Essays on Structural Transformation in International Economics

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Dedication

Rodzicom. Dziękuje za wszystko.

- Radek Stefański, Minneapolis, July 2009.

Abstract

This thesis investigates the impact of structural transformation in large, newly industrializing countries on the international price of oil and on carbon emissions.

The first essay measures the impact of industrialization in China and India on the oil price in the OECD. I identify an inverted-U shaped relationship in the data between aggregate oil intensity and the extent of structural transformation. I construct and calibrate a multi-sector, multi-country, general equilibrium growth model that accounts for this fact and use it to show that structural transformation in China and India explains up to a quarter of the oil price increase in the OECD between 1970 and 2007. Continued structural transformation however, results in a falling oil price. A standard one-sector growth model misses this non-linearity. To understand the impact of growth on the oil price, it is necessary to take a more disaggregated view than is standard in macroeconomics.

The second essay empirically analyzes the source of the Environmental Kuznets Curve (EKC) - an inverted-U shaped relationship between emissions and income per capita. Recent theory claims that the EKC relationship is driven by falling growth rates associated with convergence to a balanced growth path. A decomposition of emissions however, shows that falling emission intensity growth rates dominate growth effects by an order of magnitude. Structural transformation is one mechanism capable of generating the observed patterns in emission intensity growth rates.

The third essay investigates the extent to which a country's structural transformation influences its emission profile. I document how CO_2 emission intensity follows an inverted-U with income, despite *falling* energy intensities. This pattern is driven by changing fuel mix and improvements in energy efficiency associated with structural transformation. I construct and calibrate a two-sector, general equilibrium model that accounts for the emission, emission intensity and energy intensity profiles of the UK for 150 years. I show that a one sector framework is incapable of matching both a hump-shape emission *and* a falling energy intensity; that timing of structural transformation matters for emission profiles and that improvements in energy efficiency may be insufficient to explain observed falling emissions in rich countries.

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Chapter 1

Introduction

The industrial revolution that started in the 19^{th} century in the United Kingdom is recognized as one of the most significant socio-economic events in human history. It was the beginning of a transition in advanced economies, between two techniques of production: from a regime were countries maintained a roughly constant, "subsistence" level of output per capita, to one were continuous improvements in technology made sustained output per capita growth possible (Lucas, 2002). The industrial revolution is relevant today, because most of the world's population, live in countries that have not yet started or have only just started the process of structural transformation.[1]

The large size, and the high levels of sustained growth in countries such as China and India, suggest that this new industrial revolution may affect more people, more quickly than the industrial revolution of the nineteenth century ever did (both in total, and as a fraction of the world population). Although this process may bring billions of people out of poverty, its effects on already industrialized nations are not well understood. This thesis investigates two specific effects of structural transformation in large, poorer countries: its impact on the international oil price and its contribution to rising global pollution levels.

Chapter 2, measures the impact of industrialization in China and India on the oil price in the OECD over the last thirty years and asks whether continued structural transformation in these countries will result in a permanently higher oil price. I identify

[1] According the WDI (2007), 72% of the world's population lived in low and lower middle income countries in 2007.

an inverted-U shaped relationship in the data between aggregate oil intensity and the extent of structural transformation - countries in the middle stages of transition spend the highest fraction of their income on oil. A decomposition of aggregate oil intensity shows that only in the middle stages of transition are an economy's largest sectors also its most oil intensive ones. I construct a multi-sector, multi-country, general equilibrium growth model that accounts for these facts and use it to measure the impact of changing sectoral composition in China and India on world oil demand and hence the oil price in the OECD. I find that structural transformation in China and India accounts for up to a quarter of the oil price increase in the OECD between 1970 and 2007. However, the model implies that continued structural transformation in China and India results in falling oil intensity and a drop in the oil price. A key implications of this theory is that using a standard one sector growth model misses this non-linearity and can give misleading implications about the long-term oil price. The reason for this, is that a multi-sector model is capable of generating an endogenously changing elasticity of substitution between oil and other factors of production. To understand the impact of growth on the oil price, it is necessary to take a more disaggregated view than is standard in macroeconomics.

Chapter 3, investigates empirically the source of the so-called Environmental Kuznets Curve (EKC) - a relationship between various indicators of environmental degradation and income per capita, which is hypothesized to follow an inverted-U shape with income. In particular, I comment on a paper by Brock and Taylor (2004) who construct a theory of pollution emissions that fits neatly into the standard one-sector Solow model of economic growth. They argue that in the presence of exogenous and constant technological progress in abatement technology, an inverted-U shaped relationship between income and emissions can arise from a country's convergence to its balanced growth path. The driver of the EKC in Brock and Taylor (2004) is thus the falling growth rate of an economy associated with convergence. Instead, I show that - in the data - changes in growth rates are relatively unimportant in generating the EKC. Rather, it is falling emission intensity growth rates - i.e. changes in the dirtiness of output over time - that are key to influencing emission patterns. In particular, I show that emission intensities of various pollutants, tend to follow an inverted-U shape with income. Whilst convergence effects can certainly contribute to falling emissions, the changing emission intensity effect dominates the growth effect by an order of magnitude. In a simple example, I demonstrate that structural transformation is a mechanism that is capable of generating the observed changes in emission intensity growth rates. As the economy shifts from clean agriculture to dirty non-agriculture, output becomes dirtier over time. However, improvements in abatement technology can ultimately lead to falling emission intensities and emissions.

