and labour transformation into clean energy, which decreases marginal costs of its production. Therefore, our model extends the idea of “directed technical change" models (see Acemoglu (2002) for the standard model, and Aghion and Howitt (2008), Acemoglu et al. (2012) or Eriksson (2018) for its application to the environmental issue) from substitution between the elected sector where research is devoted to, to substitution in the type of technique researched for a given sector. As Acemoglu (2008) points out, and as our model will reflect, the simultaneous inclusion of quality- and process-improving techniques is expected to be redundant to explain long-term growth. However, our model will show the importance of their inclusion since this will allow for integration of different paths of evolution in intermediate goods production, such as energy production, inside a general equilibrium model without incurring in unbalanced growth paths.

The rest of the study is structured as follows. Section 5.2 reviews the relevant literature. Section 5.3 details the base economic model. Section 5.4 analyses conditions for sustainable growth. Section 5.5 extends the base model with political and economic institutions and analyses their impact on sustainable growth. Section 5.6 presents simulations of the complete model. Finally, section 5.7 presents the conclusions and policy implications.

5.2 Literature Review: Energy-growth nexus

Despite important advances in growth theory, the role of energy on gross output and long-term wealth has been largely ignored by the mainstream approach (Stern and Cleveland, 2004; Stern, 2011). This is an important flaw of contemporaneous growth theory, given the present concern about accelerated climate change, which is practically a consequence of fossil fuel consumption. Starting with Tahvonen and Salo (2001), their model aligns with the learning-by-doing growth models, ignoring the importance of profit-maximizing actions for technological progress. Another problem that can be observed is the nonrivalry in the use of capital for final production and renewable energy production, assuming then that capital stock is also a positive externality for energy production. Other models cannot harmonize the coexistence between endogenous accumulation processes and energy production, ignoring individual actions, such as saving, which are crucial understanding the growth process (Smulders and de Nooij, 2003; Fröling, 2011). Nevertheless, although Smulders and de Nooji (2003) consider technical progress as a consequence of R&D investments, strong assumptions are made since they assume primary inputs, such as labour or natural resources, as exogenously given. However, they present a coherent transition from one type of technology to another: for initial scarcity in energy resources, agents prefer to invest in energy-related technologies. As energy per capita grows, preferences start to shift to other sources of income. On the other hand, Fröling (2011) returns to the classical dyad of labour and land augmented with energy services, considering capital stock as exogenously given and constant, representing a serious drawback. Moreover, the author models energy production as a byproduct of fixed amounts of labour, an assumption the author considers an oversimplification.

Subsequent works fall again into the trap of considering energy as exogenously given (Stern and Kander, 2012; Kander and Stern, 2014). Moreover, they keep treating energy, or those raw materials that produced it, as primary inputs completely detached from capital stock. Additionally, they do not take an endogenous viewpoint for long-term growth, leaving aside important links between technical progress and resource scarcity/abundance for energy production. Therefore, their models leave several important variables to unexplained dynamics, ignoring the relevance of individual decisions such as saving decisions and market mechanisms in the growth-energy issue. These works, such as those of Barreto (2018) and Eriksson (2018), mainly focus on energy transitions. More precisely, Eriksson (2018) takes a more sophisticated approach thanks to the consideration of endogenous mechanisms of technical progress, combining both learning-by-doing and decreasing returns to scale research labour. In addition, all inputs, aside from labour, are produced by investing part of the gross output. Nevertheless, this work does not depict a realistic relationship between energy and GDP since the balanced growth path is characterized by a constant decreasing trend. Moreover, this is a consequence of public intervention rather than free-market results since it creates social disutility. In Barreto (2018), technological growth rates are again treated as exogenously given; thus, although the model successfully explains energy shifts via relative rental prices of capital and resource scarcity, it does not explain the long-term relationship between energy and growth or the evolution of energy intensity. To the best of our knowledge, only Van Zon and Yetkiner (2003) have introduced an explicit energy-saving technique in an endogenous growth model *à la Romer*. Nevertheless, although their approach allows for endogenous increases in productivity of intermediate production, the general equilibrium solution of the model for both aggregate output and energy production relies on exogenous energy prices, which represents a downside. In contrast, our model will endogenize energy prices and explain different paths of long-term evolution in energy intensity levels due to differences in sector and technique R&D efforts.

In summary, i) most of the previous models are focused on resource extraction for energy production and depend on exogenous technical progress; ii) none of these models has already consider the existence of two types of cohabiting techniques measuring for quality and process-improving innovations, which may lead to misconceptions on the driving forces behind paths for a clean energy transition or improvements in energy intensity levels; iii) the role of different political and economic institutions is widely ignored in models relating energy and economic growth. Moreover, there has been no attempt to endogenize the emergence of different economic institutions constrained to climate change.

5.3 Base model

We consider a dynamic model of a closed economy without public intervention. The production structure and technical system of the economy are mainly based on those of Aghion and Howitt (1998, 2008, 2017), Howitt and Aghion (1998) and Howitt (2000), where economies grow endogenously due to a “creative-destructive" process. That is, creators of better batches of goods expel former producers and seize extraordinary rents. Conversely, our model will not only allow for purposeful upgrades on output quality entailing higher marginal costs. Instead, innovators can also be focused on reducing marginal costs thanks to better production techniques related to more efficient combinations of the existing inputs. We extend their model to include more than one intermediate productive phase, considering the role of energy as an essential and reproducible input, as in Van Zon and Yetkiner (2003), Eriksson (2018) and Barreto (2018). Moreover, our model augments the aforementioned models by allowing different degrees of market competition in the intermediate stages of production: monopoly, dominant firm and perfect competition.

The productive process of the representative economy presents three stages: i) The production of the final good uses labour and manufactured goods. ii) Manufactured goods are produced employing labour, machines, and energy flows. iii) Machinery and energy producers require of labour and capital stock. Final output can be used for consumption, investment in capital stock and investment in R&D. The economy is inhabited by a representative household with L members who inelastically supply one unit of labour each. They also own assets, rent capital to firms and obtain utility from consumption and disutility for every unit of stocked pollution. Time t is assumed to be continuous.

5.3.1 Preferences and production technologies

Final output production Y requires L_Y workers with exogenous productivity factor A_L. Final producers do not possess any technique or specific recipe for production, thus they always operate under perfect competition. An array of manufacturing goods X, indexed by $i \in 1, 2, ..., N$, are also needed for final goods production, which comes with quality level A_X. The number of varieties in manufacturing goods N is exogenously given, as in Acemoglu and Ventura (2002) and Riekhof et al. (2019). The production function of final output takes the product-variety form of Ethier (1982), as in works such as Romer (1990), Smulders and de Nooij (2003) and Van Zon and Yetkiner (2003)

$$Y(t) = \big(A_L(t) L_Y(t)\big)^{1-\eta} \sum_{i=1}^{N} A_X(t,i) X(t,i)^{\eta} \tag{5.1}$$

with $0 < \eta < 1$ for constant returns to scale in both inputs.

Similar to Van Zon and Yetkiner (2003) and Eriksson (2018), each intermediate good i employs machines Z and energy flows E. In addition, we also consider the need for effective labour services L_X weighed by their productivity factor A_L. This constant returns to scale function equals

$$X(t,i) = \frac{T_X(t,i)}{A_X(t,i)} \big(A_L(t) L_X(t,i)\big)^{1-\varsigma-\xi} A_Z(t,i) Z(t,i)^{\varsigma} A_E(t,i) E(t,i)^{\xi} \tag{5.2}$$

where $0 < \varsigma + \xi < 1$. According to (5.2), marginal costs of manufactured goods are increasing in their quality levels A_X, as in Aghion and Howitt (1998), Howitt and Aghion (1998) and Howitt (2000), which can be endogenously generated by entrant manufacturers. Additionally, both machines and energy flows also come with quality levels A_Z and A_E, which are perceived by the i manufacturer as exogenously given, while T_X can be improved by manufacturers and measures the quality of production processes that are not contained in the aforementioned input qualities (e.g., improvements in firm organization). Therefore, both input qualities $\{A_Z, A_E\}$, and process quality T_X result in lower marginal costs for the manufacturer, and each output quality A_X increases marginal costs but leads to increases in demand of the i manufactured good.

Contrary to gross labour productivity A_L, the quality of intermediate goods A_v and process techniques T_v -where $v : X, Z, E$-, present different degrees of appropriability. Regarding quality-improving techniques, a successful innovator creating a new batch of a v intermediate good in a given i line of production $A_v(i)' > A_v(i)$, becomes the monopolist of the supply of that intermediate good in the aforementioned line of production for $\tilde{t} > 0$ periods, which is the time required to fully imitate the new quality at zero cost and is exogenously given. For the sake of simplicity, assume $\tilde{t} = t + dt$, where t is the instant of time when the new quality was discovered. That is, the exclusive use of innovation in A'_v only lasts the next period after discovery.

On the other hand, improvements in T_v after $t' > \tilde{t}$ periods -that is, after any individual in the economy can perfectly imitate the best quality associated to the v intermediate in line i-, can be copied according to exogenous technical diffusion rates $\psi_v \in (0,1]$, whose values can be explained by the existing system of property rights and represents an economic institution. From now on, $\psi_v T_v$ represents the size of the leading process technique that has been successfully copied at zero cost, and the existing gap in terms of marginal costs will equal $MC_{vF} - MC_v = \left(\frac{1}{\psi_v} - 1\right) MC_v$, where F is for follower. All intermediate techniques will grow due to intentional R&D expenditure, as it will be explained in the subsection devoted to innovation.

Machines Z and energy flows E consumed by the i manufactured good are produced combining labour and capital stock as in (5.2)

$$Z(t,i) = \frac{T_{A_Z}(t,i)}{A_Z(t,i)} \left(A_L(t) L_Z(t,i)\right)^{1-\varrho} K_Z(t,i)^{\varrho} \tag{5.3}$$

$$E(t,i) = \frac{T_{A_E}(t,i)}{A_E(t,i)} \left(A_L(t) L_E(t,i)\right)^{1-\chi} K_E(t,i)^{\chi} \tag{5.4}$$

with $0 < \varrho < 1$ and $0 < \chi < 1$. According to (5.3), L_Z and K_Z measure raw labour and capital stock devoted to machinery production respectively. L_E and K_E will therefore measure the same inputs for energy production. T_Z and T_E are specific process techniques whose improvements lead to lower marginal costs producing machines or energy flows. As for manufacturing techniques, these can be copied at rates ψ_Z and ψ_E respectively.

Households have preferences over consumption described by

$$U = \int_0^{\infty} e^{-\rho t} \frac{\left[\kappa(t) C(t)\right]^{1-\theta_C} - 1}{1-\theta_C} dt \tag{5.5}$$

where $\rho > 0$ is the time discount factor, θ_C is the elasticity of intertemporal substitution of consumption, and κ is the impact factor of pollution stock $Q(t)$ on gross consumption, which fulfils $\lim \kappa_{Q \to Q^*} = 0$ for pollution stock close to the collapse level Q^*, and $\lim \kappa_{Q \to 0} = 1$ for null pollution. Similar to Acemoglu et al. (2012), we assume the specific form

$$\kappa(t) = \frac{\left(Q^* - Q(t)\right)^{\theta_Q} - \theta_Q \left(Q^*\right)^{\theta_Q - 1} \left(Q^* - Q(t)\right)}{\left(1-\theta_Q\right)\left(Q^*\right)^{\theta_Q}} \tag{5.6}$$

5.3.2 Optimal production choices

Since final output producers operate under perfect competition, and taking Y as the numeraire good, maximization of profits imposes that prices of each manufacturing good p_X and salaries w_Y equal their marginal product, that is,

$$p_X(t,i) = \eta \frac{Y(t,i)}{X(t,i)} \tag{5.7}$$

$$w_Y(t) = (1-\eta)\frac{Y(t)}{L_Y(t)} \tag{5.8}$$

We take the quantity-setting dominant firm framework (Tasnádi, 2010) as the general environment for intermediate producers, a type of market competition that has been previously used in works such as Nakov and Nuño (2013). That is, there is a share $\sigma_v(\psi_v) \in [0,1]$ of demanded intermediate goods v, which are supplied by follower firms with imitated process technique $\psi_v T_v < T_v$ under perfect competition, while the residual demand $(1-\sigma_v(\psi_v))v$ is provided by the leader firm acting as a supplier with market power. This model works very similarly to an oligopoly with quantity leadership *á la Stackelberg* (Varian, 1992). Moreover, Tasnádi (2010) proves that for a sufficiently large number of competitive firms, the equilibrium converges to that of a price-setting dominant firm model.

5.3.2.1 Lemma 1: For $0 < \sigma_v(\psi_v) < 1$, equilibrium prices of every intermediate output must equal marginal costs of the competitive fringe, that is $p_v(t,i) = \frac{1}{\psi_v} MC_v(t,i)$ (Proof in Appendix).

Setting direct demand of the i manufacture as $\sigma_X X$ for the follower fringe, where firms maximize their profits taking prices as exogenously given, and $(1-\sigma_X)X$ for the leader firm, which maximizes profits considering that the price of manufacture i is controllable, yields aggregate inverse demands for manufacturing labour L_X, machines Z, and energy E (use (5.1), (5.2) and (5.7))

$$p_Z(t,i) = \psi_X \varsigma \eta \frac{Y(t,i)}{Z(t,i)} \tag{5.9}$$

$$p_E(t,i) = \psi_X \xi \eta \frac{Y(t,i)}{E(t,i)} \tag{5.10}$$

$$w_X(t) = \psi_X(1-\varsigma-\xi)\eta \frac{Y(t,i)}{L_X(t,i)} \tag{5.11}$$

Repeating the same process for machinery and energy markets, and taking into account (5.1)-(5.4), (5.7), (5.9) and (5.10), yields

$$R_Z(t) = \psi_Z \psi_X \varrho \varsigma \eta \frac{Y(t,i)}{K_Z(t,i)} \tag{5.12}$$

$$R_E(t) = \psi_E \psi_X \chi \xi \eta \frac{Y(t,i)}{K_E(t,i)} \tag{5.13}$$

$$w_Z(t) = \psi_Z \psi_X (1-\varrho)\varsigma \eta \frac{Y(t,i)}{L_Z(t,i)} \tag{5.14}$$

$$w_E(t) = \psi_E \psi_X (1-\chi)\xi\eta \frac{Y(t,i)}{L_E(t,i)} \tag{5.15}$$

where $\psi_X \in [\eta, 1]$, $\psi_Z \in [\eta\varsigma, 1]$ and $\psi_E \in [\eta\xi, 1]$. Therefore, equilibrium prices diminish as technical diffusion rates fall, showing the negative effect of input demand dominated by firms with market power, which maximize their profits by hiring inputs at a cost lower than their marginal product.

Primary inputs in the economy are capital stock K_t and labour L_t. The aggregate demand of each factor is constrained to

$$\sum_{i=1}^{N} K_Z(t,i) + \sum_{i=1}^{N} K_E(t,i) \leq K(t) \tag{5.16}$$

$$L_Y(t) + \sum_{i=1}^{N} L_X(t,i) + \sum_{i=1}^{N} L_Z(t,i) + \sum_{i=1}^{N} L_E(t,i) \leq L(t) \tag{5.17}$$

Now, set $\varepsilon \in (0,1)$ as the capital share used in the production of energy flows, and $\{\mu_X, \mu_Z, \mu_E\} \in (0,1)$ as the shares of labour devoted to each intermediate stage of production. Using the inverse demands (5.7)-(5.15) in (5.1), (5.2), (5.3) and (5.4) leads to stylized production functions

$$Y(t) = B_Y \left(A_{L_Y}(t) L(t)\right)^{1-\alpha} K(t)^{\alpha} \tag{5.18}$$

$$X(t,i) = a_{L_Y}(t,i) B_X \left(A_{L_X}(t,i) L(t)\right)^{1-\beta} K(t)^{\beta} \tag{5.19}$$

$$Z(t,i) = a_{L_Y}(t,i) B_Z \left(A_{L_Z}(t,i) L(t)\right)^{1-\varrho} K(t)^{\varrho} \tag{5.20}$$

$$E(t,i) = a_{L_Y}(t,i) B_E \left(A_{L_E}(t,i) L(t)\right)^{1-\chi} K(t)^{\chi} \tag{5.21}$$

where $\alpha = \eta\beta$ and $\beta = \varsigma\varrho + \xi\chi$. Similar to Howitt (2000), $a_{L_Y}(i) = A_{L_Y}(i)/A_{L_Y}$ represents the effective labour productivity of the i manufactured good relative to the final output of effective labour productivity, which also measures the share of final output from line of production i with respect to the aggregate final output $a_{L_Y}(i) = Y(i)/Y$. This ratio remains constant in the long term as growth rates converge to the same value $\dot{A}_{L_Y}/A_{L_Y}(i) = g_c$. Effective labour productivity for final output production equals

$$A_{L_Y}(t) = A_L(t) \left(\sum_{i=1}^{N} \left[A(t,i) T(t,i)\right]^{\frac{1}{1-\eta}} \right)^{\frac{1-\eta}{1-\eta\beta}} \tag{5.22}$$

with effective process technique factor for each manufacture i

$$T(t,i) = T_{A_X}(t,i)^{\eta} T_{A_Z}(t,i)^{\eta\varsigma} T_{A_E}(t,i)^{\eta\xi} \tag{5.23}$$

and effective quality

$$A(t,i) = A_X(t,i)^{1-\eta} A_Z(t,i)^{\eta(1-\varsigma)} A_E(t,i)^{\eta(1-\xi)} \tag{5.24}$$

Effective labour productivities in intermediate production stages equal

$$A_{L_X}(t,i) = A_L(t) \left(\frac{T(t,i) A(t,i)}{A_X(t,i)} \right)^{\frac{1}{\eta(1-\beta)}} \tag{5.25}$$

$$A_{L_Z}(t,i) = A_L(t) \left(\frac{T_{A_Z}(t,i)}{A_Z(t,i)} \right)^{\frac{1}{1-\varrho}} \tag{5.26}$$

$$A_{L_E}(t,i) = A_L(t) \left(\frac{T_{A_E}(t,i)}{A_E(t,i)} \right)^{\frac{1}{1-\chi}} \tag{5.27}$$

Therefore, these will grow at the combined rate of exogenous gross labour productivity $\dot{A}_L/A_L = g_{A_L}$ and endogenous quality and process techniques $\dot{A}_v/A_v(i)$, $\dot{T}_{A_v}/T_{A_v}(i)$. Additionally, $B : \{B_Y, B_X, B_Z, B_E\} \in (0,1)$ factors measure efficiency levels in allocation of primary inputs $K(t)$ and $L(t)$. These can be read as

$$B_Z = \mu_Z^{1-\varrho}(1-\varepsilon)^{\varrho} \tag{5.28}$$

$$B_E = \mu_E^{1-\chi}\varepsilon^{\chi} \tag{5.29}$$

$$B_X = \mu_X^{1-\varsigma-\xi} B_Z^{\varsigma} B_E^{\xi} \tag{5.30}$$

$$B_Y = (1-\mu_X-\mu_Z-\mu_E)^{1-\eta} B_X^{\eta} \tag{5.31}$$

Aggregating costs of capital stock and labour, and using (5.8), (5.11), (5.12)-(5.15), as well as (5.31), average rental prices and wages can be read as

$$R(t) = \psi_K \alpha B_Y \tilde{k}(t)^{\alpha-1} \tag{5.32}$$

$$w(t) = \left(1 - \frac{\alpha}{\psi_L}\right) B_Y A(t) \tilde{k}(t)^{\alpha} \tag{5.33}$$

where $\tilde{k} = K/\left(A_{L_Y} L\right)$ is capital stock per effective worker and

$$\psi_K = \frac{(\psi_Z \varsigma \varrho + \psi_E \xi \chi)\psi_X}{\beta} \in (0,1] \tag{5.34}$$

$$\psi_L = \frac{\beta}{1 - \big((1-\varsigma-\xi) + \psi_Z\varsigma(1-\varrho) + \psi_E\xi(1-\chi)\big)\psi_X} \in (0,1] \tag{5.35}$$

are the market efficiency factors of capital stock and labour respectively. It is easy to see that perfectly competitive markets $\{\psi_X, \psi_Z, \psi_E\} = 1$ lead to competitive prices of capital stock $R^* (t) = \alpha B_Y \tilde{k} (t)^{\alpha-1}$ and labour $w^* (t) = (1 - \alpha) B_Y A (t) \tilde{k} (t)^{\alpha}$. In contrast, lower rates of technical diffusion will depress average rewards to investment and labour.