Finally, Chapter 4 investigates the extent to which a country's energy consumption and resulting emission profiles are influenced by structural transformation. I document how emission intensity of CO_2 follows an inverted-U with income per capita, but energy intensities tend to decline - as countries grow, output first becomes dirtier, then it becomes cleaner even though output is continually becoming more energy efficient. I argue that this pattern is caused by a changing fuel mix and improvements in energy efficiency, associated with structural transformation. Improving energy efficiency in both sectors, results in energy intensities that always fall. However, as economies shift from agriculture to non-agriculture, they begin to use carbon-emitting fossil fuels rather than carbon-neutral biomass. This results in emission intensities that rise initially, but later fall as improvements in energy efficiency outweigh the effects of changing fuel mix. I construct and calibrate a two-sector general equilibrium model and use it to show that the simple mechanism above successfully replicates emission, emission intensity and energy intensity profiles of the UK for 150 years. Furthermore, I show that a one sector framework is incapable of matching both a hump-shape emission intensity *and* a falling energy intensity; that timing of structural transformation matters for emission profiles and that improving energy efficiency may be insufficient to explain falling emissions in rich countries.

Chapter 2

Structural Transformation and the Price of Oil

2.1 Introduction

A structural transformation is a shift in the composition of an economy, away from agriculture towards industry and services, that accompanies growth[1] . Between 1970 and 2007 as the real price of oil in the United States and other countries rose by over 500% BP (2008), world employment share in agriculture fell from 56% in 1970 to just under 36% in the mid-2000's ILO (2003). This transformation was driven - to a large extent - by declines in agricultural employment in the world's two largest countries, China and India. Employment in the agricultural sector in China and India declined from nearly 80% of the labor force in 1970 to just under 50% by the mid-2000's[2] . What part of the increase in the price of oil in rich countries can structural transformation in very large, poorer countries account for? In particular, what part of the oil price increase is driven by structural transformation in China and India and are the effects on prices necessarily permanent?

Why does structural transformation influence the price of oil? I document how the demand for oil changes with structural transformation - as the structure of an economy

[1] Both in terms of employment shares and value-added per sector shares.
[2] A back-of-the-envelope calculation that assumes that China and India's share in the world's total labor force is 1/3, reveals that structural transformation in China and India accounted for just over 40% of the world's decline in agriculture employment over this period.

shifts away from agriculture towards industry and services, economies first spend a rising and then a falling share of their income on oil. Intuitively, countries at different phases of structural transformation use different intensities of oil: industrialization, urbanization and the construction of new infrastructure involves the use of large quantities of raw materials. China and India have reached the most commodity-intensive stage of their development and are the last large countries to enter this phase of transformation. Due to their size, they can potentially exert a very large impact on the world oil demand and hence on the world oil price. As China and India industrialize, they consume a higher share of world oil supply, leaving a smaller share for other countries - resulting in upward oil price pressure in the rest of the world. By the same argument, as structural transformation in China and India comes to a close in the future, their demand for oil should ease and the upward pressure on oil prices should drop.

I develop a multi-sector, multi-country, general equilibrium growth model similar to Echevarria (1997), Duarte and Restuccia (2007) and Rogerson (2007) - but with international trade and oil as an intermediate input - that explains the existence of the inverted-U oil intensity curve through changing sectoral oil intensities over the transition of an economy. I use the model to measure the impact of structural transformation in China and India on the price of oil in the OECD. I find that structural transformation in China and India accounts for up 24% of the increase in oil prices in the OECD. Furthermore, I find that the upward price pressure caused by structural transformation is not necessarily permanent.

Since the model is designed to to capture the effects of structural transformation on the price of oil, it focuses on the evolution of oil demand - and abstracts away from oil supply dynamics, uncertainty, speculation and imperfect competition. In particular, oil output is modeled as inelastically increasing. In the model, structural transformation is driven by two channels: income effects arising from non-homothetic preferences as in Kongsamut et al. (2001) and substitution effects due to unbalanced productivity growth across sectors as in Ngai and Pissarides (2007). The oil price result is driven by a further two channels: a supply side effect caused by inelastically growing oil supply and a demand side effect that arises from changing sector-specific oil intensities.

2.2 Facts

In this section I document two sets of facts. The first set demonstrate that: 1) there has been a rising trend in oil prices since the 1970's; 2) China and India have undergone a large structural transformation and that 3) China and India's share in world oil consumption has risen, whilst that of more advanced countries has fallen. The second set of facts is associated with structural transformations in general: 4) the existence of an inverted-U aggregate oil intensity curve along a structural transformation[3] ; 5) the changing size of sectors along a structural transformation and 6) changing sector specific oil intensities. I use facts 5) and 6) to motivate the existence of fact 4) - the inverted-U aggregate oil intensity. I conclude the section by motivating a seventh fact: 7) the inelastic nature of oil supply.

2.2.1 The Price of Oil

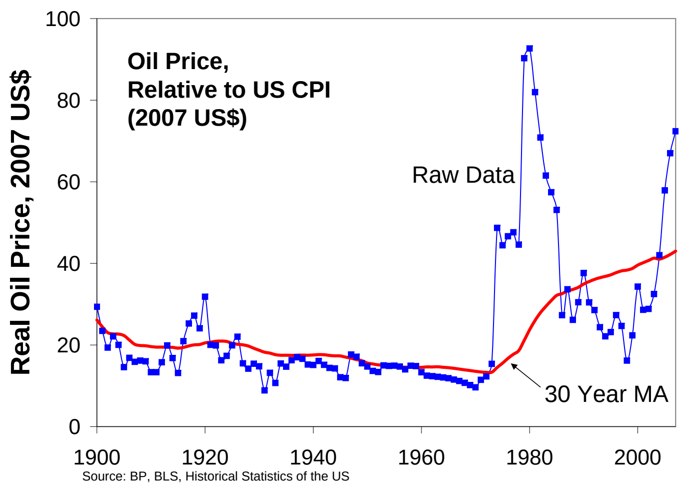

Figure 2.1: Real oil price and its trend (Relative to the US CPI).