5.3.2.2 Lemma 2: Allocation shares of capital and labour change with relative technical diffusion rates, according to $\varepsilon = \frac{\psi_X \psi_E \xi \chi}{\psi_K \beta}$, $\mu_X = \frac{\psi_X \alpha(1-\varsigma-\xi)}{\beta(1-\psi_L \alpha)}$, $\mu_Z = \frac{\psi_X \psi_Z \alpha\varsigma(1-\varrho)}{\beta(1-\psi_L \alpha)}$ and $\mu_E = \frac{\psi_X \psi_E \alpha\xi(1-\chi)}{\beta(1-\psi_L \alpha)}$ (Proof in Appendix)

Proposition 1: *Widespread and perfect technical diffusion $\{\psi_X, \psi_Z, \psi_E\} = 1$, leads to market efficiency in primary input markets $\{\psi_K, \psi_L\} = 1$, optimal input prices $\{R (t), w (t)\} = \{R^* (t), w^* (t)\}$, and optimal factor-allocation factors $\{B_Y, B_X, B_Z, B_E\} = \{B^*_Y, B^*_X, B^*_Z, B^*_E\}$.*

(Proof: use $\{\psi_X, \psi_Z, \psi_E\} = 1$ in Lemma 2, then substitute in (5.28)-(5.35). It is straightforward to see Pareto optimality requires maximization of (5.18)-(5.21), which also requires the most efficient factor allocation $B_v = B^*_v = \text{Max} (B_v)$).

The major implication of Proposition 1 is that aggregate static efficiency is related to the chosen economic institutions related to technical diffusion ψ_v. That is, gross output Y at each period t constrained to a given set of primary inputs and technical factors $\{A_{L_Y}, K, L\}$ will reach its maximum value as economic institutions ruling technical diffusion are statically efficient in the sense of perfect technical diffusion $\psi_v = 1$ leading to perfectly competitive markets in all sectors of the economy.

5.3.3 Technical innovations and optimal R&D expenditure

Innovation follows the same pattern as in Howitt and Aghion (1998) and Howitt (2000), but it can be directed to two types of technologies for each intermediate stage of production A_v and T_v. Additionally, the inclusion of these two types of techniques will allow us to include the “escape-competition" effect found in seminal models of step-by-step innovations (Aghion, Harris and Vickers, 1997; Aghion and Howitt, 1998; Aghion et al., 2001). That is, for certain parameter combinations, an inverted-U relationship between technical diffusion rates and aggregate technical progress can emerge, which, as far as we know, has only been considered in the framework of environmentally sustainable growth in Acemoglu et al. (2016).

At the beginning of every period, each R&D firm decides how many resources they want to devote to quality- or process-improving techniques A_v and T_v, as well as at which intermediate stage of production v they do so. Each of them is randomly allocated to at most one line i of production and seeks to increase quality levels of goods or process techniques $\gamma > 1$ times. If innovation is successful, the R&D firm immediately turns into a leading intermediate producer.

As commented before, if the R&D firm innovates in A_v, they expel both follower and incumbent firms, given that the new quality of intermediate good v cannot be imitated until $t' > t + dt$. At t', the competitive fringe always returns if $\psi_v < 1$. This yields monopolistic profits $\Pi_{Av}(i) = \left(1 - \text{Min}(\psi_v)\right) \tilde{\pi}_v Y(i)$ for the innovator during the subsequent period $t + dt$. If the successful innovation is in process-improving techniques T_v, the follower competitive fringe remains as long as $\psi_v > \text{Min}(\psi_v)$. Therefore, extraordinary gains for the leader equal $\Pi_{Tv}(i) = (1 - \psi_v) \tilde{\pi}_v Y(i)$. Innovations arrive according to Poisson rate $\hat{D}_v(i) = D_v(i) / Y(i)$, which increases with R&D expenditure relative to final output to rule out scale effects from technical progress (see Jones critique). As in Aghion et al. (2001) and Aghion and Howitt (2008), we assume the following cost function in terms of gross output for R&D activities

$$\hat{\phi}_v(t,i) = \frac{1}{2\lambda_{Av}} \hat{D}_{Av}(t,i)^2 + \frac{1}{2\lambda_{Tv}} \hat{D}_{Tv}(t,i)^2 \tag{5.36}$$

where $\lambda_v : \{\lambda_{Av}, \lambda_{Tv}\} > 0$ are the productivity factors of innovators, which are different depending on the intermediate sector and type of researched technique.

For the sake of simplicity, assume R&D firms look only one period ahead according to $t+dt < \tilde{t}$. Given that new qualities render existing process techniques obsolete, research in process-improving innovations will be more profitable as the arrival rate of new qualities $\hat{D}_{Av}(t,i)$ diminishes. Hence, the expected flow of profits due to successful innovations can be read as

$$E(\Pi_v) = \hat{D}_{Av}(t,i)\,\Pi_{Av}(t,i) + \left(1 - \hat{D}_{Av}(t,i)\right) \hat{D}_{Tv}(t,i)\,\Pi_{Tv}(t,i) - \phi_v(t,i) \tag{5.37}$$

where $\phi_v(t,i) = \hat{\phi}_v(t,i)\, Y(t,i)$. Optimal R&D expenditures can be read as[13]

$$\hat{D}_{Av} = \lambda_{Av} \frac{\left(1 - \text{Min}(\psi_v)\right) - \lambda_{Tv}(1-\psi_v)^2 \tilde{\pi}_v}{1 - \lambda_{Av}\lambda_{Tv}(1-\psi_v)^2 \tilde{\pi}_v^2} \tilde{\pi}_v \tag{5.38}$$

$$\hat{D}_{Tv} = \lambda_{Tv} \frac{1 - \lambda_{Av}\left(1 - \text{Min}(\psi_v)\right)\tilde{\pi}_v}{1 - \lambda_{Av}\lambda_{Tv}(1-\psi_v)^2 \tilde{\pi}_v^2} (1-\psi_v)\, \tilde{\pi}_v \tag{5.39}$$

where $\tilde{\pi}_v = \left(p_v(t,i)\, v(t,i)\right) / Y(t,i)$ measures elasticity of final output respect to each intermediate output[14]. As in Aghion and Howitt (1998, 2008), we can observe two effects in (5.38) and (5.39) regarding technical diffusion rates and rates of innovation

- The “escape-competition" effect: this effect only appears in (5.38) as long as $\lambda_{Av} < \frac{1}{\left(1-\text{Min}(\psi_v)\right)\tilde{\pi}_v}$. Since innovators can temporarily seize monopolistic profits through upgrades in quality-improving techniques, they will try to eliminate the competitive fringe as technical diffusion rates increase.
- The Schumpeterian effect: the driving force behind creative destruction. As technical diffusion rates reduce expected extraordinary gains, R&D expenditure falls to maximize the expected gains of innovation.

[13] To assure non-negativity in equilibrium R&D expenditure rates, we impose $0 \leq \lambda_{Av}\lambda_{Tv}(1-\psi_v)^2 \tilde{\pi}_v^2 < 1$; $0 \leq \lambda_{Av} \leq \frac{1}{\left(1-\text{Min}(\psi_v)\right)\tilde{\pi}_v}$ and $0 \leq \lambda_{Tv} \leq \frac{\left(1-\text{Min}(\psi_v)\right)}{(1-\psi_v)^2 \tilde{\pi}_v}$.

[14] Specific factors are $\tilde{\pi}_X = \eta$, $\tilde{\pi}_Z = \psi_X \varsigma \eta$, $\tilde{\pi}_E = \psi_X \xi \eta$.

5.3.4 Rate of aggregate technical progress

Taking logs of (5.22)-(5.27) and deriving with respect to time, effective labour productivity for gross output grows at rate

$$g_c = \frac{\dot{A}_{L_Y}}{A_{L_Y}(t)} = g_{A_L} + \frac{(\gamma-1)}{1-\alpha}\left(\hat{D}_A + \hat{D}_T\right) \tag{5.40}$$

where $\hat{D}_A = (1-\eta)\hat{D}_{AX} + \eta(1-\varsigma)\hat{D}_{AZ} + \eta(1-\xi)\hat{D}_{AE}$ and $\hat{D}_T = \eta\hat{D}_{TX} + \eta\varsigma\hat{D}_{TZ} + \eta\xi\hat{D}_{TE}$.

5.3.4.1 Lemma 3: For productivity parameters $\lambda_{TZ} < \frac{1-\varsigma}{\psi_X\eta\varsigma^2}$, $\lambda_{TZ} \leq \lambda_{AZ}\frac{(1-\varsigma)^2}{\varsigma^2}$ and $\lambda_{TE} < \frac{1-\xi}{\psi_X\eta\xi^2}$, $\lambda_{TE} \leq \lambda_{AE}\frac{(1-\xi)^2}{\xi^2}$, there exists an interval for technical diffusion rates in machinery and energy markets $\eta\varsigma < \psi_Z < \psi_Z^*$ and $\eta\xi < \psi_E < \psi_E^*$ where the "escape-competition" effect dominates aggregate technical progress. Additionally, if process-improving researchers in machinery and energy markets present comparative advantage respect to quality innovators $\lambda_{TZ} >> \lambda_{AZ}$ and $\lambda_{TE} >> \lambda_{AE}$, and/or the contrary holds for manufacturing markets $\lambda_{TX} << \lambda_{AX}$, there is also an interval $\eta < \psi_X < \psi_X^*$ for which the "escape-competition" drives aggregate technical progress

(Proof in Appendix)

Interpretation of Lemma 3 is quite straightforward: according to (5.38) and (5.39), differences in productivity parameters in research activities determine the existence and persistence of the Schumpeterian and "escape-competition" effects. Therefore, if these are sufficiently skewed in favor to quality-improving research, initial increases in technical diffusion rates that depress extraordinary gains can be counteracted by innovation in new input qualities that temporarily expel the competitive fringe. In this sense, since aggregate technical progress has been "microfounded" as a compound of individual efforts in different intermediate markets, the "escape-competition" effect will be translated from a specific to a general domain. Moreover, since aggregators $\hat{D}_A$ and $\hat{D}_T$ depend on output elasticities, differences in the dependency of aggregate production respect to each intermediate input will impact on constraints for pure Schumpeterian or step-by-step growth.

5.3.5 Household's optimal choices

Each household owns net assets equal to

$$\mathcal{A}(t) = K(t) + \sum_{i=1}^{N}\left(V_X(t,i) + V_Z(t,i) + V_E(t,i)\right) \tag{5.41}$$

where $K(t)$ and $V_v(t,i) = \Pi_v(t,i)/r(t)$ are the present values of capital stock invested in intermediate firms and market value of R&D firms respectively. Dynamics of assets equal

$$\dot{\mathcal{A}}(t) = r(t)\,\mathcal{A}(t) + w(t)\,L(t) - D(t) - C(t) \tag{5.42}$$

where $r(t) = R(t) - \delta$ is the average real interest rate with exogenous depreciation rate $\delta > 0$. Given that equilibrium R&D expenditure has been already set in Subsection 5.3.3, the value of assets devoted to firms with extraordinary gains is not a control variable. Therefore, the budget constraint that each individual faces can be expressed in the following terms

$$\dot{k}(t) = r(t)\,k(t) + w(t) + \pi(t) - d(t) - c(t) \tag{5.43}$$

with transversality condition that guarantees no valuable physical asset is left unexploited in the limit

$$\lim_{t\to\infty}\left(\exp\left(-\int_0^t \big(r(j) + g_L\big)\,dj\right)k(t)\right) = 0 \tag{5.44}$$

and initial capital stock endowment $k_0 > 0$.

Since individuals cannot directly control polluting emissions from production of goods and services, they maximize (5.5) constrained to (5.43), (5.44) and $k_0 > 0$. The Euler equation can be read as

$$\frac{\dot{c}}{c(t)} = \frac{r(t) - \rho - (1-\theta_C)\,\theta_Q\theta_\Delta(t)\,g_Q(t)}{\theta_C} \tag{5.45}$$

where $\theta_\Delta(t) = \frac{\left(Q^*-Q(t)\right)^{\theta_Q} - (Q^*)^{\theta_Q-1}\left(Q^*-Q(t)\right)}{\left(Q^*-Q(t)\right)^{\theta_Q} - \theta_Q (Q^*)^{\theta_Q-1}\left(Q^*-Q(t)\right)} \in [0,1)$ is a factor that increases the impact of pollution accumulation on consumption growth as pollution stock approaches its critical level Q^*, and $g_Q(t)$ measures the growth rate of pollution stock. $\theta_\Delta(t)$ implies that a stationary and feasible steady state requires $Q < Q^*$ and $g_Q = 0$.

5.3.6 Long-term growth

From (5.43)-(5.45), a stable stationary state compatible with balanced growth -$\dot{Y}/Y(t) = \dot{K}/K(t)$- requires

$$r = \rho + g_c\theta_C \tag{5.46}$$

where g_c is the long-term growth rate of output per capita.

5.4 Pollution stock and economic growth

Our model focuses on pollution derived from energy consumption. Take, for instance, CO_2 concentrations that may lead to accelerated climate change. Pollution stock $Q(t)$ accumulates according to dynamic equation

$$\dot{Q} = \omega E(t) - \Psi Q(t) \tag{5.47}$$

where emissions at time t equal $\omega E(t)$, with $\omega > 0$ as the rate of pollution resulting from energy consumption $E(t)$.

5.4.0.1 Definition 2: With no possibilities for energy transition, sustainable growth requires $E(t) < \frac{\Psi}{\omega} Q^*$, $g_E = 0$ and $E(t) > 0$ in the steady state

5.4.0.2 Definition 3: With possibilities for energy transition, sustainable growth requires $E_P(t) < \frac{\Psi}{\omega} Q^*$, $g_{E_P} \leq 0$ and $E(t^*) > 0$ in the steady state, where $E_P(t)$ is polluting energy

5.4.1 Sustainable growth with no possibilities for energy transition

Assuming there are no possibilities for clean energy production, from (5.21), (5.27), (5.32), (5.38), (5.39), (5.40), (5.46) and Definition 2, the first condition for sustainable growth can be read as

$$\underbrace{\underbrace{\frac{B_E}{B_Y}\left(\frac{\psi_K \alpha B_Y}{\rho + g_c\theta_C + \delta}\right)^{\frac{\chi-\alpha}{1-\alpha}}}_{Composition\ Effect}\underbrace{\left(\frac{A_L(t)}{A_{L_Y}(t)}\right)^{1-\chi} Y(t)}_{Aggregate\ Demand\ Effect}}_{Scale\ Effect}\underbrace{\sum_{i=1}^{N}\underbrace{a_{L_Y}(t,i)}_{Sect.\ Effect}\underbrace{\frac{T_E(t,i)}{A_E(t,i)}}_{Pure\ T.\ Eff.}}_{Tech.\ Effect} < \frac{\Psi Q^*}{\omega} \tag{5.48}$$

which assures emission levels do not lead to an environmental catastrophe $Q > Q^*$ at the steady state. Condition (5.48) can be decomposed into two major economic components determining polluting emissions: the scale effect, which measures the size of energy aggregate demand in terms of relative importance of energy in gross production (composition effect) and size of economy's aggregate demand (aggregate demand effect); and the technical effect, which measures the role of energy innovations in energy production marginal costs at line of production i (pure technical effect), and the share of these innovations respect to the N lines of production (sector effect).

From (5.48), the second condition for sustainability is

$$g_{A_E} = g_L + \chi g_c + (1-\chi) g_{A_L} + g_{T_E} \tag{5.49}$$

which assures that energy consumption does not grow unbounded and reaches a constant value in the steady state.

Proposition 2: *Sustainable growth with no possibilities for energy transition and no public intervention, requires (5.48) to hold for all t as well as:*

- *if $\lambda_{AE} \to 0$, economic growth must stop. Hence, if $g_L > 0$ and/or $g_{A_L} > 0$, the environment converges to its collapse $\kappa \to 0$. If $g_L = g_{A_L} = 0$, all markets must be operated under perfect competition $(\psi_X, \psi_Z, \psi_E) = (1, 1, 1)$ to maintain $\kappa > 0$ for all t;*

- *if $\lambda_{TE} \to 0$, productivity of quality innovators in energy markets must increase with population and gross labour productivity growth $\left(g_L, g_{A_L}\right)$, and R&D relative expenditure in other intermediate markets $\tilde{D}$ according to rule $\lambda_{AE} = \frac{\frac{1-\alpha}{\gamma-1}\left(g_L+g_{A_L}\right)+\chi\tilde{D}}{\left(1-\alpha-\eta(1-\xi)\chi\right)\left(1-Min(\psi_E)\right)\tilde{\pi}_E}$ for $\kappa > 0$ for all t. This situation allows for positive economic growth;*

- *for $\{\lambda_{AE}, \lambda_{TE}\} > 0$, a vector of technical diffusion rates $(\psi_X, \psi_Z, \psi_E) = \left(\psi_X^{CC}, \psi_Z^{CC}, \psi_E^{CC}\right)$ that assures $\kappa > 0$ for all t is allowed to exist constrained to exogenous parameters. This vector is more likely to exist as $g_L \to 0$ and $g_{A_L} \to 0$. Moreover, for $0 < \lambda_{AE} < \frac{1}{\left(1-Min(\psi_E)\right)\tilde{\pi}_E}$ and $\lambda_{AE} >> \lambda_{TE}$, $\psi_E \to \psi_E^*$ makes more feasible sustainable growth, while for $\lambda_{AE} << \lambda_{TE}$ there is need for $\psi_E \to 1$.*

(Proof in Appendix)

The most important conclusion from Proposition 2 is that, before absent possibilities of transition to clean energy sources, positive and sustainable growth will be based on low energy intensity paths, according to condition (5.48). That is, innovation in quality-improving techniques for energy producers must arrive at a sufficiently fast rate, as it can be observed in (5.49), thus the economy will shift its composition from gross energy consumption to effective energy consumption $\frac{A_E(t)}{A_E(t)E(t)} \to 1$.

In this sense, productivity levels of researchers in different stages of production and types of techniques λ_{Av} and λ_{Tv}, as well as degrees of market competition measured through rates of technical diffusion ψ_v, reveal determinant for a successful transition to economies based on quality rather than quantity of energy flows. More precisely, the “escape-competition" effect in energy R&D markets turns to be crucial for sustainable growth. That is, if this effect is dominant in technical progress for energy markets according to Lemma 3 ($\lambda_{AE} >> \lambda_{TE}$), then the sustainable level of market efficiency for energy production must approach the situation of maximization of energy innovation rates according to $\psi_E \to \psi_E^*$, what requires no perfectly competitive markets. On the other hand, if process innovators are sufficiently more productive than quality researchers ($\lambda_{AE} << \lambda_{TE}$, see again Lemma 3), then maximization of technical progress in energy markets through $\psi_E \to \text{Min}\,(\psi_E)$ is not a sustainable solution, since $g_{A_E} < g_{T_E}$ yields sustained improvements in marginal costs that will lead to an excessive supply of gross energy flows, but technical diffusion rates should be chosen to foster perfect competition in energy markets, that is $\psi_E \approx 1$. The existence of quality-improving researchers $\lambda_{AE} > 0$ will allow for non-optimized positive rates of innovation in energy markets, but sufficient to cancel process innovations and allow for sustainable growth. Recall, however, all these solutions are conditioned to elasticity output parameters and exogenous growth rates of population and gross labour productivity, hence if g_L and/or g_{A_L} grow at sufficiently fast rates, or gross output is too dependent on gross capital stock ($(\varsigma, \varrho, \xi, \chi) \to (1,1,1,1)$, what leads to $\alpha \to 1$), manipulation of market incentives to research in new quality levels for energy flows ψ_E can turn useless to attain sustainable growth.

5.4.2 Sustainable growth with possibilities for energy transition

As in Acemoglu et al. (2012) and Eriksson (2018), we assume now there exist possibilities of substitution between dirty and clean energy sources. More precisely, assume effective energy supply in line i of production can be written as $\bar{E} = A_E E^{\xi}$ and comes from the aggregator

$$\bar{E}(t,i) = A_E^P(t,i) E_P(t,i)^{\xi} + A_E^{NP}(t,i) E_{NP}(t,i)^{\xi} \tag{5.50}$$

where E_P is gross polluting energy with productivity T_E^P/A_E^P, and E_{NP} is gross non-polluting energy with T_E^{NP}/A_E^{NP}.

Equilibrium gross energy production in the i line of production $E = E_P + E_{NP}$ can be rewritten as

$$E(t,i) = a_Y(t,i) B_E \left(A_{L_E}(t,i) L(t)\right)^{1-\chi} K(t)^{\chi} \tag{5.51}$$

which is very similar to (5.21), but with aggregate effective labour productivity in energy production

$$A_{L_E}(t,i) = A_L(t) \left(\bar{\Theta}(t,i) \psi_{E_P} \frac{T_E^P(t,i)}{A_E^P(t,i)} + \left(1 - \bar{\Theta}(t,i)\right) \psi_{E_{NP}} \frac{T_E^{NP}(t,i)}{A_E^{NP}(t,i)}\right)^{\frac{1}{1-\chi}} \tag{5.52}$$

The share of effective polluting energy sources respect to aggregate effective energy $\bar{\Theta} = \left(A_E^P E_P^{\xi}\right)/\bar{E}$ can be written as

$$\bar{\Theta}(t,i) = \left(1 + \left(\frac{A_E^{NP}(t,i)}{A_E^P(t,i)}\right)^{1-\xi} \left(\frac{T_E^{NP}(t,i)}{T_E^P(t,i)}\right)^{\xi}\right)^{-1} \tag{5.53}$$

which governs incentives to improve each type of process technique according to extraordinary gains for polluting energy sources $\bar{\Theta}\left(1 - \psi_{E_P}\right)\tilde{\pi}_E$, and decreases as its respective market share diminishes[15]. Share of gross polluting energy $\Theta = E_P/E$ can be read as

$$\Theta(t,i) = \left(1 + \frac{\psi_{E_{NP}}}{\psi_{E_P}} \cdot \left(\frac{A_E^P(t,i)}{A_E^{NP}(t,i)}\right)^{\xi} \cdot \left(\frac{T_E^{NP}(t,i)}{T_E^P(t,i)}\right)^{1+\xi}\right)^{-1} \tag{5.54}$$

which converges to zero as the relative process efficiency of the non-polluting input T_E^{NP}/T_E^P, or relative quality A_E^P/A_E^{NP}, grow unbounded.

[15] Another way of understanding $\bar{\Theta}$ needs to recall the "price effect" for innovation, which represents relative prices p_E^P/p_E^{NP} increasing with relative quality-improving techniques A_E^P/A_E^{NP}, given the polluting good becomes more interesting to manufacturers, and costly to energy producers, therefore scarce, as well as decreasing in process-improving techniques T_E^P/T_E^{NP} due to the inverse argument.

According to Definition 2, now long-term sustainability can be attained with positive growth in gross energy consumption $g_E > 0$, given that possibilities of substitution allow for energy consumption dominated by clean sources. The first condition for sustainability can be read now as

$$\underbrace{\bar{Y}(t)}_{Scale\ Effect} \underbrace{\sum_{i=1}^{N} \underbrace{a_{L_Y}(t,i)}_{Sect.\ Effect} \underbrace{\bar{\Theta}(t,i)\,\psi_{E_P}}_{Market\ Share\ Eff.} \underbrace{\frac{T_E^P(t,i)}{A_E^P(t,i)}}_{Pure\ T.\ Eff.}}_{Tech.\ Effect} < \frac{\Psi Q^*}{\omega} \tag{5.55}$$

with $\bar{Y}(t) = \frac{B_E}{B_Y}\left(\frac{\psi_K \alpha B_Y}{\rho+g_c\theta_C+\delta}\right)^{\frac{\chi-\alpha}{1-\alpha}}\left(\frac{A_L(t)}{A_{L_Y}(t)}\right)^{1-\chi} Y(t)$. A new element emerges inside the technical effect on polluting energy consumption: the market share effect. This represents how dominant are polluting energy producers supplying manufacturers respect to aggregate supply of energy flows. Therefore, if the economy converges to $\bar{\Theta} \to 0$, due to relatively cheaper and better-quality clean energy (see (5.53)), polluting-energy producers will progressively leave the energy market in favor of clean producers, and sustainability will become more feasible.

Now, the second condition is conditional to long-term growth of energy consumption. In the case that $g_E = 0$, the second condition for sustainability is

$$g_{A_E^P} = g_L + \chi g_c + (1-\chi) g_{A_L} + g_{T_E^P} \tag{5.56}$$

which is analogous to that of no possibilities of substitution and leads to a positive share of gross polluting energy $\Theta > 0$. In the case that $g_E > 0$, there is need for a complete transition to clean energy sources, hence the second condition can be read as

$$\xi\left(g_{A_E^P} - g_{A_E^{NP}}\right) + (1+\xi)\left(g_{T_{A_E}^{NP}} - g_{T_{A_E}^P}\right) > 0 \tag{5.57}$$

which assures $\Theta(t,i) \to 0$ in the long term.

Proposition 3: *Sustainable growth with possibilities for energy transition and no public intervention requires (5.55) to hold for all t as well as*

- *for null long-term growth in energy consumption $g_E = 0$:*
  - *Proposition 2 remains valid after replacement of $\{\lambda_{AE}, \lambda_{TE}, \psi_E\}$ for $\{\lambda_{AE_P}, \lambda_{TE_P}, \psi_{E_P}\}$, and taking into account that losses in the market share for polluting energy producers $\bar{\Theta} \to 0$ requires higher productivity levels in the polluting energy quality researchers λ_{AE_P} if $\lambda_{TE_P} \to 0$, as well as make less feasible the emergence of an environmentally friendly vector of technical diffusion rates $\left(\psi_X^{CC}, \psi_Z^{CC}, \psi_{E_P}^{CC}, \psi_{E_{NP}}^{CC}\right)$.*
- *for positive long-term growth in energy consumption $g_E > 0$:*

- *if* $\lambda_{AE_P} \to 0$ *and* $\lambda_{TE_{NP}} \to 0$*, there is no energy transition driven by market incentives. Hence, if* $g_c > 0$ *and* $\bar{\Theta} > 0$*, the environment converges to its collapse* $\kappa \to 0$*;*
- *if* $\lambda_{TE_P} \to 0$ *and* $\lambda_{AE_{NP}} \to 0$*, there is an energy transition to clean sources* $\bar{\Theta} \to 0$ *for any combination of rates of technical diffusion in energy markets* $\left(\psi_{E_P}, \psi_{E_{NP}}\right) \in [\eta\xi, 1]$*. This solution leads to sustainable growth, thus* $\kappa > 0$ *for all* t*. Additionally, if* $\lambda_{AE_P} >> \lambda_{TE_{NP}}$*, and/or* $\psi_{E_{NP}} \to 1$*, the energy transition will be driven by energy-saving innovations for polluting sources, thus the energy market will be progressively more dominated by polluting energy producers* $\bar{\Theta} \to 1$ *until the energy transition is completed, where* $\bar{\Theta} = \Theta = 0$*. On the other hand, if* $\lambda_{AE_P} << \lambda_{TE_{NP}}$ *and/or* $\psi_{E_{NP}} \to \eta\xi$*, the energy transition will be dominated by increasingly cheaper gross clean energy* $\bar{\Theta} \to 0$*;*
- *for* $\{\lambda_{AE_P}, \lambda_{TE_P}, \lambda_{AE_{NP}}, \lambda_{TE_{NP}}\} > 0$*, a vector of technical diffusion rates* $\left(\psi_{E_P}, \psi_{E_{NP}}\right) = \left(\psi^{CC}_{E_P}, \psi^{CC}_{E_{NP}}\right)$ *that assures a clean energy transition* $\bar{\Theta} \to 0$*, thus* $\kappa > 0$ *for all* t*, is allowed to exist constrained to exogenous parameters. Moreover, for* $0 < \lambda_{AE_P} < \frac{1}{\left(1-Min(\psi_E)\right)\bar{\Theta}\tilde{\pi}_E}$*,* $0 < \lambda_{AE_{NP}} < \frac{1}{\left(1-Min(\psi_E)\right)\left(1-\bar{\Theta}\right)\bar{\Theta}\tilde{\pi}_E}$*,* $\lambda_{AE_P} >> \lambda_{TE_P}$ *and* $\lambda_{TE_{NP}} >> \lambda_{AE_{NP}}$*, vector* $\left(\psi_{E_P}, \psi_{E_{NP}}\right) \to \left(\psi^*_{E_P}, \eta\xi\right)$ *makes more feasible sustainable growth, while for* $\lambda_{AE_P} << \lambda_{TE_P}$ *and* $\lambda_{TE_{NP}} << \lambda_{AE_{NP}}$ *there is need for* $\psi_{E_P} \to 1$ *and* $\psi_{E_{NP}} \to \eta\xi$ *if* $\psi^*_{E_{NP}} \to 1$*, while* $\psi_{E_{NP}} \to 1$ *if* $\psi^*_{E_{NP}} \to \eta\xi$*. In addition, if* $\lambda_{AE_P} >> \lambda_{TE_{NP}}$*, the clean energy transition path will be based on quality-improving techniques for polluting energy until* $\Theta = 0$*, hence requirements on* ψ_{E_P} *loosen up as* $\bar{\Theta} \to 1$*, while for* $\psi_{E_{NP}}$ *become more strict. If* $\lambda_{AE_P} << \lambda_{TE_{NP}}$*, the clean energy transition path will be based on process-improving or cost reduction techniques, thus requirements on* ψ_{E_P} *and* $\psi_{E_{NP}}$ *will follow the reverse argument.*

(Proof in Appendix)

Comparing Propositions 2 and 3, a first noteworthy difference is that sustainable growth paths with unbounded energy consumption are now possible due to our assumption of possibilities of substitution between clean and polluting energy flows, as well as positive rates of innovation in their respective techniques. As in Proposition 2, if the technical effect determining long-term emissions is growing unbounded due to relatively fast improvements in marginal costs for polluting energy production $g_{T^P_E} > g_{A^P_E}$, effective aggregate labour productivity $A_{L_Y}(t)$ must grow at a sufficiently fast pace to avoid emissions leading to critical levels of pollution stock Q^* before the clean energy transition can be successfully performed. Additionally, possibilities of substitution allow for the inclusion of a market share effect in condition (5.55), which depending on the path followed for a clean energy transition and levels of market efficiency ψ_{E_P}, may support or hinder the role of average technical progress g_C on sustainable growth paths.

More precisely, if this transition is led by improvements in quality levels of polluting energy flows A^P_E, due to a dominant "escape-competition" effect in the polluting-energy market $\lambda_{AE_P} >> \lambda_{TE_P}$ reinforced by technical diffusion rates $\psi_{E_P} \to \psi^*_{E_P}$, as well as a comparative advantage in the productivity levels of their quality researchers respect to those of the clean energy market $\lambda_{AE_P} >> \{\lambda_{AE_{NP}}, \lambda_{TE_{NP}}\}$, according to (5.53) we will observe a positive feedback effect between R&D expenditure for quality-improving techniques $\hat{D}_{AE_P}$ and the market share of polluting energy $\bar{\Theta}$, a standard result in directed technical change models in presence of possibilities of substitution. That is, the increase in relative quality levels A_E^P/A_E^{NP} will shift effective demand from clean to polluting energy producers at the same time gross production of polluting energy flows diminishes to compensate higher marginal costs. This price effect raises expected gains from innovation in techniques associated to polluting energy, while those for clean sources become less profitable, leading to faster technical progress among polluting producers. Therefore, this path leads to sustained improvements in levels of energy intensity, what can be actually observed in worldwide empirical data (see WDI database), but at the same time it may endanger fulfillment of condition (5.55) if the negative evolution of the pure technical effect T_E^P/A_E^P cannot compensate the temporary increase in the market share effect $\bar{\Theta}\psi_{E_P}$ and the sustained expansion in the scale effect $\bar{Y}$. In this sense, if $\lambda_{TE_{NP}} >> \lambda_{AE_{NP}}$, fostering innovation in process-improving techniques for clean energy producers T_E^{NP} through more market concentration $\psi_{E_{NP}} \to \mathrm{Min}\,(\psi_E)$ can temper the evolution of the market share effect.

On the other hand, when the energy transition is driven by improvements in the cost structure of clean energy producers through more efficient combinations of capital and labour, measured by the technical factor T_E^{NP}, it will require a dominant Schumpeterian effect on clean energy research markets $\lambda_{TE_{NP}} >> \lambda_{AE_{NP}}$, anti-competition technical diffusion rates $\psi_{E_{NP}} \to \mathrm{Min}\,(\psi_E)$, and a comparative advantage in research productivity levels respect to polluting energy researchers $\lambda_{TE_{NP}} >> \{\lambda_{AE_P}, \lambda_{TE_P}\}$. Similar to the previous quality-driven path, this quantity-driven path will lead to a positive feedback effect between relative R&D expenditure for process-improving innovations in clean energy production $\hat{D}_{TE_{NP}}$ and its market share $1-\bar{\Theta}$. That is, a steady and strong increase in relative gross technical efficiency levels T_E^{NP}/T_E^P leads to sufficiently fast reductions in relative marginal costs so the energy market is flooded with cheaper clean energy flows which can easily substitute part of gross polluting energy. This sustained expansion in the supply side of clean energy is sufficient to compensate the fall in relative prices p_E^{NP}/p_E^P, hence the market size effect dominates and extraordinary gains of the clean energy leading producer increase. This attracts a larger share of gross income to R&D activities in the clean energy research market, what makes that relative gross technical efficiency levels T_E^{NP}/T_E^P keeps growing at an increasing rate until $\bar{\Theta} = 0$. Having said that, this quantity- or cost-driven energy transition is not exempt of problems, since condition (5.55) can also be violated if the market share of polluting energy producers $\bar{\Theta}$ does not converge to zero at a sufficiently fast pace to compensate positive scale $\bar{Y}$ and pure technical effects T_E^P/A_E^P in long-term emissions. Again, collaboration between innovations in both types of energy flows makes the clean energy transition more likely to happen. In this case, if $\lambda_{AE_P} >> \lambda_{TE_P}$, technical diffusion rates in polluting energy markets fostering technical progress $\psi_{E_P} \to \psi^*_{E_P}$ will temper the pure technical effect, while for $\lambda_{AE_P} << \lambda_{TE_P}$ technical diffusion rates must lead to perfectly competitive markets $\psi_{E_P} \to 1$.

To summarize, our base model shows that relative productivity levels of researchers as well as market efficiency measured by efficient economic institutions controlling technical diffusion rates are crucial to attain sustainable growth without public intervention. Moreover, it poses that clean transitions are more likely to occur, and will be faster, if research efforts in the energy market are driven towards improvements in the quality of polluting energy flows -a decreasing pure technical effect- as well as in the productive process of clean energy flows -a decreasing market share effect-. These two effects combined will lead to a shift in polluting to clean energy intensity levels which, in contrast to previous works such as Eriksson (2018), imply that a successful energy transition is not necessarily constrained to a GDP growth drag. Therefore, economic policies should be aimed to improve productivity levels of specific researchers related to the energy transition[16] $\{\lambda_{AE_P}, \lambda_{TE_{NP}}\}$, that is improving human capital, as well as fostering the "escape-competition" effect among polluting energy researchers and the Schumpeterian effect among clean energy researchers $\left(\psi_{E_P}, \psi_{E_{NP}}\right) \to \left(\psi^*_{E_P}, \mathrm{Min}\left(\psi_E\right)\right)$.

5.5 Extractive institutions and economic growth

We extend the previous model by introducing a public sector ruled by a subset of the population that we name "the political elite". The main framework is based on the seminal works of Acemoglu (2005, 2006) and Acemoglu and Robinson (2006, 2008), where the group in power makes public decisions: in this case, it will always be the political elite, without disagreement; thus, voting processes are omitted. Depending on the existing type of state, which can take the form of a non-democratic or democratic political regime as in Acemoglu and Robinson (2008), elites will face different constraints to maximize their present value of disposable income. Additionally, we also consider a third possibility when the state is entirely dominated by the citizens. Inspired in Acemoglu (2005) and Acemoglu and Robinson (2008), the non-ruling subset of the population, "the citizens", can spend part of their disposable income in the political arena to climb the political ladder and substitute the former elite in a fashion similar to the idea of Schumpeterian creative destruction. Policy instruments of the ruling elite are divided among tax rates, public expenditure and manipulation of rates of technical diffusion. Net transfers, which come from gross public revenues discounted from aggregate public expenditure, are entirely perceived by the ruling subset of the population. We divide between base tax rates, which are chosen to maximize the discounted net income of rulers, and environmentally friendly tax rates, which increase with environmental damage and fund subsidies for a clean energy transition. Public expenditure can be devoted to productive and unproductive activities. The productive ones are general and environmentally friendly subsidies to R&D firms.

[16] This could be easily endogenized by considering a production function of ideas *à la Romer* (1990), where $\dot{\lambda}_v = h_v(t)\,\lambda_v(t)$, with h_v as the human capital devoted to that scientific or technical area. However, this falls outside the scope of the present work, so we will omit it.

The unproductive activities are expenditure devoted to base tax collection.

5.5.1 Extractive and supportive elites

Every instant of time t presents $L_R \leq L$ individuals who are part of the ruling, elite or upper-class representative household. The working time of the elite class is entirely devoted to political affairs; hence, productive work in the economy is given by $L_C = L - L_R$, where C is for citizens or middle-class people, and R is for rulers, elites, or upper-class people. The L_R elites always face the same individual preferences as those of the L_C citizens or middle-class people, as shown in (5.5). Assets are divided according to exogenous parameter $\vartheta \in [0,1]$, which measures the share of assets hold by the elites and represents wealth inequality levels. A representative public agent is randomly chosen from the ruling elite, who sets base tax rates $\tau_B \in [0,1]$, environmentally friendly taxes $\tau_{CC} \in [0,1]$, public expenditure for base tax collection $G_\tau \geq 0$ and for general and environmentally subsidies to R&D firms $\{G_v, G_v^{CC}\} \geq 0$.

5.5.2 Tax collection

In the present model tax collection is a costly action. That is, the public agent needs to spend $G_\tau = (1-\lambda_\tau)\,\tau_B Y$ units of public funds to mobilize tax collectors or coercive forces to successfully capture $\tau_B Y$ units of gross output, where $\lambda_\tau > 0$ is the inverse of the quality of political institutions restraining expropriating activities. Therefore, for $\lambda_\tau \to 1$, the elites have no constraint on revenue extraction. Similar assumptions can be found in Acemoglu (2005), who allows citizens to hide part of their income from tax collectors, but in this case the cost of taxation is charged to the public agent.

5.5.3 General subsidies to private R&D

The public agent may be interested in increasing expected gross tax revenues by improving private producers' techniques. Since we have assumed that this task corresponds to the private sector, the public agent can only subsidize R&D activities with public expenditure for entrant firms $G_v(i) \geq 0$. The probability of success is assumed to take the form $\varphi_v(i) = (1-\lambda_{Sb})\,\lambda_v \hat{G}_v(i)^{\varpi}$, where $\varpi < 1$, and we consider the presence of lack of commitment problems by introducing λ_{Sb} as the inverse of the quality of political institutions controlling the supportive actions of the elites. Hence, if $\lambda_{Sb} \to 1$, the elites will not perceive subsidies to R&D as sufficiently rewarding to diminish their current net transfers. Incentives to subsidize innovation are based on the expected increase in the tax base $\mathcal{T}_B = \tau_B Y$ due to a successful improvement at time t by entrant firms

$$E\left(\mathcal{T}_B(t,i)\right) = \varphi_v(t,i)\,\tau_B(t)\,(\gamma_v - 1)\,Y(t) - G_v(t,i) \tag{5.58}$$

where $1 < \gamma_v < \gamma$ measures the increase in aggregate final output due to successful innovations.[17]

[17] These can be read as $\gamma_{AX} = \gamma^{1-\eta}$, $\gamma_{AZ} = \gamma^{\eta(1-\varsigma)}$, $\gamma_{AE_P} = 1 + \bar{\Theta}_Y(t,i)\left(\gamma^{\eta(1-\xi)} - 1\right)$, $\gamma_{AE_{NP}} = 1 + \left(1-\bar{\Theta}_Y(t,i)\right)\left(\gamma^{\eta(1-\xi)} - 1\right)$, $\gamma_{TX} = \gamma^{\eta}$, $\gamma_{TZ} = \gamma^{\eta\varsigma}$, $\gamma_{TE_P} =$

5.5.4 Environmentally friendly taxes and subsidies to private R&D

In addition to the base tax rate derived from a tax revenue maximization viewpoint, the elites are also allowed to impose an extraordinary tax rate $\tau_{CC}(t)$ linked to environmentally friendly subsidies $G_v^{CC}(t,i)$. Imposing this tax rate is costless for the public sector, since individuals assume it will be entirely devoted to avoiding environmental damage. Their willingness to pay the tax increase with perceived environmental damage $\kappa(t)$, and subsidies will be directed only to improve technical factors A_E^P and T_E^{NP} since, according to (5.54), these are the drivers for a clean energy transition. Having said that, environmentally friendly tax rates can be read as

$$\tau_{CC}(t) = \big(1-\kappa(t)\big)\big(1-\tau_B(t)\big) \tag{5.59}$$

5.5.5 Timing of events

Each instant of time t is assumed to be subdivided into a set of ordered actions

- Firms produce goods and services $\{Y, X, Z, E\}$ constrained to state variables $\{A_L, \bar{A}_v(i), \bar{T}_v(i), L, K\}$ and inherited economic institutions $\{\tau, \psi_v, G_\tau, \bar{G}_v, \bar{G}_v^{CC}\}$.
- Households make investment decisions on their respective asset portfolios $\{I_R + D_R, I_C + D_C\}$.
- The public agent chooses new base tax rates τ_B, technical diffusion rates $\{\psi_X, \psi_Z, \psi_{E_P}, \psi_{E_{NP}}\}$ and items of public expenditure $\{G_\tau, \bar{G}_v, \bar{G}_v^{CC}\}$.

5.5.6 Markov perfect equilibrium

We analyse the optimal choice of economic policies and institutions[18] by the relevant decision-maker. Following Acemoglu (2005, 2006) and Acemoglu and Robinson (2006), we focus on the Markov perfect equilibrium (MPE). The MPE is defined as a set of strategies at each instant of time t over the control variables defined at Subsection 5.5.5. These strategies only depend on the current (payoff-relevant) state of the economy Y, and on prior actions within the same date according to the timing of the events above.