The curve labeled "Raw Data" in Figure 2.1, shows the 1900-2007 average annual oil price in 2007 US dollars[4] BP (2008). The oil price shocks of the 1970's and 80's

[3] As far as I am aware, this paper is the first to document this fact for oil.
[4] In this section all dollar amounts refer to 2007 USD. Quantities are deflated by the US Consumer Price Index. The CPI data for 1900-1913 data comes from the Historical Statistics of the United States (http://hsus.cambridge.org), whilst the 1913-2007 data comes from the BLS.

as well as recently rising oil prices are clearly visible in the figure. The focus of this paper however, are not the sharp shocks in the raw data, but rather the oil price trend. The average oil price for the 38 year period, 1970-2007, was approximately 41 USD. The average oil price in the 38 years preceding that (1932-1969), was 14 USD. This represents an almost 200% increase in oil prices. Taking a 30 year moving average of the raw data emphasizes this upward trend. From 1970 to 2007, the real oil price (as measured by the 30 year MA) has also roughly tripled - from 14 to 43 dollars. In this paper, "the oil price" will refer to this 30 year MA. Finally, notice that there is a significant change in the trend of the oil price after the 1970's: the oil price, which had been falling for nearly a century, began to rise sharply. A part of this is due to the oil shocks of the 1970's and 1980's, however in this paper I argue that a significant portion of this changing trend stems from structural transformation in China and India.

2.2.2 China and India's Structural Transformation

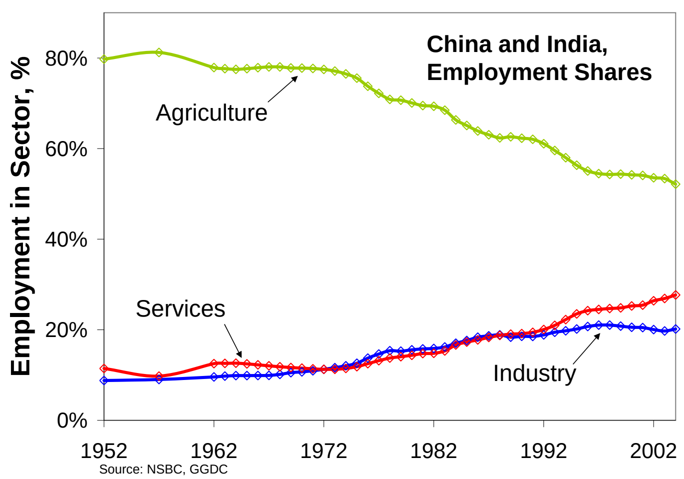

Figure 2.2: Structural transformation in China and India: Employment shares by sector in China and India (1952-2004).

Figure 2.2 shows how China and India's employment share in agriculture has fallen from nearly 80% in 1970 to approximately 50% by 2004. At the same time, the share of employment in industry and services has risen from approximately 10%, to approximately 20% in industry and 30% in services[5] . In absolute terms, this is one of the largest inter-sectoral movement of labor in history[6] .

2.2.3 World Oil Shares

China and India's structural transformations coincided with a rise in their share in world oil consumption. Figure 2.3 shows how China and India's share in world oil consumption rose by approximately 13% between 1970-2007. Meanwhile, the share of the EU-25, the US and Japan in world oil consumption fell by approximately 21%[7] .

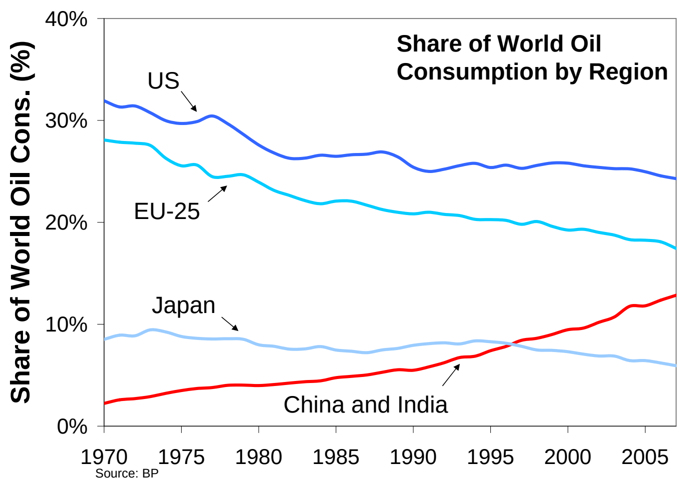

Figure 2.3: World oil shares in China, India and the world's largest oil consumers (1970-2007).

In what follows, I index the progress of a country along a structural transformation by its share of employment in agriculture[8] . Countries with high shares of employment in GDP are relatively structurally undeveloped whereas countries that have lower agriculture shares are more structurally developed.

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[5] The sources for this data are: Timmer and de Vries (2007), NBSC (2006).

[6] Notice, that in this paper I choose to concentrate on movement of labor across sectors rather than changing shares of GDP.

[7] This data comes from BP (2008).

[8] The index itself is fairly unimportant. Alternatively, I could consider a country's share of GDP arising from agriculture or its income per capita - any yardstick that is positively correlated with a structural transformation is appropriate and was checked to give similar results.

2.2.4 Aggregate Oil Intensity

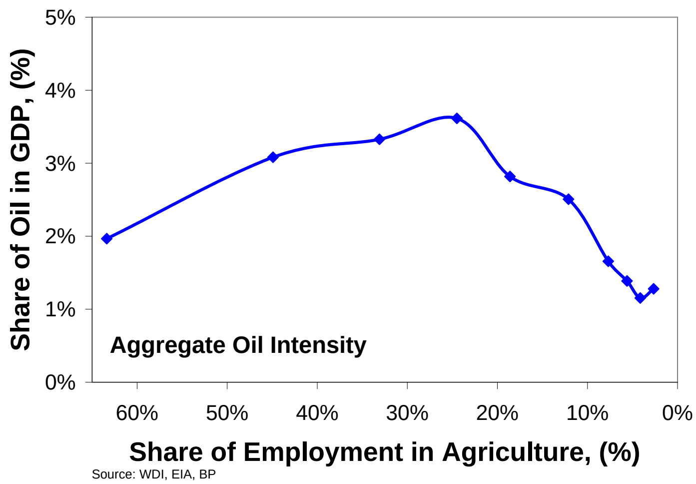


Figure 2.4: Share of oil in GDP vs. share of employment in agriculture for a panel of the world's 100 largest countries by population (in 2000) for the years, 1980-2005. Line indicates the decile averages of the data.

The share of GDP spent on oil (or the aggregate oil intensity) varies with the progress of a structural transformation. Countries at the beginning and end of a structural transformation spend the lowest share of their income on oil, whilst countries in the "middle" of a structural transformation spend the highest share. This is shown in Figure 2.4, which plots decile averages of aggregate oil intensity versus the share of employment in agriculture for a panel of the world's largest 100 countries (for the years 1980-2005)[9] . Oil consumption come from the EIA (2009) and GDP shares data comes from WDI (2007), whilst price data come from BP (2008)[10] . The pooled data is sorted according to employment share in agriculture, divided into ten groups, and the average employment share in agriculture and the average oil intensity of each group is shown in the above graph. The inverted-U shape of aggregate oil intensity is clearly visible. To test the robustness of this result, I run a quadratic regressions (both OLS and LAV) with time dummies on the panel data - the results are shown in Table 2.1.

[9] This is done in order to avoid including many small island economies. The largest 100 countries are chosen according to their population in the year 2000.

[10] Oil prices used to calculate the above shares, are smoothed using a 30 year moving average to remove sharp spikes in prices. For more details on the construction of the data see Appendix 2.9.1.

Agg. Oil Int. vs. Share of Agr. in Emp and Time Dummies

	(1)	(2)
COEFFICIENT	Aggregate Oil Int. (OLS)	Aggregate Oil Int. (LAV)
agrShare	0.130***	0.091***
	(0.0063)	(0.00430)
agrShareSq	-0.168***	-0.110***
	(0.0091)	(0.00624)
R^2	0.330	
Pseudo R^2		0.229

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 2.1: Regression of aggregate oil intensity versus share of employment in agriculture (and time dummies) for a panel of 100 countries over the period 1980-2005. (Coefficients for time dummies and constant term not shown.)

In both regressions all coefficients are highly significant. Furthermore, the structural development of a country (as measured by the share of employment in agriculture) can explain 33% of the variation in aggregate oil intensity across countries and time. I also run several non-parametric regressions - all of which confirm the existence of an inverted-U aggregate oil curve in the panel data.

I motivate the existence of the inverted-U by a particular decomposition of aggregate oil intensity. Intuitively, the oil intensity of an entire economy, must result from the oil intensities of individual sectors, weighed by their size. In particular, suppose Y is the value added and O the total oil consumption of a three sector economy composed of agriculture (A), industry (I) and services (S). Let Y_i denote the value added and O_i the oil consumption of each of the three sectors, $i = A, I, S$, so that $O = \sum_i O_i$ and $Y = \sum_i Y_i$. Finally, let p_O be the price of oil. The oil intensity of an entire economy ($N \equiv \frac{p_O O}{Y}$), is simply the sum of oil intensities of each sector ($n \equiv \frac{p_O O_i}{Y_i}$), weighted by its size ($s_i = \frac{Y_i}{Y}$):

$$N \equiv \frac{p_O O}{Y} = \sum_i \left(\frac{p_O O_i}{Y_i} \frac{Y_i}{Y} \right) = \sum_i n_i s_i. \quad (2.1)$$

Aggregate oil intensity of an economy depends on both the sector specific oil intensity *and* the size distribution of individual sectors at any point along a structural transformation. To understand how aggregate oil intensity changes, it is necessary to understand how the size of sectors and the sector specific oil intensities change over a structural transformation.

2.2.5 Changing Sector Size

The process of structural transformation has been widely documented in the literature. It is characterized by shares employment and value added that are falling in agriculture, rising in services, and initially rising and later falling in industry[11] . Figure 2.5 shows this typical pattern for employment shares in the United States over the 1860-2004 period.

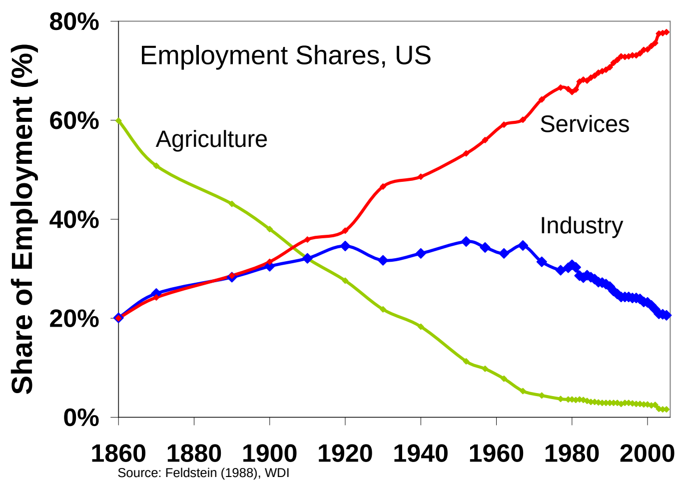


Figure 2.5: Employment share by sector in the US, 1860-2004.