Definition 4: *Policies and institutions will be defined as inefficient as they hinder sustainable growth. The most efficient institutional framework implies* $g_c^* = Max(g_c)$, $\bar{\Theta} = 0$ *and* $\kappa = 1$ *in the long term.*

Therefore, we follow the definition presented in Acemoglu (2005, 2006) that poses inefficient economic policies and institutions are those which slow down economic growth and diminishes aggregate economic welfare -recall that in the present model economic

$1 + \bar{\Theta}_Y(t,i)\left(\gamma^{\eta\xi}-1\right)$, $\gamma_{TE_{NP}} = 1 + \left(1-\bar{\Theta}_Y(t,i)\right)\left(\gamma^{\eta\xi}-1\right)$, where $\bar{\Theta}_Y(t,i) = \left(1+\left(\frac{A_E^{NP}(t,i)}{A_E^P(t,i)}\right)^{\eta(1-\xi)}\left(\frac{T_E^{NP}(t,i)}{T_E^P(t,i)}\right)^{\eta\xi}\left(\frac{\left(1-\bar{\Theta}(t,i)\right)\psi_{E_{NP}}}{\bar{\Theta}(t,i)\psi_{E_P}}\right)^{\eta\xi}\right)^{-1} \approx \bar{\Theta}(t,i)$.

[18] Economic institutions can be defined as formal and informal rules that determine economic incentives and opportunities (Acemoglu and Robinson, 2019).

welfare also comprises environmental quality levels κ. Moreover, as in Acemoglu (2005), four possible sources creating inefficient economic institutions are considered, each constrained to political institutions parameters: revenue extraction λ_τ, factor price manipulation λ_R, political consolidation λ_R and commitment controls λ_{Sb}.

5.5.7 MPE public expenditure on subsidies to R&D and elite capture

According to (5.54) and (5.59), MPE relative expenditure in environmentally friendly subsidies can be read as

$$\hat{G}^{CC}_{AE_P}(t) = \frac{\xi}{1+2\xi}(1-\lambda_{Sb})\big(1-\kappa(t)\big)\big(1-\tau_B(t)\big) \tag{5.60}$$

$$\hat{G}^{CC}_{TE_{NP}}(t) = \frac{1+\xi}{1+2\xi}(1-\lambda_{Sb})\big(1-\kappa(t)\big)\big(1-\tau_B(t)\big) \tag{5.61}$$

with $\hat{G}_{CC} = (1-\lambda_{Sb})\big(1-\kappa(t)\big)\big(1-\tau_B(t)\big)$.

From (5.58), the MPE relative expenditure in general subsidies for technical progress are

$$\hat{G}_v(t) = \big((1-\lambda_{Sb})(\gamma_v-1)\varpi\lambda_v\tau_B(t)\big)^{\frac{1}{1-\varpi}} \tag{5.62}$$

5.5.8 MPE taxes and technical diffusion rates

Assume public transfers perceived by the elite equal net tax revenues. In terms of gross output, it can be read as

$$\hat{TR}_R(t) = \tau(t) - \hat{G}_\tau(t) - \sum_v^M \hat{G}_v(t) - \hat{G}_{CC}(t) \tag{5.63}$$

where $\tau = (1-\kappa)+\kappa\tau_B$ measures effective tax rates on income. Elites with uncontested power seek to maximize the present value at time t of their disposable income, taking gross output as exogenously given according to Subsection 5.5.5, that is (for the sake of simplicity, evaluate this problem in the steady state, where $\dot{\tau} = \dot{\hat{TR}}_R = 0$)

$$V_R(t) = \left((1-\tau)\frac{\vartheta\alpha}{\psi_L} + \hat{TR}_R\right)\int_t^\infty e^{-\rho j}Y(j)\,dj \tag{5.64}$$

Maximization of (5.64), with respect to τ_B, yields (use (5.60)-(5.64))

$$\tau_B^R = \left(\frac{(1-\varpi)\left(\lambda_\tau + (1-\kappa)\lambda_{Sb} - \kappa\frac{\vartheta\alpha}{\psi_L}\right)}{\varpi^{\frac{1}{1-\varpi}}\left((1-\lambda_{Sb})\sum(\gamma_v-1)\lambda_v\right)^{\frac{1}{1-\varpi}}}\right)^{\frac{1-\varpi}{\varpi}} \tag{5.65}$$

where $\tau_B^R = 0$ for $\lambda_\tau < \kappa\frac{\vartheta\alpha}{\psi_L} - (1-\kappa)\lambda_{Sb}$. Maximization with respect to ψ_L leads to

$$\psi_L^R = \mathrm{Min}(\psi_L) = \frac{\beta}{1-\big((1-\varsigma-\xi)+\eta\varsigma^2(1-\varrho)+\psi_E\eta\xi^2(1-\chi)\big)\eta} \tag{5.66}$$

Therefore, MPE technical diffusion rates equal $\psi_v^R = \mathrm{Min}\left(\psi_v\right)$, that is, $\left(\psi_X^R, \psi_Z^R, \psi_{E_P}^R, \psi_{E_{NP}}^R\right) = \left(\eta, \eta\varsigma, \bar{\Theta}\eta\xi, \left(1-\bar{\Theta}\right)\eta\xi\right)$.

In the case of a dominant middle class, who siphon elite public transfers towards them, the objective function changes to

$$V_C\left(t\right) = \left(\left(1-\tau\right)\left(1-\frac{\vartheta\alpha}{\psi_L}\right) + \hat{TR}_R\right)\int_t^\infty e^{-\rho j} Y\left(j\right) dj \tag{5.67}$$

with MPE base tax rates

$$\tau_B^C = \left(\frac{\left(1-\varpi\right)\left(\lambda_\tau + \left(1-\kappa\right)\lambda_{Sb} - \kappa\left(1-\frac{\vartheta\alpha}{\psi_L}\right)\right)}{\varpi^{\frac{1}{1-\varpi}}\left(\left(1-\lambda_{Sb}\right)\sum\left(\gamma_v - 1\right)\lambda_v\right)^{\frac{1}{1-\varpi}}}\right)^{\frac{1-\varpi}{\varpi}} \tag{5.68}$$

where $\tau_B^C = 0$ for $\lambda_\tau < \kappa\left(1-\frac{\vartheta\alpha}{\psi_L}\right) - \left(1-\kappa\right)\lambda_{Sb}$. MPE labour market efficiency equals

$$\psi_L^C = Max\left(\psi_L\right) = 1 > \psi_L^R \tag{5.69}$$

Therefore, MPE technical diffusion rates equal $\psi_v^C = Max\left(\psi_v\right)$, that is $\left(\psi_X^C, \psi_Z^C, \psi_{E_P}^C, \psi_{E_{NP}}^C\right) = \left(1, 1, \bar{\Theta}, 1-\bar{\Theta}\right)$.

5.5.9 MPE taxes and technical diffusion rates under political replacement

Now, assume that members from the ruling elite can be overthrown by individuals from the middle class. To avoid this, the elites must appease the middle class transferring $\hat{G}_R = \left(1-\lambda_R\right)\left(1-\tau\right)\varphi\hat{Y}_C^\varpi$ units of public revenue in terms of output where $\varphi > 0$, and inspired in Acemoglu (2006), increase with spending capacity of the middle class $\left(1-\tau\right)\hat{Y}_C$, and more inclusive institutions allowing for cheaper access to the political arena $\lambda_R \to 0$. Now, the constrained elites maximize their expected present disposable income according to

$$V_{CR}\left(t\right) = \left(\left(1-\tau\right)\frac{\vartheta\alpha}{\psi_L} + \hat{TR}_R - \hat{G}_R\right)\int_t^\infty e^{-\rho j} Y\left(j\right) dj \tag{5.70}$$

Maximization respect to τ_B yields

$$\tau_B^{CR} = \left(\frac{\left(1-\varpi\right)\left(\lambda_\tau + \left(1-\kappa\right)\lambda_{Sb} - \kappa\left(\frac{\vartheta\alpha}{\psi_L} - \left(1-\lambda_R\right)\varphi\left(1-\frac{\vartheta\alpha}{\psi_L}\right)^\varpi\right)\right)}{\varpi^{\frac{1}{1-\varpi}}\left(\left(1-\lambda_{Sb}\right)\sum\left(\gamma_v - 1\right)\lambda_v\right)^{\frac{1}{1-\varpi}}}\right)^{\frac{1-\varpi}{\varpi}} \tag{5.71}$$

where $\tau_B^{CR} = 0$ for $\lambda_\tau < \kappa\left(\frac{\vartheta\alpha}{\psi_L} - (1-\lambda_R)\varphi\left(1-\frac{\vartheta\alpha}{\psi_L}\right)^{\varpi}\right) - (1-\kappa)\lambda_{Sb}$. MPE labour market efficiency factor equals

$$\psi_L^{CR} = \frac{\vartheta\alpha}{1-(1-\vartheta\alpha)(1-\lambda_R)^{\frac{1}{1-\varpi}}} \tag{5.72}$$

where, for the sake of simplicity, we have normalized $\varphi = \frac{(1-\vartheta\alpha)^{1-\varpi}}{\varpi}$, thus for $\lambda_R = 0$, all markets operate under perfect competition $\psi_L^{CR} = \psi_L^C = 1$. On the other hand, for $\lambda_R = 1$, $\psi_L^{CR} = \vartheta\alpha$ if $\vartheta \geq \text{Min}(\psi_L)/\alpha$; while $\psi_L^{CR} = \psi_L^R = \text{Min}(\psi_L)$ for $\vartheta < \text{Min}(\psi_L)/\alpha$. Moreover, since $\alpha = \eta\beta$, from (5.68) we know that $\text{Min}(\psi_L)/\alpha > 1$ holds for $\eta \in (0,1)$, $\varsigma \in (0,1)$, $\xi \in (0,1)$, $\varrho \in (0,1)$ and $\chi \in (0,1)$. Therefore $\vartheta < \text{Min}(\psi_L)/\alpha$ will always be true and $\psi_L^{CR} = \psi_L^R = \text{Min}(\psi_L)$ for $\lambda_R \to 1$.

Lemma 4:

- *For $\vartheta < \frac{Min(\psi_L)}{\alpha(1+Min(\psi_L))}$, the MPE equilibrium yields $\tau_C < \tau_R < \tau_{CR}$ and $\psi_L^R < \psi_L^{CR} < \psi_L^C$, where $\{\tau_R, \tau_C, \tau_{CR}\}$ are depicted in (5.65), (5.68) and (5.71); technical diffusion rates follow $\left(\psi_X^C, \psi_Z^C, \psi_{E_P}^C, \psi_{E_{NP}}^C\right) = \left(1, 1, \bar{\Theta}, 1-\bar{\Theta}\right)$, $\left(\psi_X^R, \psi_Z^R, \psi_{E_P}^R, \psi_{E_{NP}}^R\right) = \left(\eta, \eta\varsigma, \bar{\Theta}\eta\xi, \left(1-\bar{\Theta}\right)\eta\xi\right)$ and vector $\bar{\psi}_v^{CR}$ is constrained to (5.72) as well as to $\psi_v \in \left[Min(\psi_v), 1\right]$. For $\vartheta > \frac{Min(\psi_L)}{\alpha(1+Min(\psi_L))}$, the MPE equilibrium changes in $\tau_R < \tau_C$;*
- *increases in extractiveness of political institutions -more “de jure" power to the ruling subset- related to effective taxation and commitment to R&D subsidies $(\lambda_\tau, \lambda_{Sb}) \to (1,1)$ lead to higher MPE income tax rates $\tau \to 1$ for a given political regime. On the contrary, increases in extractiveness of political institutions focused on entry possibilities to the political arena $\lambda_R \to 1$ alleviate fiscal pressure $\tau \to 0$ for a given political regime. Additionally, MPE technical diffusion rates in the political regime with “constrained elites" converge to more statically inefficient levels $\psi_v \to Min(\psi_v)$ as entry possibilities to the political arena diminish $\lambda_R \to 1$;*
- *environmental damage $\kappa \to 0$ increases MPE fiscal pressure $\tau \to 1$, for any political regime. Moreover, dictatorship of the elites and lower controls on the commitment of the ruling subset $\lambda_{Sb} \to 1$ under dictatorship of the middle class or constrained ruling elites always lead to a faster reaction of effective tax rates for initial low levels of environmental deterioration $\kappa \approx 1$. This effect is increased with political institutions that lead to higher base tax rates $(\lambda_\tau, \lambda_{Sb}, \lambda_R) \to (1,1,0)$. In addition, increases in the extractiveness of political institutions in terms of effective taxation also lead to shifts in the share of environmentally friendly taxes towards base taxes $\tau_{CC}/\tau \to 0$.*

(Proof can be directly obtained from Subsections 5.3.2 and 5.3.3. For the impact of environmental damage on effective tax rates see Appendix).

Interpretation of MPE solutions can be summarized as follows: in the case of dictatorship of the elites, their objective is to maximize net public revenues in terms of gross output $\tau - \hat{G}$, where for sufficiently low restrictions to public sector's extractivity $\lambda_\tau > \kappa \frac{\vartheta \alpha}{\psi_L} - (1-\kappa)\,\lambda_{Sb}$, it presents a concave relationship with base tax rates τ_B. This is the revenue extraction effect leading to more statically inefficient levels of taxation before lower controls to decisions of the elites. Additionally, given that dictatorial elites only perceive capital gains, whether they come from competitive or extraordinary sources, they choose the lowest level of market efficiency, with minimum technical diffusion rates, to channel income from labour to capital markets. This is the price manipulation effect, since it siphons income from the middle class to the elites due to public sector's intervention.

In the case of dictatorship of the citizens, if they do not hold a sufficiently high share of aggregate wealth $\vartheta < \frac{\mathrm{Min}(\psi_L)}{\alpha\left(1+\mathrm{Min}(\psi_L)\right)}$, tax rates will be chosen with the aim of revenue extraction against the elites, leading to a shift in levels of State tax pressure where $\tau_C > \tau_R$. Regarding market efficiency, for positive wealth owned by the elites $\vartheta > 0$, the citizens always seek to transfer income from capital to labour sources $\Pi/Y \to 0$ and $wL/Y \to Max\left(wL/Y\right)$, given this option always leads to less income shared with the elites. Therefore, the price manipulation effect now leads to more efficient economic institutions fostering perfect market competition.

When political elites rule threatened by the middle class $\lambda_R < 1$, the former internalize the effects of taxation and wealth inequality over the citizens through public transfers $G_R = G_R\left(\lambda_R, \tau, Y_C\right)$ aimed to appease the middle class. Therefore, the elites will seek to maintain themselves in power by reduction of disposable income of the citizens, which we have assumed a proxy for their political power, through higher effective tax rates τ. Additionally, the elites will be encouraged to increase market efficiency levels $\psi_v \to 1$ in order to increase their net transfers by shifting fiscal pressure from them to the middle class. Therefore, the political consolidation effect leads to more extractive economic institutions in terms of taxation, while the price manipulation effect leads more inclusive institutions in terms of technological adoption levels.

Finally, the interpretation of the impact of the environmental quality factor κ on public sector's extractiveness is straightforward. According to our model, as pollution stock increases the population is keener to yield their gross income to accelerate technical progress directed to energy efficiency and a successful transition to renewable energy sources. In this sense, the ruling group of power perceives an increase in gross public revenues τ at cost of augmenting environmental friendly subsidies G_{CC}. Since rulers seek to maximize the discounted present value of their disposable income, without internalization of environmental damage, as political institutions become more lax on rulers' extractiveness they will try to siphon effective tax revenues to base tax revenues, thus environmentally friendly subsidies are minimized and the ruling group increase their perceived net transfers.

5.5.10 Extractive institutions and sustainable growth

This subsection presents the impact of endogenous public intervention controlled by a specific subset of the population constrained to a given array of exogenous political institutions. We focus on the extended version of the base model, where there exist possibilities of substitution between polluting and clean energy inputs. Therefore, Definition 3 continues to establish the requirements for sustainable growth as well as conditions (5.55), (5.56) and (5.57) are still necessary for it. According to our model, the velocity and composition of technical progress remains as the crucial factor to attain the aforementioned conditions. Therefore, before delving into the question of sustainable growth in presence of public intervention we must first analyse its implications on R&D investments. Considering taxation as well as public subsidies, optimal R&D expenditure can be read now as

$$\hat{D}^{\tau}_{Av} = \lambda_{Av} \frac{\hat{\Pi}^{\tau}_{Av} - \lambda_{Tv} \left(\hat{\Pi}^{\tau}_{Tv}\right)^2}{1 - \lambda_{Av}\lambda_{Tv} \left(\hat{\Pi}^{\tau}_{Tv}\right)^2} \tag{5.73}$$

$$\hat{D}^{\tau}_{Tv} = \lambda_{Tv} \frac{1 - \lambda_{Av}\hat{\Pi}^{\tau}_{Av}}{1 - \lambda_{Av}\lambda_{Tv} \left(\hat{\Pi}^{\tau}_{Tv}\right)^2} \hat{\Pi}^{\tau}_{Tv} \tag{5.74}$$

where $\hat{\Pi}^{\tau}_{Av} = (1-\tau)\,\mathrm{Max}\left(\hat{\Pi}_v\right) + \hat{G}_{Av}$ and $\hat{\Pi}^{\tau}_{Tv} = (1-\tau)\,\hat{\Pi}_v + \hat{G}_{Tv}$, with τ as the effective tax rate and $\hat{G}_v$ as public subsidies to R&D, which act as public prizes to successful private innovations.

Lemma 5:

- *For* $\tau_B(t) > \left(\frac{\left(\kappa Max\left(\hat{\Pi}_v\right)\right)^{1-\varpi}}{(1-\lambda_{Sb})(\gamma_v-1)\varpi\lambda_{Av}}\right)^{\frac{1}{\varpi}}$ *and technical progress in a given intermediate stage dominated by quality-improving research* $\lambda_{Av} >> \lambda_{Tv}$*, increases in base tax rates according to Lemma 4 lead to faster arrival rates of quality-improving innovations* $\partial\hat{D}_{Av}/\partial\tau_B > 0$*, as well as a drag in the arrival of process-improving techniques* $\partial\hat{D}_{Tv}/\partial\tau_B < 0$;
- *for* $\tau_B(t) > \left(\frac{\left(\kappa\hat{\Pi}_v\right)^{1-\varpi}}{(1-\lambda_{Sb})(\gamma_v-1)\varpi\lambda_{Tv}}\right)^{\frac{1}{\varpi}}$ *and technical progress in a given intermediate stage dominated by process-improving research* $\lambda_{Av} << \lambda_{Tv}$*, increases in base tax rates according to Lemma 4 lead to slower arrival rates of quality-improving innovations* $\partial\hat{D}_{Av}/\partial\tau_B > 0$*, as well as a boost in the arrival of process-improving techniques* $\partial\hat{D}_{Tv}/\partial\tau_B > 0$.

(Proof: see Appendix)

Interpretation of Lemma 5 is as follows: if there exist strong differences in research productivity parameters $\{\lambda_{Av}, \lambda_{Tv}\}$ for a given intermediate market v, public intervention in terms of taxation on sources of gross income τ and subsidies for R&D activities G_v can strengthen or reverse the existing dominance of one type of innovation over the other. More precisely, if base tax rates τ_B are sufficiently high according to Lemma 5, as τ_B keeps increasing, subsidies to the dominant type of research overcome the negative effect of income extraction on expected extraordinary gains. Therefore, net incentives to private

R&D for that class of innovations increase more than those of the not dominant one, which reinforces the existing substitution effect between the quality- and process-improving techniques according to the leading research productivity parameter $\{\lambda_{Av}, \lambda_{Tv}\}$. On the other hand, if τ_B does not fulfill Lemma 5 the effect will be the contrary. Thus, incentives to innovation in the not dominant technique -according to differences in productivity parameters $\{\lambda_{Av}, \lambda_{Tv}\}$-, will now increase faster (or decrease at a slower pace) than those of the dominant technique. This will therefore diminish the existing gap in relative rates of innovation, and may even shift dominant roles between both types of research.

To conclude, we can present the last proposition regarding efficient political institutions in terms of Definition 4, which grant the fastest and most sustainable of the possible balanced growth paths.