More generally this patterns has been documented for employment shares and value added shares in cross-section and over time for individual countries. Maddison (1982) presents evidence for this process for 16 industrialized countries since 1820-1973[12] . Echevarria (1997) provides examples of this pattern holding in cross-section. More

[11] Here, and in the rest of the paper unless noted otherwise, I divide sectors according to the standard ISIC III classification. Agriculture is defined to correspond to categories 1-5 (agriculture, forestry, hunting, and fishing). Industry corresponds to categories 10-45 (mining, manufacturing, construction, electricity, water, and gas) and services refers to categories 50-99 (wholesale, retail, transport, government,financial etc).

[12] The countries are: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Netherlands, Norway, Sweden, Switzerland, U.K., and USA

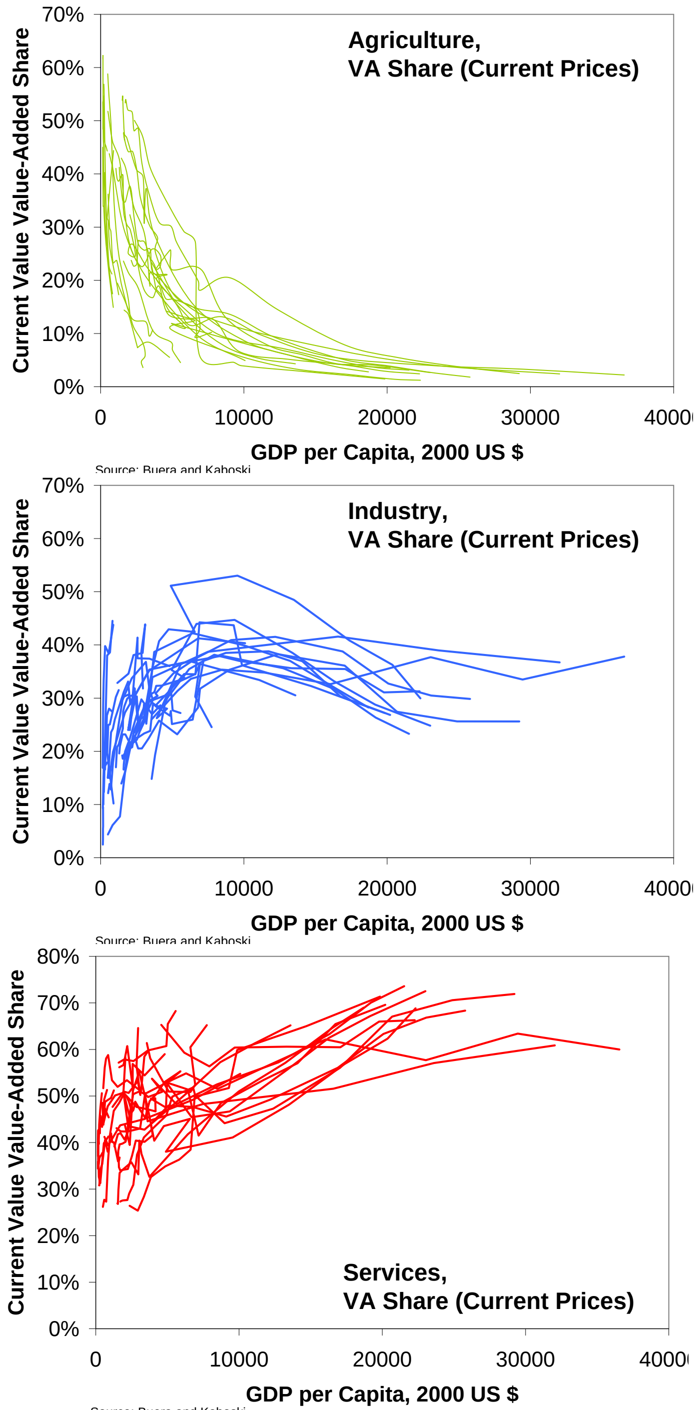


Figure 2.6: Sectoral shares vs. real GDP per capita (2000 US $) for country panels

recently, Duarte and Restuccia (2007) construct a panel of 29 countries[13] for the period 1956-2000 and document the structural transformation (and its influence on aggregate productivity) in each of the countries over time. Finally, Buera and Kaboski (2008) construct long run panel data that contains decade level data on current value share of GDP by major sector for 30 countries[14] from 1820 to 2001. Using their data, in Figure 2.6 I plot current price value-added shares in each of the sectors (Agriculture, Industry and Services) versus GDP per capita (in 2000 US dollars). Once again, the characteristic pattern of structural transformation is clearly visible.

2.2.6 Changing sectoral oil intensities

Next, I consider how oil intensities of individual sectors (agriculture, industry and services) change with a structural transformation. I run the following regression:

$$SectOilShare^{s}_{i,t} = \beta_0 + \beta_1 agrEmpShare_{i,t} + \sum_{i=1}^{T-1} D_{i,t} + \varepsilon_{i,t}, \tag{2.2}$$

which relates the emission intensity of each sector $s = A, I, S$ in country i at time t ($SectOilShare^{s}_{i,t}$), to how far countries are in the process of structural transformation. As before, I use employment in agriculture to index the progress of structural transformation ($agrEmpShare_{i,t}$). Since I am using panel data, I also include time specific dummies ($D_{i,t}$) in the regression (one less than the total number of years). The data under consideration is for Australia, Canada, Denmark, France, Germany, Italy, Japan, the Netherlands, the UK and the US for the years 1970, 1972, 1975, 1977, 1980, 1985, 1986, 1990. For the years 1995 and 2000, the data consists of countries from the OECD[15] as well as Argentina, Brazil, China, Israel, India, Indonesia and Russia and South Africa. The oil intensity by sector data, is derived from Input-Output tables constructed by the OECD (2006) and is calculated by dividing the value of sectoral inputs

[13] These include OECD countries such as Austria, Australia, Belgium, Canada, Denmark, Finland, France, Greece, Ireland, Italy, Japan, Korea, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Turkey, U.K., and U.S. and Latin American countries such as Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Mexico, Peru, and Venezuela.