Proposition 4:

- *For $\kappa > 0$ and $\gamma_v > 1$, there exists a critical value $\lambda_{Sb}^* \in [0,1]$ before which better controls on commitment of public sector's subsidies $\lambda_{Sb} \to 0$ lead to aggregate technical progress driven by the private sector's initiative $\lim_{\tau_B \to 0} g_c = Max(g_c)$. If $\kappa = 0$, there is no private initiative in the economy, and for $\lambda_{Sb} < 1$, economic growth will be driven by the public sector $\lim_{\tau_B \to 1} g_c = Max(g_c)$. If the average size of innovations is too small $\gamma_v \approx 1$, incentives to public investment in R&D will be practically non-existent, thus economic growth is always driven by the private sector for any $\lambda_{Sb} \in [0,1]$;*

- *if aggregate technical progress is driven by the private sector according to the previous point, Proposition 3 remains valid to assure sustainable growth as the vector of political institutions converge to $(\lambda_\tau, \lambda_{Sb}, \lambda_R) \to \left(0, 0, \lambda_R^*\right)$ and $\tau_B = 0$, where λ_R^* represents the access level to the political arena generating $\psi_L^*\left(\psi_{E_P}^{CC}, \psi_{E_{NP}}^{CC}\right)$. If the vector of optimal political institutions $(\lambda_\tau, \lambda_{Sb}, \lambda_R)$ does not lead to $\tau_B = 0$, sustainable growth is less feasible before $\lambda_{AE_P} << \lambda_{TE_P}$ and/or $\lambda_{TE_{NP}} << \lambda_{AE_{NP}}$ as base tax rates exceed $\tau_B(t) > \left(\frac{\left(\kappa\hat{\Pi}_{E_P}\right)^{1-\varpi}}{(1-\lambda_{Sb})\left(\gamma_{E_P}-1\right)\varpi\lambda_{TE_P}}\right)^{\frac{1}{\varpi}}$ and/or $\tau_B(t) > \left(\frac{\left(\kappa Max\left(\hat{\Pi}_{E_{NP}}\right)\right)^{1-\varpi}}{(1-\lambda_{Sb})\left(\gamma_{E_{NP}}-1\right)\varpi\lambda_{AE_{NP}}}\right)^{\frac{1}{\varpi}}$, whose values are more likely to emerge as $\kappa \to 0$;*

- *if aggregate technical progress is driven by the public sector due to $\lambda_{Sb}^* < \lambda_{Sb} < 1$, and assuming positive growth rates of energy consumption in the long term $g_E > 0$, $\lambda_{AE_P} > \lambda_{TE_P}$ and $\lambda_{TE_{NP}} > \lambda_{AE_{NP}}$; or $\lambda_{AE_P} >> \{\lambda_{TE_P}, \lambda_{AE_{NP}}\}$; or $\lambda_{TE_{NP}} >> \{\lambda_{TE_P}, \lambda_{AE_{NP}}\}$ allow for sustainable growth as the vector of political institutions converge to $(\lambda_\tau, \lambda_{Sb}, \lambda_R) \to \left(1, \lambda_{Sb}^*, 0\right)$ and $\lambda_{Sb}^* \to 0$.*

(Proof: see Appendix as well as Proposition 3, Lemma 4 and 5)

Implications of Proposition 4 can be summarized as follows: i) levels of environmental quality and constraints to the holdup problem related to public subsidies determine whether the public or the private sector drives long-term growth. More precisely, as $\kappa \to 0$, effective tax rates raise $\tau \to 1$ given our previous assumption of the whole population demanding a faster energy transition through specific R&D subsidies as the environment worsens. Therefore resources are siphoned from the private to the public sector, and for more inclusive public intervention in terms of non-appropriation of public funds by the ruling subset of the population $\lambda_{Sb} \to 0$, higher incentives to private innovation will rely on the public sector instead of market inefficiency. On the other hand, if the private sector takes the leading role, efficient political institutions in terms of fast economic growth will be those that, according to Lemma 4, decrease τ at the same time technical diffusion rates maximize incentives to private innovation $\psi_v \to \psi_v^*$. That implies states where the revenue extraction effect to enrich the ruling subset is minimized $\lambda_\tau \to 0$, the political consolidation effect is intensified through lower entry barriers to the political arena $\lambda_R \to 0$ and the holdup problem is constrained through better controls on public expenditure $\lambda_{Sb} \to 0$.

ii) When long-term growth is driven by the private sector and differences in research productivity parameters support an energy transition led by market incentives, the aforementioned political institutions are efficient in terms of sustainable growth as long as the price manipulation effect yields an average level of technological diffusion $\psi_L^*\left(\psi_{E_P}^{CC}, \psi_{E_{NP}}^{CC}\right)$, thus institutions controlling the capacity of public dissent must equal $\lambda_R = \lambda_R^*$. On the other hand, since base tax rates are very likely to be positive under this efficient subset of political institutions for sustainable growth led by the private sector, according to Lemma 5 as $\kappa \to 0$ and differences in research productivity parameters are contrary to an energy transition based on market incentives, the risk for an environmental collapse rises as public subsidies distort incentives to innovation even more. Before this situation, a more efficient set of political institutions would require $\lambda_{Sb} \to 1$ in order to cancel the distorting effect of public intervention. In the case that the public sector determines long-term growth, the revenue extraction effect should dominate $\lambda_\tau \to 1$ in order to maximize the size of R&D expenditure, as well as controls on public sector's commitment must increase up to their maximum attainable value $\lambda_{Sb} = \lambda_{Sb}^*$.

To summarize, the set of efficient political institutions in terms of fast and sustainable long-term growth depends on the current damage to the environment and differences in productivity levels of researchers in the energy market, hence there is not a unique solution. However, we can affirm that each of the already commented sets of efficient political institutions have in common that they are not the best option for the enrichment of the ruling group at the expense of the citizens, but they always seek to foster the energy transition as well as widespread economic growth. Therefore, political institutions whose first objective is maximization of disposable income of the rulers are more inefficient, hence they are more likely to endanger sustainable growth.

5.6 Simulations

5.6.1 Parameter values

Regarding output elasticities, we assume machinery and energy production as activities intensive in capital stock, thus $\varrho = \chi = 0.7$; manufactured goods as highly dependent of machines and energy flows, $\varsigma = 0.5$, $\xi = 0.4$; and identical contribution of manufactures and labour force to final goods, hence $\eta = 0.5$. These output elasticities yield capital share $\alpha = 0.315$, which is very close to the standard parameter $\alpha = 1/3$. Regarding technical progress, the size of innovations is assumed to be $\gamma = 2$, and the productivity parameters of researchers take the value $\lambda_{Av} = \lambda_{Tv} = 0.05$. The chosen technical progress parameters, alongside the aforementioned output elasticities, yield aggregate relative R&D expenditure without environmental policy equal to $\hat{D} \approx 3$, as well as growth rates of aggregate technical progress equal to $g_A \approx 1.5$. These figures are also in line with empirical data (see, for instance, WDI database (World Bank, 2021)). Initial values for relative technical factors $\left(\frac{A_P}{A_{NP}}, \frac{T_{NP}}{T_P}\right)$ are imposed to fit the world's share of gross polluting energy over gross aggregate energy in 2012 $\Theta \approx 0.8$. Finally, we follow Acemoglu et al. (2012) for modelling the temperature increase function $\Delta(t) \approx 3 \log_2 \left(Q/280\right)$, where Q is CO_2 atmospheric concentration in ppm. Additionally, the chosen environmental awareness parameter is $\theta_Q = 0.15$.

5.6.2 Example 1: Market Efficiency and Sustainability

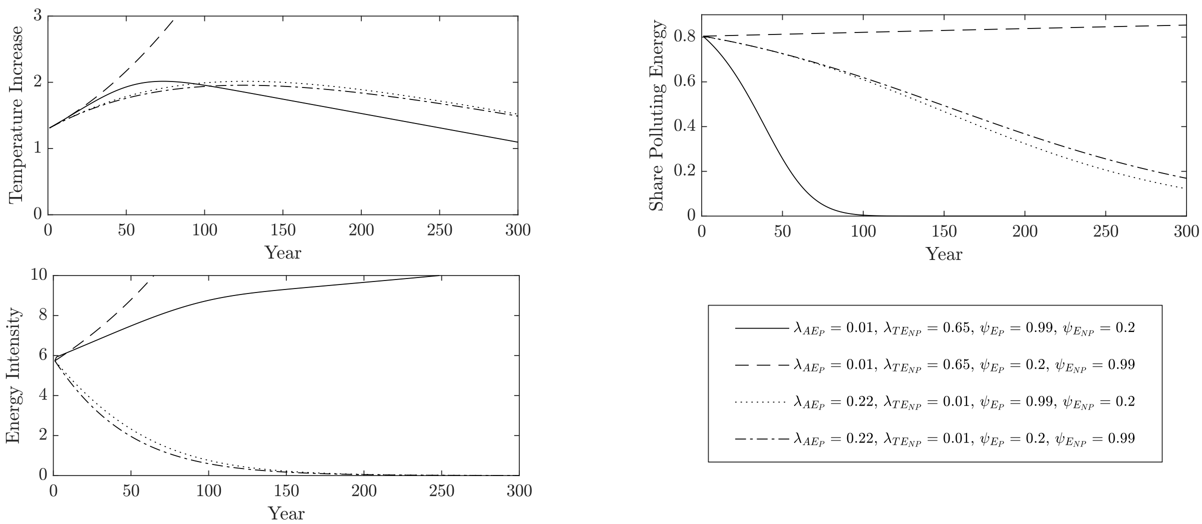

Figure 5.1: Market Efficiency and Climate Change

For illustrative purposes, we first present the results obtained from a numerical analysis focused on the effects of technical diffusion rates on the energy transition and the climate change. The chosen parameters are based on those of the following subsection, where they will be appropriately explained, and the starting period of time is 2012. There is an exception regarding different values for λ_{AE_P} and $\lambda_{TE_{NP}}$, thus we can show how changes in technical diffusion rates or market efficiency levels can lead or not to further increases in temperature. Their values represent the minimum required for sustainability when market efficiency factors are in line with them. The results of this simple simulation can be observed in Figure 5.1, which reflects the importance of Propositions 2 and 3 for sustainable growth. These can be summarized as:

- When the energy transition is based on the Schumpeterian or "creative destruction" effect, that is $\lambda_{TE_{NP}} >> \lambda_{AE_P}$, highly monopolized non-polluting energy markets are required to assure the fastest energy transition and keep the temperature increase levels below the Paris Agreement objective of $2°C$ (the turning point for increasing temperature would be reached in the 2060s). Moreover, increasing market competition in polluting energy markets, thus fostering the "escape-competition" effect in them, would also accelerate this process through slight improvements in energy intensity levels.
- When the energy transition is based on the "escape-competition" effect, that is $\lambda_{AE_P} >> \lambda_{TE_{NP}}$, there is no need for specific market structures. The energy transition is performed at a slower pace -more than 3 times slower than the previous one-, and the turning point for non-increasing temperatures requires 100 more years. The reason lies in the fact that innovation focused on quality-improving techniques for polluting producers slows down -or even holds constant- the shift of polluting energy demand from manufacturers. Therefore, incentives for innovation in non-polluting energy markets evolve more slowly. However, the paths followed in energy efficiency levels -the inverse of energy intensity- are positive and fast, compared to the previous case. Hence the economy is basing its energy transition on effective, not gross, energy production

5.6.3 Example 2: Complete Model

Three institutional frameworks are portrayed: two situations approaching to dictatorships of the elites and the middle class, and the state with constrained elites that will serve as the benchmark state. For institutional parameters, we first set $\varpi = 0.5$ constant between different state forms. Additionally, wealth inequality is defined to be $\vartheta = 0.455$ (the World Inequality Database estimates world's wealth concentration for the top percentile as approximately 50%). For the State with constrained elites, the chosen vector of political institutions is $\left(\lambda_\tau^{CR}, \lambda_R^{CR}, \lambda_{Sb}^{CR}\right) = (0.75, 0.23, 0.5)$. This yields income tax rate $\tau^{CR} \approx 0.22$, also in line with world's average tax rate (see WDI database (World Bank, 2021)), and allows us to choose technical diffusion rates $\left(\psi_X^{CR}, \psi_Z^{CR}, \psi_{E_P}^{CR}, \psi_{E_{NP}}^{CR}\right) = (0.75, 0.7, 0.7, 0.7)$, where markets are more concentrated in the energy sector with dominant energy firms controlling $\approx$ 40% of market share. For the remaining state forms, political institutional vectors are $\left(\lambda_\tau^{R}, \lambda_R^{R}, \lambda_{Sb}^{R}\right) = (0.99, 0.99, 0.99)$ and $\left(\lambda_\tau^{C}, \lambda_R^{C}, \lambda_{Sb}^{C}\right) = (0.67, 0, 0)$, which yield economic institutions $\left(\psi_X^{R}, \psi_Z^{R}, \psi_{E_P}^{R}, \psi_{E_{NP}}^{R}, \tau^R\right) = (0.5, 0.25, 0.2, 0.2, 0.4)$ and $\left(\psi_X^{C}, \psi_Z^{C}, \psi_{E_P}^{C}, \psi_{E_{NP}}^{C}, \tau^C\right) = (0.9, 0.9, 0.9, 0.9, 0.02)$. Following Acemoglu et al. (2012),

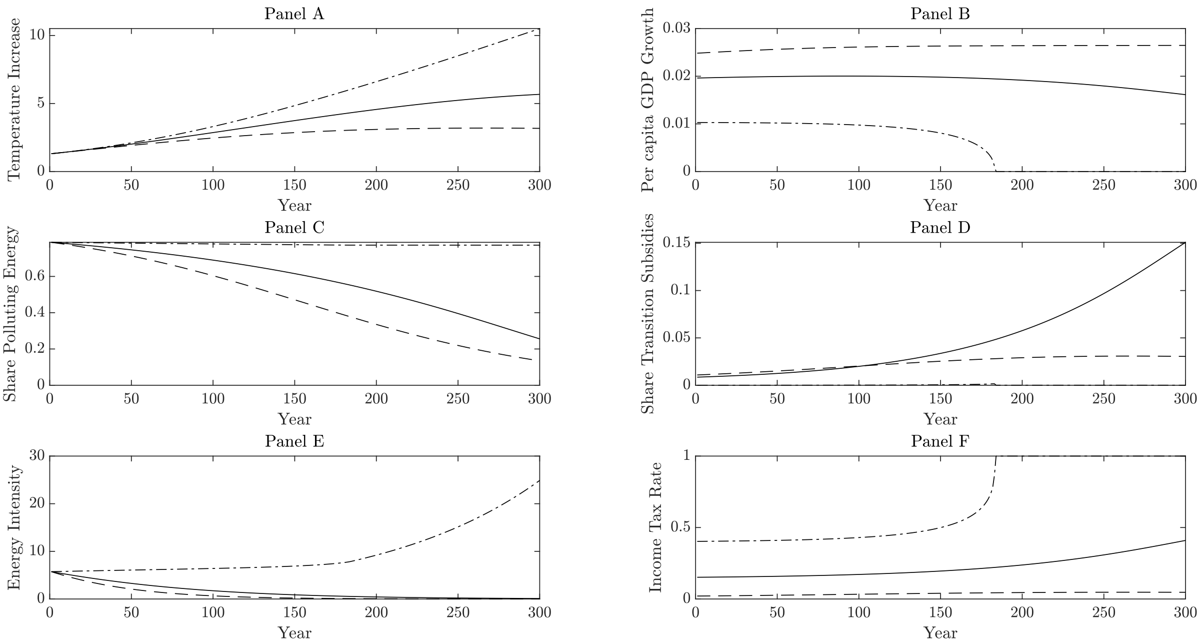

Figure 5.2: Institutional Quality and Climate Change (Smooth line for benchmark State; dashed line for extractive institutions; dashed-dotted line for inclusive institutions)

the disaster temperature increase is $\Delta^* = 6°C$ with $Q^* = 1120$ ppm. Research productivity parameters required to not exceed the $6°C$ disaster level in the state with constrained elites and observe sustained decreases in energy intensity levels must take values $\lambda_{AE_P} = 0.2$ and $\lambda_{T_{ENP}} = 0.05$.

Figures 2 and 3 show the results of this numerical simulation, where the latter includes different combinations of research productivity parameters required for the state with constrained elites to avoid the $2°C$ temperature increase, as well as an additional scenario with Pigouvian taxes/subsidies to on energy markets τ_E and increased environmental awareness θ_Q. The results can be summarized as:

- Our model and parameter choice for the benchmark state is in line with predictions from the IPCC and WMO, given that global temperatures will exceed the $2°C$ objective before 2060. Additionally, a turning point close to $6°C$ is simulated for 2400.

- The benchmark state requires whether a shift in research productivity parameters $\left(\lambda_{AE_P}, \lambda_{TE_{NP}}\right) = (0.05, 1.75)$ or increase productivity of quality-improving researchers for polluting energy firms $\left(\lambda_{AE_P}, \lambda_{TE_{NP}}\right) = (0.38, 0.05)$ to fulfill the Paris Agreement objective of temperatures not increasing beyond $2°C$. The first one leads to a faster transition to clean energy production at the expense of lower increases in energy efficiency, while the second accelerates reductions in energy intensity levels with a lagged energy transition.

- Pigouvian taxes/subsidies alone create strong distortions on the path to attain a

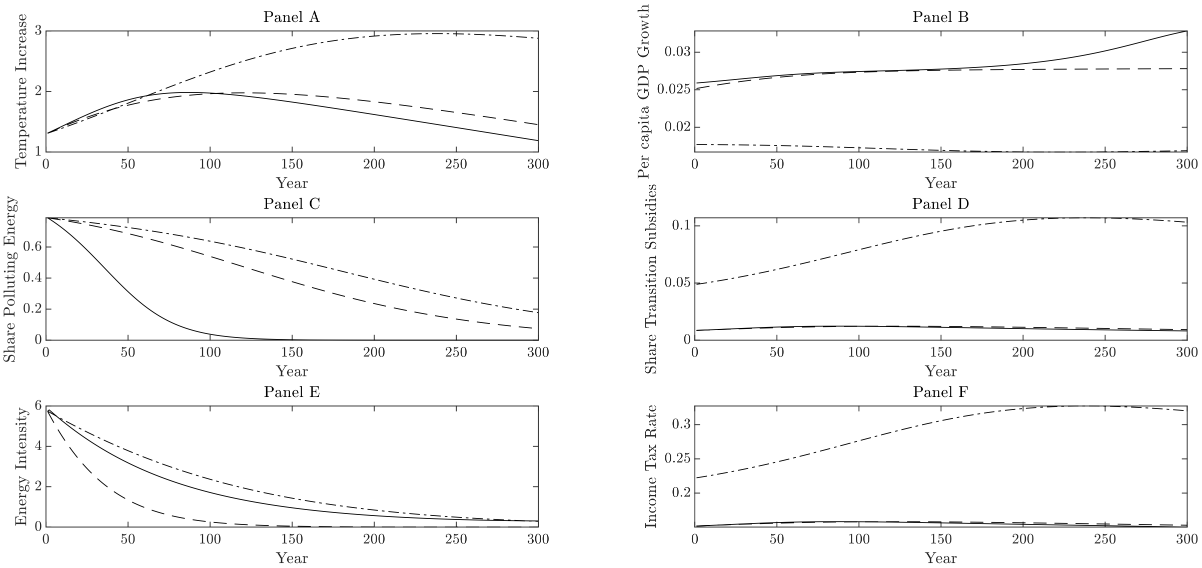

Figure 5.3: Parameters for Paris Agreement $2°C$ (Smooth line for $\left(\lambda_{AE_P}, \lambda_{TE_{NP}}\right) = (0.05, 1.75)$; dashed line for $\left(\lambda_{AE_P}, \lambda_{TE_{NP}}\right) = (0.38, 0.05)$; dashed-dotted line for $\left(\tau_E, \theta_Q\right) = (0.2, 0.99)$)

clean transition if this transition is based on improvements in energy efficiency levels, which is the case of the benchmark state. The explanation lies on τ_E shifting incentives from polluting to non-polluting production and innovation, which slows down the transition due to their relative disadvantage in research productivity levels. Figure 5.3 shows the combination of Pigouvian tax/subsidy rate for polluting energy producers and levels of environmental awareness that yield the lowest maximum increase in temperatures, which is $3°C$.

- As institutions become more extractive the turning point in temperature increase rises (see Figure 5.2, Panel A). This is a consequence of an inefficient public sector imposing discouraging taxation for private innovators and scarce public subsidies to research.

- In line with the previous point, our model predicts that states characterized by more inclusive institutions present a faster energy transition as well as require a smoother and temporary increase in fiscal pressure (from 2% in 2012 to a maximum of 4.4% around 2270) to fund transition subsidies (Figure 5.2, Panel D and F).

- Assuming there exist good substitution possibilities between polluting and non-polluting energy production, the boost to energy transitioning research due to increases in green taxes and public subsidies lead to a higher per capita GDP growth slowdown as political institutions converge to more extractive states (Figures 2 and 3, Panel B). Moreover, highly inclusive states may even present a positive increase in long-term growth rates due to an efficient usage of public taxation.

5.7 Conclusions

In this article, we introduced endogenous Schumpeterian and "escape-competition" innovations in a growth model considering environmental damage due to polluting energy consumption. We allowed for different degrees of market competition through exogenous technical diffusion in three intermediate productive stages, and included two types of technical factors: quality- and process-improving techniques. We also endogenized the role of extractive and inclusive political institutions on economic institutions, technical progress, and environmental protection. Long-term sustainability is dependent on institutional inclusiveness.

The implications of our model can be summarized as follows: i) clean energy transitions can be obtained through the absolute disappearance of polluting energy producers through rapid improvements in the marginal costs of clean energy producers and/or sustained and fast improvements in quality levels of polluting energy flows; ii) manipulation of market efficiency through technical diffusion rates can foster or hamper the energy transition. Differences in researchers' productivity levels will determine the most effective competition policy, which according to our simulation and empirical data, seems to be biased towards quality-improving techniques among polluting energy producers; iii) more inclusive institutions in terms of lower taxation and more efficient public expenditure in terms of higher R&D subsidies fostering the energy transition lead to more sustainable growth. Therefore states characterized by extractive elites are very likely to endanger sustainable growth.

We also carry out a numerical simulation whose results of excessive increase in temperatures are in line with the forecasts of the IPCC. The most important variables, such as growth rates or tax rates, are in line with empirical evidence and follow smooth paths, which may indicate the robustness of the present model. The simulation of fiscal pressure and public intervention in R&D markets shows elites and citizens will only be prone to seriously tackle climate change as long as damage levels are too close to the environmental disaster. This suggests that improvements in human capital of certain researchers in energy markets, more inclusive institutions leading to more efficient public taxation and expenditure, higher Pigouvian taxes/subsidies when the energy transition is driven by decreases in marginal costs of clean energy producers, and higher environmental awareness are required to avoid excessive increases in global temperatures.

5.8 Appendix of Chapter 3

5.8.1 Proof of Lemma 1

Tracing back to the problem of maximization of intermediate firms, the assumption of existence of positive technical diffusion rates $\psi > 0$ alongside quantity setting firms, hence $0 < \sigma(\psi) < 1$ is a necessary condition for a feasible equilibrium. Otherwise, competitive firms will face losses thus leave the market. Additionally, free access to copied techniques $\psi T(t, i)$ ensures that long-term equilibrium of the competitive fringe is characterized by a sufficient large number of entrant firms until extraordinary gains of that fringe become null.

5.8.2 Proof of Lemma 2

Since capital and labour inputs are homogeneous, arbitrage conditions for equilibrium in capital and labour markets are

$$R_Z(t) = R_E(t) \tag{5.75}$$

$$w_Y(t) = w_X(t) = w_Z(t) = w_E(t) \tag{5.76}$$

Using price equations (5.7)-(5.15) in (5.32) and (5.33) leads to Lemma 2.

5.8.3 Proof of Lemma 3

Derivatives of (5.40) respect to ψ_v and condition $\partial g_A/\partial\psi_v > 0$ imply

$$\frac{1-\eta}{\eta} > -\frac{\frac{\partial\hat{D}_{TX}}{\partial\psi_X} + (1-\varsigma)\frac{\partial\hat{D}_{AZ}}{\partial\psi_X} + \varsigma\frac{\partial\hat{D}_{TZ}}{\partial\psi_X} + (1-\xi)\frac{\partial\hat{D}_{AE}}{\partial\psi_X} + \xi\frac{\partial\hat{D}_{TE}}{\partial\psi_X}}{\partial\hat{D}_{AX}/\partial\psi_X} \tag{5.77}$$

$$\frac{1-\varsigma}{\varsigma} > -\frac{\partial\hat{D}_{TZ}/\partial\psi_Z}{\partial\hat{D}_{AZ}/\partial\psi_Z} \tag{5.78}$$

$$\frac{1-\xi}{\xi} > -\frac{\partial\hat{D}_{TE}/\partial\psi_E}{\partial\hat{D}_{AZ}/\partial\psi_E} \tag{5.79}$$

From (5.38) and (5.39), derivatives of relative R&D expenditures respect to technical diffusion rates can be read as

$$\frac{\partial\hat{D}_{Av}}{\partial\psi_v} = \frac{1-\lambda_{Av}\left(1-\mathrm{Min}\left(\psi_v\right)\right)\tilde{\pi}_v}{\left(1-\lambda_{Av}\lambda_{Tv}\left(1-\psi_v\right)^2\tilde{\pi}_v^2\right)^2} 2\lambda_{Av}\lambda_{Tv}\left(1-\psi_v\right)\tilde{\pi}_v^2 \tag{5.80}$$

$$\frac{\partial\hat{D}_{Tv}}{\partial\psi_v} = -\frac{1-\lambda_{Av}\left(1-\mathrm{Min}\left(\psi_v\right)\right)\tilde{\pi}_v}{\left(1-\lambda_{Av}\lambda_{Tv}\left(1-\psi_v\right)^2\tilde{\pi}_v^2\right)^2}\lambda_{Tv}\tilde{\pi}_v\left(1+\lambda_{Av}\lambda_{Tv}\left(1-\psi_v\right)^2\tilde{\pi}_v^2\right) \tag{5.81}$$

$$\frac{\partial\hat{D}_{A(\bar{Y})}}{\partial\psi_X} = -\lambda_{A\bar{Y}}\frac{\left(1-\mathrm{Min}\left(\psi_{\bar{Y}}\right)\right)\left(1+\lambda_{A\bar{Y}}\lambda_{T\bar{Y}}\left(1-\psi_{\bar{Y}}\right)^2\tilde{\pi}_{\bar{Y}}^2\right) - 2\lambda_{T\bar{Y}}\left(1-\psi_{\bar{Y}}\right)^2\tilde{\pi}_{\bar{Y}}}{\left(1-\lambda_{A\bar{Y}}\lambda_{T\bar{Y}}\left(1-\psi_{\bar{Y}}\right)^2\tilde{\pi}_{\bar{Y}}^2\right)^2}\frac{\partial\tilde{\pi}_{\bar{Y}}}{\partial\psi_X} \tag{5.82}$$

$$\frac{\partial\hat{D}_{T(\bar{Y})}}{\partial\psi_X} = \lambda_{T\bar{Y}}\left(1-\psi_{\bar{Y}}\right)\frac{1+\lambda_{A\bar{Y}}\lambda_{T\bar{Y}}\left(1-\psi_{\bar{Y}}\right)^2\tilde{\pi}_{\bar{Y}}^2 - 2\lambda_{A\bar{Y}}\left(1-\mathrm{Min}\left(\psi_{\bar{Y}}\right)\right)\tilde{\pi}_{\bar{Y}}}{\left(1-\lambda_{A\bar{Y}}\lambda_{T\bar{Y}}\left(1-\psi_{\bar{Y}}\right)^2\tilde{\pi}_{\bar{Y}}^2\right)^2}\frac{\partial\tilde{\pi}_{\bar{Y}}}{\partial\psi_X} \tag{5.83}$$

where, since $\partial\tilde{\pi}_Z/\partial\psi_X = \varsigma\eta$ and $\partial\tilde{\pi}_E/\partial\psi_X = \xi\eta$, $\partial\hat{D}_{A(\bar{Y})}/\partial\psi_X = \hat{D}'_{A(\bar{Y})}$ and $\partial\hat{D}_{T(\bar{Y})}/\partial\psi_X = \hat{D}'_{T(\bar{Y})}$ are independent of ψ_X. Substitution of (5.82) and (5.83) in (5.78) and (5.79) yields

$$(1-\psi_Z)\left(\lambda_{AZ}\lambda_{TZ}(1-\psi_Z)\tilde{\pi}_Z^2 - 2\frac{1-\varsigma}{\varsigma}\lambda_{AZ}\tilde{\pi}_Z\right) + 1 < 0 \tag{5.84}$$

$$(1-\psi_E)\left(\lambda_{AE}\lambda_{TE}(1-\psi_E)\tilde{\pi}_E^2 - 2\frac{1-\xi}{\xi}\lambda_{AE}\tilde{\pi}_E\right) + 1 < 0 \tag{5.85}$$

Therefore $\psi_Z < 0$, $\psi_E < 0$ as well as $\lambda_{TZ} < (1-\varsigma)/(\varsigma\tilde{\pi}_Z)$ and $\lambda_{TE} < (1-\xi)/(\xi\tilde{\pi}_E)$ are necessary conditions for $\partial g_A/\partial\psi_Z > 0$ and $\partial g_A/\partial\psi_E > 0$. Solutions to (5.84) and (5.85) lead to

$$\psi_Z < 1 - \frac{\lambda_{AZ}\frac{1-\varsigma}{\varsigma} - \left(\lambda_{AZ}\left(\lambda_{AZ}\frac{(1-\varsigma)^2}{\varsigma^2} - \lambda_{TZ}\right)\right)^{\frac{1}{2}}}{\lambda_{AZ}\lambda_{TZ}\tilde{\pi}_Z} \tag{5.86}$$

$$\psi_E < 1 - \frac{\lambda_{AE}\frac{1-\xi}{\xi} - \left(\lambda_{AE}\left(\lambda_{AE}\frac{(1-\xi)^2}{\xi^2} - \lambda_{TE}\right)\right)^{\frac{1}{2}}}{\lambda_{AE}\lambda_{TE}\tilde{\pi}_E} \tag{5.87}$$

with supplementary necessary conditions $\lambda_{TZ} \leq \lambda_{AZ}\frac{(1-\varsigma)^2}{\varsigma^2}$ and $\lambda_{TE} \leq \lambda_{AE}\frac{(1-\xi)^2}{\xi^2}$.

Substituting now (5.80)-(5.83) in (5.77) yields

$$1+\lambda_{AX}\lambda_{TX}(1-\psi_X)^2\tilde{\pi}_X^2 - \frac{\left(\frac{1}{\lambda_{TX}\tilde{\pi}_X} - \lambda_{AX}(1-\psi_X)^2\tilde{\pi}_X\right)^2}{1-\lambda_{AX}\left(1-\mathrm{Min}(\psi_X)\right)\tilde{\pi}_X}\hat{D}' - \frac{1-\eta}{\eta}2\lambda_{AX}(1-\psi_X)\tilde{\pi}_X < 0 \tag{5.88}$$

with $\hat{D}' = (1-\varsigma)\hat{D}'_{AZ} + \varsigma\hat{D}'_{TZ} + (1-\xi)\hat{D}'_{AE} + \xi\hat{D}'_{TE}$. Since $\frac{\left(\frac{1}{\lambda_{TX}\tilde{\pi}_X} - \lambda_{AX}(1-\psi_X)^2\tilde{\pi}_X\right)^2}{1-\lambda_{AX}\left(1-\mathrm{Min}(\psi_X)\right)\tilde{\pi}_X} \neq 0$ leads to a fourth degree polynomial in $1-\psi_X$, we cannot present a closed-form solution to this problem. Nevertheless, for $\psi_X \to \mathrm{Min}(\psi_X)$

$$\hat{D}' > \frac{\left(1 + \left(\lambda_{TX}(1-\eta)\tilde{\pi}_X - 2\frac{1-\eta}{\eta}\right)\lambda_{AX}(1-\eta)\tilde{\pi}_X\right)\left(1-\lambda_{AX}(1-\eta)\tilde{\pi}_X\right)}{\left(\frac{1}{\lambda_{TX}\tilde{\pi}_X} - \lambda_{AX}(1-\eta)^2\tilde{\pi}_X\right)^2} \tag{5.89}$$

and for $\psi_X \to 1$

$$\hat{D}' \leq \left(1-\lambda_{AX}\left(1-\mathrm{Min}(\psi_X)\right)\tilde{\pi}_X\right)\lambda_{TX}^2\tilde{\pi}_X^2 \tag{5.90}$$

we then can affirm that $\partial g_A/\partial\psi_X > 0\ \forall\psi_X \in [\eta, 1)$.

5.8.4 Proof of Proposition 2

Using (5.38), (5.39) and (5.40) in (5.49) leads to second order polynomial

$$\tilde{a}\left(1-\psi_{\bar{E}}\right)^{2}-\tilde{b}\left(1-\psi_{\bar{E}}\right)-\tilde{c}=0 \tag{5.91}$$

where

$$\tilde{a}=\left(\frac{1-\alpha}{(\gamma-1)}\left(g_{L}+g_{A_{L}}\right)+\chi\tilde{D}-\left(1-\alpha-\eta\left(1-\xi\right)\chi\right)\right)\lambda_{A\bar{E}}\lambda_{T\bar{E}}\tilde{\pi}_{\bar{E}} \tag{5.92}$$

$$\tilde{b}=\left(1-\alpha+\eta\xi\chi\right)\lambda_{T\bar{E}}\left(1-\lambda_{A\bar{E}}\left(1-\mathrm{Min}\left(\psi_{\bar{E}}\right)\right)\tilde{\pi}_{\bar{E}}\right) \tag{5.93}$$

$$\tilde{c}=\frac{\frac{1-\alpha}{(\gamma-1)}\left(g_{L}+g_{A_{L}}\right)+\chi\tilde{D}-\lambda_{A\bar{E}}\left(1-\alpha-\eta\left(1-\xi\right)\chi\right)\left(1-\mathrm{Min}\left(\psi_{\bar{E}}\right)\right)\tilde{\pi}_{\bar{E}}}{\tilde{\pi}_{\bar{E}}} \tag{5.94}$$

with $\tilde{D}=\left(1-\eta\right)\hat{D}_{AX}+\eta\left(1-\varsigma\right)\hat{D}_{AZ}+\eta\hat{D}_{TX}+\eta\varsigma\hat{D}_{TZ}$, and solution

$$\psi_{E}=1-\frac{\tilde{b}\pm\sqrt{\tilde{b}^{2}+4\tilde{a}\tilde{c}}}{2\tilde{a}} \tag{5.95}$$

Assume that $1-\lambda_{A\bar{E}}\left(1-\mathrm{Min}\left(\psi_{\bar{E}}\right)\right)\tilde{\pi}_{\bar{E}}$ If we focus on extreme situations, we know first that for $\lambda_{AE}=0$, (5.95) can be read as

$$\psi_{E}=1+\frac{\frac{1-\alpha}{(\gamma-1)}\left(g_{L}+g_{A_{L}}\right)+\chi\tilde{D}}{\left(1-\alpha+\eta\xi\chi\right)\lambda_{T\bar{E}}\tilde{\pi}_{\bar{E}}} \tag{5.96}$$

which is only feasible for null growth $g_L=g_c=0$. This is not strange since the second condition for sustainability is more feasible as the arrival rate for quality-improving techniques increase.

For $\lambda_{TE}=0$, (5.49) can be read as

$$\lambda_{AE}=\frac{\frac{1-\alpha}{\gamma-1}\left(g_{L}+g_{A_{L}}\right)+\chi\tilde{D}}{\left(1-\alpha-\eta\left(1-\xi\right)\chi\right)\left(1-\mathrm{Min}\left(\psi_{E}\right)\right)\tilde{\pi}_{E}} \tag{5.97}$$

which requires $\eta<\frac{1}{\chi+\varsigma\varrho}$.

5.8.5 Proof of Proposition 3

Using (5.38) and (5.39) in (5.57) yields

$$\tilde{a}_{P}\left(1-\psi_{E_{P}}\right)^{2}+\tilde{b}_{P}\left(1-\psi_{E_{P}}\right)-\tilde{c}_{P}<0 \tag{5.98}$$

where

$$\tilde{a}_{P}=\left(\xi\left(1-\hat{D}_{AE_{NP}}\right)+(1+\xi)\hat{D}_{TE_{NP}}\right)\lambda_{AE_{P}}\lambda_{TE_{P}}\bar{\Theta}\tilde{\pi}_{E} \tag{5.99}$$

$$\tilde{b}_P = (1+\xi)\lambda_{TE_P}\left(1-\lambda_{AE_P}\left(1-\text{Min}\left(\psi_E\right)\right)\bar{\Theta}\tilde{\pi}_E\right) \tag{5.100}$$

$$\tilde{c}_P = \xi\lambda_{AE_P}\left(1-\text{Min}\left(\psi_E\right)\right) + \frac{(1+\xi)\hat{D}_{TE_{NP}} - \xi\hat{D}_{AE_{NP}}}{\bar{\Theta}\tilde{\pi}_E} \tag{5.101}$$

with solution

$$\psi_{E_P} > 1 - \frac{-\tilde{b}_P \pm \sqrt{\tilde{b}_P^2 + 4\tilde{a}_P\tilde{c}_P}}{2\tilde{a}_P} \tag{5.102}$$

for $\lambda_{AE_P} < \frac{1}{\left(1-\text{Min}(\psi_E)\right)\bar{\Theta}\tilde{\pi}_E}$ we focus on the positive root for (5.102). Moreover, since this condition is required for the existence of the "escape-competition" effect, we assume that $0 \leq \lambda_{AE_P} < \frac{1}{\left(1-\text{Min}(\psi_E)\right)\bar{\Theta}\tilde{\pi}_E}$ always holds.

Examining corner solutions, for $\lambda_{AE_P} = 0$ and using (5.38) and (5.39) in (5.102), this leads to

$$\psi_{E_P} > 1 - \frac{(1+\xi)\hat{D}_{TE_{NP}} - \xi\hat{D}_{AE_{NP}}}{(1+\xi)\lambda_{TE_P}\bar{\Theta}\tilde{\pi}_E} \tag{5.103}$$

Regarding (5.103), when $\lambda_{AE_{NP}} \to 0$, as $\psi_{E_{NP}} \to \text{Min}\left(\psi_E\right)$ constraints on sustainable ψ_{E_P} loosen up; while for $\lambda_{TE_{NP}} \to 0$, as $\psi_{E_{NP}} \to \psi^*_{E_{NP}}$, which implies $\hat{D}_{AE_{NP}} \to \text{Max}\left(\hat{D}_{AE_{NP}}\right)$, there will be need for more competitive markets for polluting energy producers.

Returning to (5.98), when $\lambda_{TE_P} = 0$, using (5.38) and (5.39) in (5.57) leads to

$$\tilde{a}_{NP}\left(1-\psi_{E_{NP}}\right)^2 + \tilde{b}_{NP}\left(1-\psi_{E_{NP}}\right) - \tilde{c}_{NP} > 0 \tag{5.104}$$

where

$$\tilde{a}_{NP} = \left(1-\lambda_{AE_P}\left(1-\text{Min}\left(\psi_E\right)\right)\bar{\Theta}\tilde{\pi}_E\right)\xi\lambda_{AE_{NP}}\lambda_{TE_{NP}}\left(1-\bar{\Theta}\right)\tilde{\pi}_E \tag{5.105}$$

$$\tilde{b}_{NP} = (1+\xi)\lambda_{TE_{NP}}\left(1-\lambda_{AE_{NP}}\left(1-\text{Min}\left(\psi_E\right)\right)\left(1-\bar{\Theta}\right)\tilde{\pi}_E\right) \tag{5.106}$$

$$\tilde{c}_{NP} = \xi\left(\lambda_{AE_{NP}} - \frac{\bar{\Theta}}{1-\bar{\Theta}}\lambda_{AE_P}\right)\left(1-\text{Min}\left(\psi_E\right)\right) \tag{5.107}$$

with solution

$$\psi_{E_{NP}} < 1 - \frac{-\tilde{b}_{NP} \pm \sqrt{\tilde{b}_{NP}^2 + 4\tilde{a}_{NP}\tilde{c}_{NP}}}{2\tilde{a}_{NP}} \tag{5.108}$$

where, after assuming $0 \leq \lambda_{AE_{NP}} < \frac{1}{\left(1-\text{Min}(\psi_E)\right)(1-\bar{\Theta})\tilde{\pi}_E}$, we must focus again on the positive root. Now, if $\lambda_{AE_{NP}} = 0$, we can re-express (5.108) as

$$\psi_{E_{NP}} < 1 + \frac{\xi\lambda_{AE_P}}{(1+\xi)\lambda_{TE_{NP}}}\frac{\bar{\Theta}}{1-\bar{\Theta}}\left(1-\text{Min}\left(\psi_E\right)\right) \tag{5.109}$$

which implies sustainability is always feasible for $\psi_{E_{NP}} < 1$ if polluting energy producers face a positive demand, that is $\bar{\Theta} > 0$.