[14] Argentina, Australia, Brazil, Canada, Chile, China, Colombia, Denmark, Egypt, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Netherlands, Norway, Pakistan/Bangladesh, South Africa, Spain, Sri Lanka, Sweden, Switzerland, United Kingdom, United States, Taiwan and Thailand

[15] Here, taken to be Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, , Ireland, Italy, Japan, South Korea, Luxembourg, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Turkey, UK and the USA

Sectoral Oil Intensity vs. Agr. Share in Emp

	(1)	(2)	(3)
COEFFICIENT	Oil Int. Agr.	Oil Int. Ind.	Oil Int. Ser.
agrEmpShare	-0.0492***	0.0599***	0.0750***
	(0.0176)	(0.0205)	(0.0092)
Constant	0.0519***	0.0411***	0.0154***
	(0.0044)	(0.0051)	(0.0022)
Observations	104	104	104
R^2	0.380	0.283	0.503

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.2: Regression of sectoral oil intensities vs employment share in agriculture

in the category "Refined petroleum products, coke and nuclear fuel" by total sectoral value added[16] in a given country and year.

Table 2.2 shows the results. The significance is high in all three regressions. Furthermore, the changing structure of the economy can explain between 28% and 50% of sectoral emission intensities. Figure 2.7 shows the resulting regression lines (extended from 0%-100% employment shares in agriculture, for illustrative purposes). As a country structurally develops (i.e. as its share of employment in agriculture falls), sectoral oil intensity in agriculture *increases* and sectoral oil intensity in industry and service *falls*. The increase in oil intensity in agriculture can intuitively be explained as a movement away from traditional agriculture, towards mechanized agriculture (a tractor replaces a plough), whilst declining oil intensity in industry and services can arise from improvements in oil use efficiency (an advanced chemical processes that needs less oil as input, a more efficient generator or a bus that runs on hydrogen instead of oil).

2.2.7 So, why the inverted-U aggregate oil intensity?

This particular pattern of changing structure and oil intensity can result in an inverted-U aggregate oil intensity curve. Consider Figure 2.7. In the early stages of structural

[16] The category "Refined petroleum products, coke and nuclear fuel" corresponds to ISIC rev. 3 category 23. More disaggregated data would be desirable, however this was the most disaggregated, comparable cross-country input-output data that I could find.

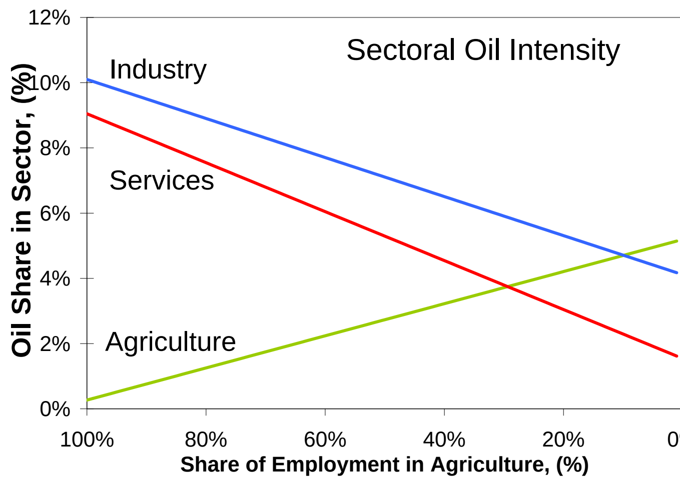


Figure 2.7: Sectoral oil intensities over structural transformation, regression lines. Extended from 0%-100% employment for illustrative purposes.

transformation, two factors contribute to rising oil intensity. First, the economy is shifting from predominantly oil unintensive agriculture towards oil intensive industry and services. Second, oil intensity of the largest sector - agriculture - is rising. Both of these developments contribute to rising aggregate oil intensity. In the late stages of structural transformation however, there are also two factors contributing to falling oil intensity. First, the economy shifts from oil intensive industry to (relatively) oil unintensive services. Second, the oil intensities of the largest sectors - industry and services - are falling. If oil intensity in agriculture rises slowly enough and oil intensity in industry and services falls fast enough, aggregate oil intensity can fall.

Notice however, that an inverted-U is not - by any means - inevitable in the above setup. If in the late stages of structural transformation oil intensity in agriculture rises quickly enough, or oil intensity in non-agriculture does not fall fast enough, aggregate oil intensity may not fall. To a large extent the existence of an inverted-U aggregate oil intensity hinges on underlying parameters of the economy.

2.2.8 Inelastically growing oil supply

Figure 2.8 shows the total world output of oil from 1970-2007 and its Hodrick-Prescott trend BP (2008). Except for the period of OPEC driven oil shocks in the mid-1970's

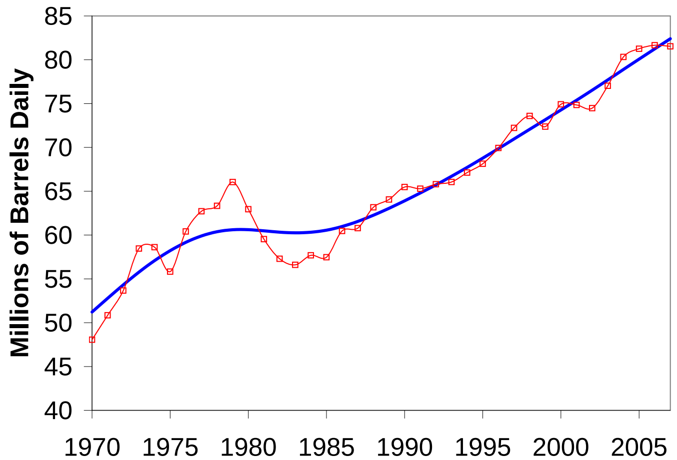


Figure 2.8: Total world oil production (and HP-trend), millions of barrels daily.

and early 1980's, the growth of oil output has been remarkably stable. This is especially evident for the period 1985-2007, where growth of world oil output is almost constant at 1.5% per annum.