5.8.6 Proof of Lemma 4

Derivative of $\tau = (1-\kappa) + \kappa\tau_B$ equals

$$\frac{\partial\tau}{\partial\kappa} = \kappa\frac{\partial\tau_B}{\partial\kappa} - (1-\tau_B) \tag{5.110}$$

where derivatives of base tax rate τ_B with respect to κ for each political regime are (use (5.65), (5.68), (5.71))

$$\frac{\partial\tau_B^R}{\partial\kappa} = -\frac{(1-\varpi)^2\left(\tau_B^R\right)^{\frac{1-2\varpi}{1-\varpi}}\left(\lambda_{Sb} + \frac{\vartheta\alpha}{\mathrm{Min}(\psi_L)}\right)}{\varpi^{\frac{2-\varpi}{1-\varpi}}\left(\left((1-\lambda_{Sb})\sum(\gamma_v-1)\lambda_v\right)^{\frac{1}{1-\varpi}}\right)} \tag{5.111}$$

$$\frac{\partial\tau_B^C}{\partial\kappa} = -\frac{(1-\varpi)^2\left(\tau_B^C\right)^{\frac{1-2\varpi}{1-\varpi}}(\lambda_{Sb} - \vartheta\alpha)}{\varpi^{\frac{2-\varpi}{1-\varpi}}\left(\left((1-\lambda_{Sb})\sum(\gamma_v-1)\lambda_v\right)^{\frac{1}{1-\varpi}}\right)} \tag{5.112}$$

$$\frac{\partial\tau_B^{CR}}{\partial\kappa} = -\frac{(1-\varpi)^2\left(\tau_B^{CR}\right)^{\frac{1-2\varpi}{1-\varpi}}\left(\lambda_{Sb} + \frac{\vartheta\alpha}{\psi_L} - (1-\lambda_R)\varphi\left((1-\vartheta\alpha)(1-\lambda_R)^{\frac{1}{1-\varpi}}\right)^{\varpi}\right)}{\varpi^{\frac{2-\varpi}{1-\varpi}}\left(\left((1-\lambda_{Sb})\sum(\gamma_v-1)\lambda_v\right)^{\frac{1}{1-\varpi}}\right)} \tag{5.113}$$

Second derivatives equal

$$\frac{\partial^2\tau_B^R}{\partial\kappa^2} = -\frac{(1-2\varpi)(1-\varpi)^3\left(\tau_B^R\right)^{-\frac{\varpi(1-2\varpi)}{(1-\varpi)(1-\varpi)}}\left(\lambda_{Sb} + \frac{\vartheta\alpha}{\mathrm{Min}(\psi_L)}\right)^2}{\varpi^{\frac{(2-\varpi)(2-\varpi)}{(1-\varpi)(1-\varpi)}}\left(\left((1-\lambda_{Sb})\sum(\gamma_v-1)\lambda_v\right)^{\frac{1}{1-\varpi}}\right)^2} \tag{5.114}$$

$$\frac{\partial^2\tau_B^C}{\partial\kappa^2} = -\frac{(1-2\varpi)(1-\varpi)^3\left(\tau_B^C\right)^{-\frac{\varpi(1-2\varpi)}{(1-\varpi)(1-\varpi)}}(\lambda_{Sb} - \vartheta\alpha)^2}{\varpi^{\frac{(2-\varpi)(2-\varpi)}{(1-\varpi)(1-\varpi)}}\left(\left((1-\lambda_{Sb})\sum(\gamma_v-1)\lambda_v\right)^{\frac{1}{1-\varpi}}\right)^2} \tag{5.115}$$

$$\frac{\partial^2\tau_B^{CR}}{\partial\kappa^2} = -\frac{(1-2\varpi)(1-\varpi)^3\left(\tau_B^{CR}\right)^{-\frac{\varpi(1-2\varpi)}{(1-\varpi)(1-\varpi)}}\left(\lambda_{Sb} + \frac{\vartheta\alpha}{\psi_L} - (1-\lambda_R)\varphi\left((1-\vartheta\alpha)(1-\lambda_R)^{\frac{1}{1-\varpi}}\right)^{\varpi}\right)^2}{\varpi^{\frac{(2-\varpi)(2-\varpi)}{(1-\varpi)(1-\varpi)}}\left(\left((1-\lambda_{Sb})\sum(\gamma_v-1)\lambda_v\right)^{\frac{1}{1-\varpi}}\right)^2} \tag{5.116}$$

Therefore we can conclude that

- $\partial\tau_B^R/\partial\kappa < 0$ and $\partial^2\tau_B^R/\partial\kappa^2 < 0$ for $\varpi < 1/2$;
- $\partial\tau_B^C/\partial\kappa < 0$ for $\lambda_{Sb} > \vartheta\alpha$ and $\partial^2\tau_B^C/\partial\kappa^2 < 0$ for $\varpi < 1/2$;

- $\partial\tau_B^{CR}/\partial\kappa < 0$ for $\lambda_{Sb} > (1-\lambda_R)\,\varphi\left((1-\vartheta\alpha)(1-\lambda_R)^{\frac{1}{1-\varpi}}\right)^{\varpi} - \frac{\vartheta\alpha}{\psi_L}$ and $\partial^2\tau_B^{CR}/\partial\kappa^2 < 0$ for $\varpi < 1/2$.

Regarding environmentally friendly taxes, derivative of (6.59) respect to κ equals

$$\frac{\partial\tau_{CC}}{\partial\kappa} = -(1-\tau_B) - (1-\kappa)\frac{\partial\tau_B}{\partial\kappa} \tag{5.117}$$

where after using (6.111), (6.112) and (6.112) we have conditions

- $\frac{\left(\tau_B^R\right)^{\frac{1-2\varpi}{1-\varpi}}}{1-\tau_B^R} > \frac{\varpi^{\frac{2-\varpi}{1-\varpi}}\left(\left((1-\lambda_{Sb})\sum(\gamma_v-1)\lambda_v\right)^{\frac{1}{1-\varpi}}\right)}{(1-\kappa)(1-\varpi)^2\left(\lambda_{Sb}+\frac{\vartheta\alpha}{\mathrm{Min}(\psi_L)}\right)}$ for $\frac{\partial\tau_{CC}^R}{\partial\kappa} > 0$;
- $\frac{\left(\tau_B^C\right)^{\frac{1-2\varpi}{1-\varpi}}}{1-\tau_B^C} > \frac{\varpi^{\frac{2-\varpi}{1-\varpi}}\left(\left((1-\lambda_{Sb})\sum(\gamma_v-1)\lambda_v\right)^{\frac{1}{1-\varpi}}\right)}{(1-\kappa)(1-\varpi)^2(\lambda_{Sb}-\vartheta\alpha)}$ for $\frac{\partial\tau_{CC}^C}{\partial\kappa} > 0$;
- $\frac{\left(\tau_B^{CR}\right)^{\frac{1-2\varpi}{1-\varpi}}}{1-\tau_B^{CR}} > \frac{\varpi^{\frac{2-\varpi}{1-\varpi}}\left(\left((1-\lambda_{Sb})\sum(\gamma_v-1)\lambda_v\right)^{\frac{1}{1-\varpi}}\right)}{(1-\kappa)(1-\varpi)^2\left(\lambda_{Sb}+\frac{\vartheta\alpha}{\psi_L}-(1-\lambda_R)\varphi\left((1-\vartheta\alpha)(1-\lambda_R)^{\frac{1}{1-\varpi}}\right)^{\varpi}\right)}$ for $\frac{\partial\tau_{CC}^{CR}}{\partial\kappa} > 0$.

which become more feasible as $\tau_B \to 1$ due to more extractive political institutions.

5.8.7 Proof of Lemma 5

Derivatives of (5.73) and (5.74) respect to τ_B equal

$$\frac{\partial\hat{D}_{Av}}{\partial\tau_B} = \frac{\lambda_{Av}\left(\partial\hat{\Pi}_{Av}^{\tau}/\partial\tau_B - 2\lambda_{Tv}\hat{\Pi}_{Tv}^{\tau}\left(1-\hat{D}_{Av}\right)\partial\hat{\Pi}_{Tv}^{\tau}/\partial\tau_B\right)}{1-\lambda_{Av}\lambda_{Tv}\left(\hat{\Pi}_{Tv}^{\tau}\right)^2} \tag{5.118}$$

$$\frac{\partial\hat{D}_{Tv}}{\partial\tau_B} = \frac{\lambda_{Tv}\left(\left(1+\lambda_{Av}\left(2\hat{D}_{Tv}\hat{\Pi}_{Tv}^{\tau}-\hat{\Pi}_{Av}^{\tau}\right)\right)\partial\hat{\Pi}_{Tv}^{\tau}/\partial\tau_B - \lambda_{Av}\left(\hat{\Pi}_{Tv}^{\tau}\partial\hat{\Pi}_{Av}^{\tau}/\partial\tau_B\right)\right)}{1-\lambda_{Av}\lambda_{Tv}\left(\hat{\Pi}_{Tv}^{\tau}\right)^2} \tag{5.119}$$

Recall that $\lambda_{Av}\lambda_{Tv}\left(\hat{\Pi}_{Tv}^{\tau}\right)^2 < 1$ is required for non-negative R&D expenditure, and derivatives of profits net of taxes and public subsidies are $\partial\hat{\Pi}_{Av}^{\tau}/\partial\tau_B = -\kappa\mathrm{Max}\left(\hat{\Pi}_v\right) + \partial\hat{G}_{Av}/\partial\tau_B$ and $\partial\hat{\Pi}_{Tv}^{\tau}/\partial\tau_B = -\kappa\hat{\Pi}_v + \partial\hat{G}_{Tv}/\partial\tau_B$, where $\partial\hat{G}_v/\partial\tau_B > 0$ for $\tau_B \in [0,1]$. Additionally, $\partial\hat{\Pi}_{Av}^{\tau}/\partial\lambda_{Av} > 0$, $\partial\hat{\Pi}_{Tv}^{\tau}/\partial\lambda_{Tv} > 0$, $\frac{\partial\left(\partial\hat{G}_{Av}/\partial\tau_B\right)}{\partial\lambda_{Av}} > 0$, $\frac{\partial\left(\partial\hat{G}_{Tv}/\partial\tau_B\right)}{\partial\lambda_{Tv}} > 0$ and are independent of other λ_v. According to these facts, it is straightforward to see that (A.64) and (A.65) are more dominated by their respective net profit derivatives $\partial\hat{\Pi}_{Av}^{\tau}/\partial\tau_B$ and $\partial\hat{\Pi}_{Tv}^{\tau}/\partial\tau_B$ with higher λ_{Av} and λ_{Tv} accordingly. Regarding net profit derivatives, if $\tau_B(t) > \left(\frac{\left(\kappa \text{Max}\left(\hat{\Pi}_v\right)\right)^{1-\varpi}}{(1-\lambda_{Sb})(\gamma_v-1)\varpi\lambda_{Av}}\right)^{\frac{1}{\varpi}}$ and $\tau_B(t) > \left(\frac{\left(\kappa\hat{\Pi}_v\right)^{1-\varpi}}{(1-\lambda_{Sb})(\gamma_v-1)\varpi\lambda_{Tv}}\right)^{\frac{1}{\varpi}}$, we can affirm that $\partial\hat{\Pi}^{\tau}_{Av}/\partial\tau_B > 0$ and $\partial\hat{\Pi}^{\tau}_{Tv}/\partial\tau_B > 0$ respectively, therefore $\hat{\Pi}^{\tau}_v$ can be whether a convex, direct or inverse function respect to $\tau_B \in [0,1]$ depending on parameters in $\frac{\left(\kappa\hat{\Pi}_v\right)^{1-\varpi}}{(1-\lambda_{Sb})(\gamma_v-1)\varpi\lambda_{Tv}}$.

For the specific cases of innovation in quality-improving techniques of polluting energy producers and process-improving techniques of clean energy producers, derivatives of net profits respect to base tax rates now equal $\partial\hat{\Pi}^{\tau}_{AE_P}/\partial\tau_B = -\kappa\left(\text{Max}\left(\hat{\Pi}_{E_P}\right) - \frac{\xi}{1+2\xi}(1-\lambda_{Sb})\right) - \frac{\xi}{1+2\xi}(1-\lambda_{Sb}) + \partial\hat{G}_{AE_P}/\partial\tau_B$ and $\partial\hat{\Pi}^{\tau}_{TE_{NP}}/\partial\tau_B = -\kappa\left(\hat{\Pi}_{E_{NP}} - \frac{1+\xi}{1+2\xi}(1-\lambda_{Sb})\right) - \frac{1+\xi}{1+2\xi}(1-\lambda_{Sb}) + \partial\hat{G}_{TE_{NP}}/\partial\tau_B$. Therefore, the impact of research productivity parameters remains identical. Besides, net profits derivatives face now

$\tau_B(t) > \left(\frac{\left(\kappa\left(\text{Max}\left(\hat{\Pi}_{E_P}\right)-\frac{\xi}{1+2\xi}(1-\lambda_{Sb})\right)+\frac{\xi}{1+2\xi}(1-\lambda_{Sb})\right)^{1-\varpi}}{(1-\lambda_{Sb})(\gamma_v-1)\varpi\lambda_{Av}}\right)^{\frac{1}{\varpi}}$ and

$\tau_B(t) > \left(\frac{\left(\kappa\left(\hat{\Pi}_{E_{NP}}-\frac{1+\xi}{1+2\xi}(1-\lambda_{Sb})\right)+\frac{1+\xi}{1+2\xi}(1-\lambda_{Sb})\right)^{1-\varpi}}{(1-\lambda_{Sb})(\gamma_v-1)\varpi\lambda_{Tv}}\right)^{\frac{1}{\varpi}}$ for $\partial\hat{\Pi}^{\tau}_{Av}/\partial\tau_B > 0$ and $\partial\hat{\Pi}^{\tau}_{Tv}/\partial\tau_B > 0$,

which increase the turning point in τ_B as $\kappa \to 0$ if
$\lambda_{Sb} < 1 - \frac{1+2\xi}{2\xi}\text{Max}\left(\hat{\Pi}_{E_P}\right)$ and $\lambda_{Sb} < 1 - \frac{1+2\xi}{2(1+\xi)}\hat{\Pi}_{E_{NP}}$ respectively.

5.8.8 Proof of Proposition 4

According to the Proof of Lemma 5, R&D expenditure with public intervention can be whether a convex, increasing or decreasing function respect to τ_B. Therefore, maximization of (5.73) and (5.74) is only attainable whether for $\tau_B = 1$, which implies $\tau = 1$; or $\tau_B = 0$, which entails $\tau = 1 - \kappa$. Using this in (40), (75) and (76) yields condition for maximization of g_c when $\tau_B = 0$

$$\lambda_{Sb} > 1 - \left(\frac{\kappa\sum_v\left(\left(1-\frac{p_v v}{Y}\right)\hat{D}^{\kappa}_{Av} + \frac{p_v v}{Y}\hat{D}^{\kappa}_{Tv}\right)}{\varpi^{\frac{1}{1-\varpi}}\sum_v\left(\left(1-\frac{p_v v}{Y}\right)\left((\gamma_{Av}-1)\lambda_{Av}\right)^{\frac{1}{1-\varpi}} + \frac{p_v v}{Y}\left((\gamma_{Tv}-1)\lambda_{Tv}\right)^{\frac{1}{1-\varpi}}\right)}\right)^{1-\varpi} \tag{5.120}$$

where $\hat{D}^{\kappa}_{Av} = \lambda_{Av}\frac{\hat{\Pi}_{Av}-\lambda_{Tv}\kappa\left(\hat{\Pi}_{Tv}\right)^2}{1-\lambda_{Av}\lambda_{Tv}\left(\kappa\hat{\Pi}_{Tv}\right)^2}$ and $\hat{D}^{\tau}_{Tv} = \lambda_{Tv}\frac{1-\lambda_{Av}\kappa\hat{\Pi}_{Av}}{1-\lambda_{Av}\lambda_{Tv}\left(\kappa\hat{\Pi}_{Tv}\right)^2}\hat{\Pi}_{Tv}$. According to (A.58), for $\kappa = 0$, $\lambda_{Sb} > 1$, thus technical progress is strictly increasing in τ_B for $\lambda_{Sb} < 1$. As $\kappa \to 1$, $\lambda_{Sb} \to 0$ for $g_c(\tau_B = 1) = \text{Max}(g_c)$. Moreover, if $\gamma \approx 1$, $g_c(\tau_B = 0) = \text{Max}(g_c)$ for $\lambda_{Sb} \in [0,1]$.

For public sector directing aggregate technical progress, assume $\tau = 1$ and substitute in (5.40), (5.60), (5.61) and (5.62), thus condition for sustainable growth equals

$$\lambda_{AE_P} > \frac{\left(\left(\left(\gamma_{AE_{NP}} - 1 \right) \lambda_{AE_{NP}} \right)^{\frac{1}{1-\varpi}} + \frac{1+\xi}{\xi} \left(\left(\left(\gamma_{TE_P} - 1 \right) \lambda_{TE_P} \right)^{\frac{1}{1-\varpi}} - \left(\left(\gamma_{TE_{NP}} - 1 \right) \lambda_{TE_{NP}} \right)^{\frac{1}{1-\varpi}} \right) \right)^{1-\varpi}}{\gamma_{AE_P} - 1} \tag{5.121}$$

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6 Conclusiones

La presente tesis estudia la viabilidad del crecimiento económico sostenible en términos de cambio climático controlado. Está dividida en tres capítulos, con contribuciones tanto empíricas como teóricas en relación al nexo entre crecimiento económico y energía, el papel de las instituciones políticas, las emisiones de CO2 y el cambio climático antropogénico. La idea clave que conecta los tres capítulos entre sí es la posible existencia de límites al progreso tecnológico en términos de productividad energética, sus restricciones institucionales y su conexión con el cambio climático.

El capítulo 1 estudia los principales determinantes económicos de los cambios en emisiones CO2 per cápita para una muestra amplia de países, incluyendo proyecciones de la evolución de la temperatura mundial bajo diferentes escenarios en base a las estimaciones realizadas. Se emplean datos provenientes de 173 países en el periodo 1990-2014, extraídos de la base de datos del Banco Mundial, con el objeto de contrastar la existencia de la Curva Medioambiental de Kuznets (EKC) para las emisiones de CO2. A diferencia de estudios previos, también se analiza la existencia de la Hipótesis del Refugio de Contaminación (PHH), así como el impacto de la difusión técnica a través de los modelos espaciales Spatial Lag of X (SLX) y Spatial Durbin Error (SDEM). Además, las estimaciones se llevan a cabo no sólo para el mundo en conjunto, sino para seis áreas continentales: Europa, América del Norte, América del Sur, Asia, Oceania y África. El objetivo es comprobar el nivel de robustez de las estimaciones, así como estimar el impacto de las variables explicativas a un nivel más desagregado. Los resultados indican que, independientemente de la especificación empleada, no se puede rechazar la existencia de la EKC para todas las áreas excepto Oceanía. Es importante destacar que, tras controlar por la existencia de correlación espacial a través de la PHH y el efecto de la difusión técnica, se observan cambios en el tamaño de los coeficientes estimados, por lo que la omisión de variables retardadas espacialmente parece dar lugar a estimaciones sesgadas en un contexto de emisiones de CO2 per cápita explicadas por determinantes económicos. En este sentido, a pesar de que el punto de inflexión para el mundo en conjunto corregido por los spillovers espaciales disminuye en casi un 70%, su valor sigue estando lejos del nivel más alto de renta per cápita observado en la muestra. Por lo tanto, se espera que el crecimiento económico bruto, sin progreso técnico dirigido a la eficiencia y transición energética, incremente las emisiones de CO2 per cápita en los años venideros.

Asimismo, el estudio revela que existen evidencias a favor de la PHH para el mundo en su conjunto en fases iniciales de desarrollo económico, una tendencia marcada principalmente por países europeos y asiáticos. En el caso de Oceanía, se observa una PHH a partir de un nivel suficiente de desarrollo económico. Estos resultados podrían apuntar hacia un posible cambio en los patrones de comercio mundial a largo plazo entre los años 1990 y 2014, donde países relativamente más desarrollados estarían exportando bienes de capital menos contaminantes. Las variables explicativas asociadas al progreso técnico doméstico en términos de reducciones en la intensidad del uso de la energía, así como a avances en la transición energética hacia fuentes renovables, disminuyen las emisiones

CO2 per cápita, independientemente del área o especificación estudiadas. En concreto, los resultados muestran un elasticidad unitaria para las emisiones respecto a cambios en los niveles de intensidad energética. En cambio, la influencia del peso relativo de la energía renovable es cercano a cero. También, la difusión técnica medida como el retardo espacial de la intensidad energética es significativa a nivel global a la hora de reducir las emisiones CO2 per cápita, siendo las economías europeas las que disfrutan de una mayor elasticidad estimada, mientras que los paises africanos parecen seguir el proceso inverso, donde spillovers técnicos dan lugar a incrementos en las emisiones per cápita.

Finalmente, se incluyen diversas proyecciones sobre la evolución de las emisiones globales de CO2, así como de sus concentraciones, entre los años 2015 y 2100. El objetivo es confirmar si el crecimiento económico sostenible es posible bajo distintos escenarios considerando las tendencias actuales de crecimiento económico, un aceleramiento en el mismo, así como diferentes sendas de eficiencia y transición energética y el efecto de la PHH. Las conclusiones son que las sendas de crecimiento a largo plazo pueden ser sostenibles ante reducciones interanuales del 2.5% en términos de intensidad energética, junto a una gradual transición a fuentes renovables.

El capítulo 2 analiza la existencia de convergencia global en términos de intensidad energética, así como su evolución entre los años 1990 y 2010 empleando dos muestras grandes de países. También contribuye a la literatura empírica a través del planteamiento de un modelo económico simple que justifica la estimación de regresiones β-convergencia en este contexto. Utilizando información procedente de las series del Banco Mundial, de las Penn World Tables y de datos relativos a la calidad institucional de Kuncic, se obtuvieron dos muestras de países, una muy amplia de 173 naciones y otra más reducida, de 130, que incluye variables relativas a los estados estacionarios de cada economía, como las tasas de ahorro o depreciación.

Las cinco principales contribuciones de este capítulo respecto a la literatura existente son: el uso de la base de datos más extensa hasta el momento para analizar la convergencia en productividad energética mundial, la propuesta de un modelo teórico que justifique la estimación de regresiones de β-convergencia controlando por el estado estacionario de una economía, la estimación de dichas regresiones condicionales para la muestra de 130 países, la consideración y control de la correlación espacial a través de la inclusión de variables explicativas retardadas espacialmente a nivel global, y la estimación del impacto de las variables empleadas en las regresiones de β-convergencia sobre diferencias a nivel nacional respecto al nivel medio de intensidad energética.