Can oil output keep growing at this rate? There is a long history of studying the impact of an exhaustible resource on an economy. Dasgupta and Heal (1974), Solow (1974) and Stiglitz (1974) investigated the drag on economic growth caused by exhaustible resources. Gray (1914) andHotelling (1931) discussed the optimal extraction decision rules of producers when faced with an exhaustible resource. Yet, despite steadily growing world oil consumption over the past thirty years, the total quantity of confirmed reserves (the amount of oil left in the ground) has grown at and average annualized rate of 2.3% over the 1980-2007 period BP (2008). This seems to indicate that even though the world is using ever more oil, improvements in location and extraction techniques have outpaced depletion. Of course, improvements in technology cannot continue to increase reserves indefinitely, since there is some physical upper bound on the quantity of reserves. However, the sheer quantity of oil left indicates that this may not be a problem in the short to medium run. A simple, back-of-the-envelope calculation that assumes that all confirmed reserves are usable, that no further new reserves will be found and that consumption of oil continues to grow at 1.5% per annum, indicates that the world will run out of oil by the year 2376. This estimate however, only refer to conventional oil reserves. The world contains enormous quantities of unconventional oil that can substitute for crude oil. For example, according to Campbell and Laherrre (1998), the Orinoco oil belt in Venezuela contains 1.2 trillion barrels of oil matter known as heavy oil - a quantity almost equal to all the worlds confirmed conventional oil reserves in 2007. Furthermore, tar sands and shale deposits in Canada and Russia may contain the equivalent of more than 300 billion barrels of oil.

As such, in this paper, I do not focus on the supply-side issue of exhaustibility, and the associated optimal extraction rules. Furthermore, I abstract from uncertainty within the oil supply framework (for example, uncertain political events) and from the imperfect competition that may be found in the oil sector in the guise of OPEC. Instead, I take the stand that world oil supply grows inelastically, that it will continue to do so into the future and that oil is supplied in a perfectly competitive environment. These simplifying assumptions allows the paper to focus on the impact of structural transformation on the demand for oil and how changing oil demand effects the world oil price.

2.3 The Model

The model is constructed to capture two facts visible in the data: 1) a shift of labor across sectors that characterizes structural transformation and 2) sector specific oil intensities that change with structural transformation. By the argument in section 2.2.7, after calibration these facts can result in an aggregate oil intensity curve in the shape of an inverted-U - an aggregate oil intensity that first rises, then falls as countries structurally transform. Countries at the beginning of structural transformation (China/India) will observe rising oil intensity, whereas countries at the end of the structural transformation (OECD) will observe falling oil intensity. The model is then used to isolate the effect of rising oil demand caused by structural transformation in China/India on the oil price. Since the model focuses on capturing demand effects, oil supply is modeled as simply as possible - oil output is assumed to grow inelastically.

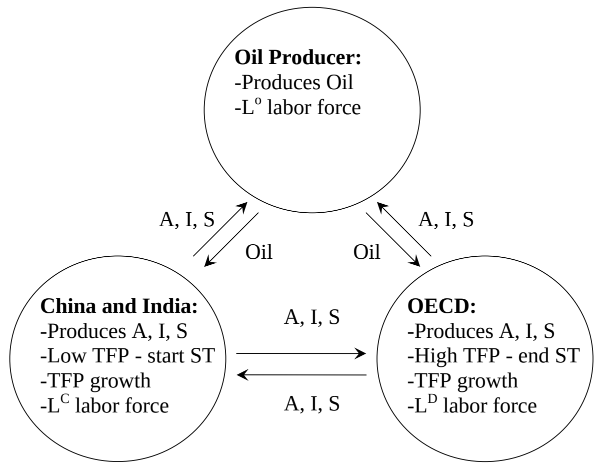


Figure 2.9: Structure of the model

2.3.1 The Economic Environment

The model consists of three countries - China/India (C), the OECD (D) and an Oil Producer (O). Country O is the only producer of oil in the world economy[17] and furthermore, it only produces oil. China/India and the OECD are qualitatively identical. They are the only producers of agriculture (A), industry (I) and service (S) goods in the world economy. Countries C and D trade these goods with each other, as well as with country O in exchange for oil. Each country then consumes baskets of agriculture, industry and services, composed of C's and D's goods. Quantitatively however, China/India and the OECD ($i = C, D$) can vary in: (1) initial levels of sector specific TFP[18], B_s^i, for $s = A, I, S$; (2) sector specific TFP growth rates, g_s^i, for $s = A, I, S$; and (3) the size of their labor force, L_i. Finally, country O is modeled as being small, in that its labor force, L_O, is significantly smaller than that of C or D. Notice also, that the model is essentially a sequence of static problems, that vary from period to period through different (exogenous) levels of TFP. The structure of the model is summarized in Figure 2.9.

[17] It is easy to extend the model to include oil production in all countries, however this setup can represent the net-flows of oil. For example, even though the US and China are very large oil producers, they are also very large net oil importers.

[18] The difference in sector specific TFP will result in countries being in different positions along their own structural transformations.