La hipótesis de σ-convergencia, o disminuciones en el tiempo en diferencias en la intensidad energética, es estudiada a través de la exploración de las desviaciones típicas y de estimadores kernel en la distribución muestral a lo largo del tiempo para ambas muestras, y tanto para cada cada una de las divisiones por grupos continentales, así como para el mundo en su totalidad. Los resultados apuntan hacia la existencia de σ-convergencia para todas las áreas excepto América en la base de datos reducida, con una tasa de σ-convergencia del -0.6% y -1% para el mundo en su conjunto. Además, la mayor parte de áreas y el mundo en conjunto parecen presentar una ralentización en las tasas de σ-convergencia a partir del año 2000, por lo que el proceso de convergencia parece ser más bien en términos condicionales respecto a los estados estacionarios de cada economía. Se detecta que las principales áreas que dirigen el proceso de convergencia global son Europa y Asia-Oceanía, mientras que África y América parecen estar ralentizándolo o incluso revirtiéndolo. La estimación de las funciones de densidad kernel por áreas refuerza los anteriores resultados, excepto por el hecho de una evolución hacia distribuciones unimodales, lo que parece apuntar hacia la convergencia en términos absolutos. Asimismo, se observa una disminución interanual en el nivel medio de intensidad energética a las tasas -1.58% y -1.34%, dependiendo de la muestra escogida, para el periodo 1990-2010.

El modelo teórico que justifica la estimación de regresiones de β-convergencia se basa en las funciones de producción de la teoría Neoclásica-Schumpeteriana del crecimiento, considerando mercados anidados y un vector de bienes intermedios ponderados por sus respectivas calidades que dan lugar al output final. Asumiendo que la energía es uno de estos bienes intermedios, la cual requiere trabajo y capital para ser producida, la solución del Modelo de Equilibrio General da lugar a una función de equilibrio de intensidad energética, la cual aumenta de acuerdo a la productividad específica a la producción de energía, así como por incrementos en el stock de capital por trabajador efectivo, y disminuye con el progreso tecnológico agregado. Por tanto, las dinámicas de transición asociadas a la acumulación de capital por trabajador efectivo influyen sobre la tasa de crecimiento de la intensidad energética, lo que permite la existencia de β-convergencia en términos de intensidad energética.

La hipótesis de β-convergencia es contrastada considerando datos de sección cruzada y de panel para intervalos de 5 años, mediante los modelos espaciales SLX y SDEM. Centrando la atención en aquellas regresiones que generan la mejor predicción ex-post de las desviaciones típicas, se observa que la estimaciones con datos de sección cruzada que no rechazan la hipótesis de β-convergencia condicional generan las mejores simulaciones de σ-convergencia. Sin embargo, los resultados para las áreas de África y América cambian en función de la muestra analizada, los cuales parecen apuntar hacia el rechazo de β-convergencia en las mismas. Además, las velocidades de convergencia estimadas para el mundo en conjunto se encuentran entre el 1.5% y 1.2%, las cuales parecen ser consistentes con las observadas en el proceso de σ-convergencia. También se detecta que la única variable robusta para explicar las tasas de crecimiento medias de la intensidad energética es el progreso técnico medido a través de la tasa de crecimiento promedio de la renta per cápita; así como que al controlar por la dependencia espacial se estiman menores velocidades de convergencia.

Finalmente, las estimaciones de panel sobre los determinantes de las diferencias respecto a la intensidad energética media muestran que el proceso de convergencia mundial está principalmente explicado por mayores niveles de progreso técnico acumulado medido por los niveles de renta per cápita y el peso relativo de las energías renovables, así como por la adopción de mejores técnicas por los importadores netos. Asimismo, cambios en la calidad institucional de grupos de países vecinos acelera el proceso de convergencia en términos de intensidad energética, siendo el caso de Europa el principal causante de este efecto.

El capítulo 3 desarrolla una aproximación analítica sobre la relación entre los límites al cambio tecnológico, determinados por la eficiencia institucional, y el crecimiento sostenible. El capítulo se divide en tres secciones. Primero, se presenta el modelo base con una institución económica exógena controlando el grado de difusión técnica doméstica que determina las barreras de entrada en diferentes mercados. El modelo está inspirado en la teoría del crecimiento Neoclásico-Schumpeteriano con progreso técnico endógeno, expandido por tres fases intermedias de producción: manufacturas, maquinaria y energía. La generación de energía puede realizarse con fuentes contaminantes y no contaminantes, considerando la posibilidad de límites a la sustitución.

La modelización de la producción de todos los bienes se realiza a través de funciones Cobb-Douglas con rendimientos constantes a escala en los inputs no tecnológicos, a excepción de la energía, para la cual se emplea una función CES. Los bienes intermedios van acompañados de sus respectivas calidades que garantizan poder de monopolio durante un periodo tras la innovación. Además, se introduce otro factor tecnológico midiendo la calidad del proceso productivo de bienes intermedios, el cual puede ser copiado tras su innovación de acuerdo a una tasa exógena de difusión técnica. Por tanto, el modelo permite la existencia de diferentes grados de competencia en los mercados intermedios entre los casos extremos de monopolio y competencia perfecta, y la existencia de una empresa dominante con una franja competitiva entre los mismos.

La inclusión de distintos grados de competencia en el contexto de modelos de crecimiento y energía ha sido ampliamente ignorada por modelos anteriores. Además, la coexistencia de varios factores tecnológicos en la misma fase del proceso productivo tiene importantes implicaciones para la generación de bienes finales e intermedios, así como para la aparición de distintas sendas de intensidad energética en comparación con trabajos previos. La innovación en las técnicas asociadas a mejoras en la calidad de los bienes y del proceso productivo es endógena, basada en una adapatación de los modelos de "innovación gradual" ("step-by-step" innovations) al contexto del nexo entre crecimiento, energía y cambio climático.

Las principales conclusiones que se extraen del modelo base son: los niveles relativos de productividad de los investigadores así como la eficiencia de mercado generada por instituciones económicas eficientes controlando la difusión técnica son determinantes para alcanzar sendas de crecimiento sostenible sin intervención pública; las transiciones hacia fuentes de energía no contaminantes son más factibles, y más rápidas, si los esfuerzos de innovación en el mercado energético se dirigen hacia la investigación en mejores calidades asociadas a la energía contaminante así como hacia mejores procesos productivos entre los productores de energía no contaminante; las políticas económicas deberán estar dirigidas a mejorar la productividad de los investigadores que aceleran la mencionada transición energética a través de inversiones en capital humano, así como a fomentar el efecto de “escape de la competición" en los mercados de energía contaminante, y el efecto Schumpeteriano en los mercados de energía limpia.

En la segunda sección, se procede a endogeneizar las instituciones económicas asociadas a la difusión técnica doméstica, impuestos sobre la renta y subsidios al I+D a través de la consideración de un problema de maximización por parte del grupo con poder político constreñido a unas instituciones políticas exógenas. Este enfoque es novedoso entre los modelos de crecimiento endógeno, energía y cambio climático. Existen dos familias representativas, la élite y la clase media, asumiendo que la primera se dedica a gestionar el sector público y sus activos, mientras que la clase media representa la fuerza de trabajo de la economía y posee aquellos activos que no son propiedad de la élite de acuerdo a una tasa exógena de distribución de riqueza. La clase dominante escoge las instituciones económicas de acuerdo a la maximización del valor presente descontado de su renta disponible. La imposición de una tasa sobre la renta bruta, al igual que los subsidios públicos, es una actividad costosa de acuerdo a las instituciones políticas. También se permite la existencia del “problema de compromiso” (holdup problem) en relación a los subsidios a través de la calidad de las instituciones políticas. Además, se introduce un tipo especial de impuesto sobre la renta y subsidios al I+D que se incrementa con la contaminación percibida por la población. Estos subsidios especiales están únicamente dirigidos a acelerar la transición energética hacia fuentes limpias.

Las conclusiones principales de esta extensión son: la existencia de instituciones políticas eficientes que maximizan el crecimiento económico sostenible, los cuales están relacionados con los niveles existentes de daño medioambiental y las productividades relativas de los investigadores. Además, las instituciones políticas cuyo objetivo principal es la maximización de la renta disponible presente de las élites son siempre más ineficientes, por lo que ponen en peligro el crecimiento sostenible.

Finalmente, en la tercera sección se presentan simulaciones derivadas de los modelos base y extendido para el mundo en conjunto. Los resultados destacan la necesidad de mejoras en el capital humano de los investigadores de técnicas asociadas a la calidad de la energía contaminante, la introducción de instituciones políticas más inclusivas en términos de imposición y gasto público más eficiente, de mayores impuestos y subsidios Pigouvianos en el caso de una transición energética dirigida por las mejoras en costes de los productores de energía limpia, y de una mayor consciencia medioambiental para evitar un excesivo incremento en la temperatura global.

A modo de síntesis, el presente trabajo muestra que, de acuerdo a las actuales tendencias de crecimiento económico y progreso tecnológico dirigido a la productividad y transición energética, es bastante probable que la temperatura global aumente en más de 2ºC antes del año 2100. En este sentido, controlar y medir por la dependencia espacial a través del comercio, la difusión tecnológica y la adopción de mejores instituciones vecinas es determinante para la obtención de estimadores insesgados, predicciones fiables y una elaboración de políticas económicas efectiva. Por último, la presente tesis enfatiza la importancia de la teoría del crecimiento Neoclásica-Schumpeteriana así como la de la

Nueva Economía Institucional a la hora de explicar y entender los límites al crecimiento derivados de un cambio climático acelerado, donde las instituciones políticas inclusivas son determinantes para un crecimiento sostenido así como un progreso técnico dirigido hacia la productividad energética y transiciones energéticas veloces.

Debido a que la presente tesis ha demostrado la relevancia de las relaciones espaciales para comprender correctamente la interacción entre el crecimiento económico y el cambio climático, una de las principales debilidades del modelo de crecimiento endógeno propuesto es el supuesto de economías cerradas. Por tanto, estudios futuros irán encaminados a la inclusión de las relaciones comerciales y la existencia de difusión tecnológica entre países sujetos a instituciones económicas endógenas en el ámbito de energía-crecimiento y cambio climático. Además, también se examinará la influencia de distintas teorías de progreso tecnológico endógeno en el contexto mencionado para poder analizar el impacto y coste de distintas polítcas públicas. Asimismo, también sería relevante estudiar cómo las presentes conclusiones sobre instituciones políticas eficientes y cambio climático pueden cambiar ante distintos planteamientos de progreso tecnológico endógeno.

7 Concluding Remarks

This thesis studies the feasibility of sustainable growth in terms of controlled climate change. It is divided into three chapters that offer both empirical and theoretical contributions regarding the energy-growth nexus, political and economic institutions, CO2 emissions and anthropogenic climate change. The main idea connecting these chapters is the importance of limits to technical change in terms of energy productivity and the institutional constraints for controlling climate change.

Chapter 1 studies major economic determinants of domestic per capita CO2 emissions employing a large dataset of countries and forecasts different scenarios for the time evolution of average global temperature according to our estimations. I use data from 173 countries for the 1990-2014 period from the World Bank database to test the existence of the Environmental Kuznets Curve (EKC) for CO2 emissions, which is one of the largest samples ever used.

Contrary to previous work, I also measure the existence of the pollution haven hypothesis (PHH) and the impact of technical diffusion using the estimation of the spatial models spatial lag of X (SLX) and spatial Durbin error (SDEM). In addition, I carry out the estimations for not only the world as a whole but also six continental areas: Europe, North America, South America, Asia, Oceania and Africa. The aim is to check how robust estimations are, in addition to analysing the impact of explanatory variables at a less aggregated level.

The results show that I cannot reject the EKC hypothesis for all areas except for the region of Oceania, regardless of the model employed. Moreover, I find that after controlling for spatial correlation justified through the PHH and the technical diffusion effect, the size of estimated coefficients changes; thus, omission of spatially lagged variables seems to lead to biased estimations of determinants of per capita CO2 emissions. Hence, despite the turning point estimated for the world as a whole decreasing by approximately 70% after controlling for spatial relationships, its value still falls outside the sample. Therefore, global economic growth, ceteris paribus, is expected to foster per capita CO2 emissions in the coming years.

In addition, the study reveals that the PHH is supported for the world as a whole with a reversal after reaching high levels of development, mainly driven by the areas of Europe and Asia. In the case of Oceania, the PHH is supported in the long term. These results point towards a long-term shift to environmentally friendly trade of capital goods at a global scale during the 1990-2014 period. The explanatory variables related to domestic technical progress in terms of less intensive use of energy and higher relative importance of renewable sources seem to lead to lower per capita CO2 emissions irrespective of the chosen geographical area. More precisely, there seems to exist a unitary elasticity between energy intensity and per capita emissions, while the role of the energy mix is closer to zero. Moreover, technical diffusion measured as the spatial lag of energy intensity is significant for reducing per capita CO2 emissions at the global scale, driven mainly by the European area and hampered by the African region, where lower levels of neighbouring energy intensity lead to domestic increases in per capita emissions.

Finally, I project several scenarios for the global evolution of CO2 emissions and concentrations between 2015 and 2100 to confirm whether sustainable growth is feasible according to current trends in per capita GDP growth, hypothetically faster rates of growth, accelerated technical progress aimed at energy productivity and transitions to renewable sources of energy, as well as the role of the estimated short-term pollution haven hypothesis. We conclude that long-term growth paths can be sustainable in terms of a global temperature increase less than 2ºC as long as aggregate technical progress grants sustained decreases in domestic energy intensity levels at an interannual rate of -2.5% and economies gradually converge to an energy mix based on renewable energy consumption.

Chapter 2 analyses global convergence in terms of energy intensity, and its worldwide evolution for the 1990-2010 period for two large datasets of countries and provides a simple theoretical model that justifies the estimation of β-convergence regressions in this context. I use data from 173 and 130 countries from the World Bank, Penn World Tables and Kuncic's databases. The smaller dataset includes data from variables related to economic steady states such as saving or depreciation rates.

The five major contributions with respect to previous work are the employment of the largest dataset of countries (173), the proposal of a theoretical model that justifies the estimation of β-convergence regressions controlling for economic steady states, the estimation of those regressions considering the aforementioned explanatory variables for the largest dataset of countries (130), the control of spatial correlation by including explanatory lagged variables at a worldwide scale, and the estimation of the impact of

β-convergence control variables on country differences in terms of energy intensity.

The hypothesis of σ-convergence, or time decreases in sample dispersion regarding energy intensity, is studied by exploring standard deviations and kernel density estimators over time for both samples and considering large continental areas, as well as for the world as a whole. The results show the existence of worldwide σ-convergence for all areas except America in the smaller dataset, with a worldwide interannual rate of decrease between 0.6% and 1%. Moreover, most areas and the world as a whole seem to present a slowdown in σ-convergence rates from 2000 onwards; thus, convergence is more likely to be conditional rather than absolute.

I find that the major drivers of σ-convergence seem to be Europe and Asia-Oceania, while Africa and America are hampering or even reversing it. The estimation of kernel densities by area reinforces the previous results, except for the shift from multimodal to unimodal distributions that may suggest absolute convergence. Furthermore, the evolution of kernel densities shows an interannual decrease in global average energy intensity levels of 1.58% and 1.34%, depending on the sample, for the 1990-2010 period.

The theoretical model that justifies the β-convergence regressions is based on the production functions from the neoclassical-Schumpeterian theory of growth, with nested markets and a vector of intermediate goods weighted by their respective qualities determining final output. Assuming that energy is one of these intermediate goods, which requires labour and capital stock to be produced, the solution to the general equilibrium model yields an equilibrium function for energy per unit of gross output, which increases with the technical factor specific to energy production and capital stock per effective worker, and decreases with aggregate technical progress. From this solution, the transitional dynamics of capital deepening determine the growth rate of energy intensity in the path to the steady state; hence, β-convergence in terms of energy intensity is allowed to emerge.

The hypothesis of β-convergence is tested considering cross-sectional and panel data for 5-year intervals, as well as the SLX and SDEM spatial models. Under the criterion of best regression yielding the best ex-post forecasts of standard deviations, I find that cross-sectional estimations implying conditional β-convergence tend to lead to the most accurate depictions of σ-convergence. Nevertheless, the conclusions for the areas of Africa and America are susceptible to the chosen sample, suggesting rejection or negligible β-convergence in line with the results observed for σ-convergence. In addition, the estimated worldwide speed of convergence ranges between 1.5% and 1.2%, which is consistent with the observed rates of convergence in the evolution of standard deviations. Domestic technical progress measured through average growth rates of per capita GDP is the only robust variable explaining average growth rates of energy intensity. Controlling for spatial dependence tends to decrease the estimated speeds of convergence.

Finally, panel data estimations of the SDEM model over individual differences in energy intensity with respect to cross-country averages show that worldwide convergence in energy intensity is driven mainly by accumulated domestic technical progress in terms of higher levels of per capita GDP and the relative weight of renewable sources in energy consumption, and by the technical adoption of net importers. Furthermore, changes in institutional quality by groups of neighbouring countries accelerate convergence in energy intensity for the world as a whole, which is found to be driven by European countries.

Chapter 3 takes an analytical approach to the relationship between limits to technical change determined by institutional efficiency, and sustainable growth. This chapter is divided into three major parts. First, I present the base model with an exogenous economic institution measuring domestic technical diffusion determining entry barriers to markets. The model draws mainly from models of neoclassical-Schumpeterian endogenous growth expanded to include three intermediate stages of production: manufacturing, machinery and energy production.

Energy production is allowed with both polluting and nonpolluting energy sources, with limits or no limits of substitution. All goods are produced with constant returns to scale in physical inputs, assuming Cobb-Douglas production functions except for energy with good possibilities of substitution, where a CES function is assumed. Intermediate goods carry quality factors that grant monopolistic power and cannot be copied for one period after innovation. In addition, I introduce a technical factor measuring the quality of the productive process employed to produce intermediates, that can be instantly copied at an exogenous technical diffusion rate. Therefore, I allow for different degrees of competitiveness in intermediate markets ranging between monopolistic and perfect competition, with a quantity-setting dominant firm in between, which has rarely been explored in the context of endogenous growth and climate change.

The coexistence of both technical factors also has important implications for the long-term evolution of gross and effective production of intermediate goods, which, in contrast to previous work, allows for different paths of energy intensity. Innovation in quality- and process-improving techniques is endogenous, based on adapting models of "step-by-step" innovations and directed technical change. In this sense, I contribute to the existing literature by shifting the idea of directed technical change from the "between sectors" sole perspective to the "within sectors" view. Moreover, there is novelty in the use of 'step-by-step" innovation models in the context of the "energy-growth" nexus and climate change.

Major conclusions from the base model are as follows: relative productivity levels of researchers and market efficiency measured by efficient economic institutions controlling technical diffusion rates are crucial to attain sustainable growth without public intervention; clean transitions are more likely to occur, and will be faster, if research efforts in the energy market are aimed towards improvements in the quality of polluting energy flows and in the productive process of clean energy flows; economic policies should aim to improve productivity levels of specific researchers related to the energy transition through investment in human capital, and to foster the "escape-competition" effect among polluting energy researchers and the Schumpeterian effect among clean energy researchers.

Second, I endogenize the economic institutions of domestic technical diffusion, income taxes and subsidies to R&D activities by considering a maximization problem of a ruling group constrained to exogenous political institutions. This approach is novel in the context of the "energy-growth" nexus and climate change. Households are divided into two major groups, the elite and the middle class. The elite is assumed to be devoted to political affairs and management of their assets, while the middle class represents the economic labour force, and owns the remaining assets according to an exogenous wealth distribution ratio. The ruling class chooses economic institutions to maximize the discounted present value of its disposable income.

Taxation, as well as public subsidisation, is costly according to political constraints. The holdup problem regarding public subsidies is allowed to exist according to political institutions. I also introduce a special type of income tax and R&D subsidies, which increase with levels of perceived pollution and accelerate the energy transition.

Major conclusions from this extension are as follows: there exists a set of efficient political institutions in terms of fast and sustainable long-term growth that depends on the current levels of damage to the environment and differences in productivity levels of researchers in the energy market; political institutions whose first objective is maximizing the disposable income of the rulers are more inefficient and hence more likely to endanger sustainable growth.

Finally, simulations of the base and extended models for the world as whole are provided. The results indicate the need for improvements in the human capital of researchers of new qualities associated with polluting energy, more inclusive institutions enabling more efficient public taxation and expenditure, higher Pigouvian taxes/subsidies when the energy transition is driven by decreases in marginal costs of clean energy producers, and higher environmental awareness to avoid excessive increases in global temperatures.

To summarize, the present thesis shows that current trends in global economic growth and technical progress regarding energy productivity and energy transitions are very likely to increase global temperatures up to 2ºC before 2100. Thus, measuring spatial relationships through trade, technical diffusion and adoption of better neighbouring institutions is crucial for unbiased estimations, accurate forecasts and effective policy-making. Last, the thesis emphasizes the importance of the neoclassical-Schumpeterian growth theory and the new institutional economics to understand the limits to growth in terms of accelerated climate change, where inclusive political institutions are required for efficient economic institutions fostering long term growth and technical progress directed to energy productivity and fast energy transitions.

Since spatial relationships have been proven to be the determinant to understand the interaction between economic growth and climate change, a major flaw of the proposed endogenous growth model is the assumption of closed economies. Therefore, further research will be aimed at considering trade relationships and technical diffusion among countries constrained to endogenous economic institutions in the growth-energy-climate nexus. In addition, different types of endogenous growth theories will be examined in the aforementioned context to analyse the impact and cost of different public policies.

Moreover, it is also relevant to analyse how my conclusions regarding efficient political institutions and climate change are also sensitive to changes in the chosen theory of endogenous technical progress.