Consumers' problems At each point in time t, the representative consumer in each country $i = C, D, O$ allocates income between goods by solving:

$$\max G\left(A[A_C^i, A_D^i] - \bar{A}, I[I_C^i, I_D^i], S[S_C^i, S_D^i]\right) \tag{2.3}$$

$$\text{s.t.} \sum_{j=C,D} \left(p_A^j A_j^i + p_I^j I_j^i + p_S^j S_j^i\right) = Y^i.$$

In the above equation, G is given by:

$$G[A, I, S] = \left(\alpha_A A^\rho + \alpha_I I^\rho + (1 - \alpha_A - \alpha_I) S^\rho\right)^{\frac{1}{\rho}}, \tag{2.4}$$

where, α_A is the utility weight on agriculture and α_I is the utility weight on industry and ρ is the parameter that determines the elasticity of substitution between agriculture, industry and service goods. The consumer is endowed with an income of Y^i in each period. In $i = C, D$ this consists of wage income from selling a unit of labor on the market, $Y^i = w^i$. For $i = O$, this is the income from oil sales, $Y^O = \frac{p^O O^O}{L^O}$, where p^O is the price of oil and L^O is the size of country O's labor force. Given income, the consumer in country i chooses how many agriculture, industry and service goods produced in country j he wishes to consume - A_j^i, I_j^i and S_j^i at price p_s^i, for each good $s = A, I, S$. The goods are then bundled together in each country using the following Armington aggregator:

$$s[C, D] = \left(\nu_s^i C^\gamma + (1 - \nu_s^i) D^\gamma\right)^{\frac{1}{\gamma}}, \tag{2.5}$$

where ν_s^i is country i's preference weight on country C's good. In particular, I assume that $\nu_s^i = 1 - \nu_s^{i'}$ for $i = C, D$. That is, consumers place the same weight on their home goods. I also assume that $\nu_s^O = 0.5$ - consumers in the oil producing country value both consumption goods equally.

In the model, structural transformation is driven by two channels: income effects arising from non-homothetic preferences as in Kongsamut et al. (2001) and substitution effects due to unbalanced productivity growth across sectors as in Ngai and Pissarides (2007).

The shift of labor away from agriculture towards other sectors is accomplished by introducing Stone-Geary, non-homothetic preferences in agriculture. In particular, it is assumed that there exists a subsistence level of consumption in agriculture, $\bar{A}$. It is easy to show that consumption of agriculture must always be at least as large as $\bar{A}$. At low levels of TFP, a high proportion of the labor force is devoted to agriculture in order to produce the required minimum. As TFP in the agricultural sector grows, less workers are needed to produce the subsistence level. These workers then shift away from agriculture towards the other two sectors.

The shift of labor away from industry towards services is accomplished by introducing an elasticity of substitution between sectors that is different from one. In particular, if TFP growth rates in Agriculture and Industry are higher than in the Service sector ($g_A, g_I > g_S$) setting the elasticity of substitution between agriculture, industry and service goods low enough ($\frac{1}{1-\rho} < 1$, i.e. so that goods are gross complements) will result in labor moving away from agriculture and industry towards services in order to maintain a relatively stable proportion of consumption across types of goods[19] . If the service sector has a higher exogenous technological growth rate than the agriculture and industry sectors ($g_S > g_A, g_I$), an EOS greater than one ($\frac{1}{1-\rho} > 1$) is needed to achieve the movement away from agriculture and industry towards services. During calibration, given TFP growth rates, the EOS is chosen to match the flow of labor from industry towards services.

Firms' problems At each point in time t, for $i = C, D$ and sectors $s = A, I, S$, firms solve the following problem:

$$\max p^i_{s,t}(g^i_s)^t B^i_s F_s[O^i_{s,t}, L^i_{s,t}] - p_{o,t} O^i_{s,t} - w^i_t L^i_{s,t}, \tag{2.6}$$

where, $F_s[L, O] = (\eta_s O^{\xi_s} + (1-\eta_s) L^{\xi_s})^{\frac{1}{\xi_s}}$. Notice, that both the initial sector-specific TFP levels, B^i_s, and the sector specific TFP growth rates, g^i_s, can all potentially vary across C and D. The share of oil in sector specific production, η_s, and the elasticity of substitution between oil and labor, $\frac{1}{1-\xi_s}$, can vary across sectors (but not across countries).

Changing sector specific oil intensity is captured by introducing an elasticity of substitution between oil and labor in production, that is different from one. In particular,

[19] If goods are gross complements, people like to consume goods in relatively fixed proportions. The only way to maintain fixed proportions when TFP growth varies across sectors is for labor to move from the faster growing sectors to the slower growing ones.

choosing an elasticity of substitution that is greater than one in agriculture ($\frac{1}{1-\xi_A} > 1$) and smaller than one in industry and services ($\frac{1}{1-\xi_i} < 1$ for $i = I, S$) results in sectoral oil intensity that is rising in agriculture and falling in services. Since it is relatively easy to substitute between labor and oil in the agriculture sector, as countries structurally transform (and income per capita increases) the share of value added in agriculture devoted to oil will rise. Since substitution between oil and labor in the industry and service sectors is more difficult, as countries structurally transform (and income per capita increases) the share of value added in industry and services devoted to oil will fall. For more details see Appendix 2.9.2.

Notice, that since the sector specific elasticities of substitutions potentially differ across sectors, as the relative size of sectors changes (due to structural transformation), the *aggregate* oil-labor elasticity of substitution will also change. Thus, even though the elasticity of substitution between oil and labor is constant is constant in each sector, this is not necessarily the case at the aggregate level. Initially, when agriculture is the largest sector, the aggregate elasticity of substitution will mostly be determined by the elasticity of substitution in the agricultural sector. As the economy shifts towards industry and services, those sectors will have the largest impact on aggregate elasticity of substitution. A high elasticity of substitution in agriculture (greater than one) and a low elasticity in industry and services (less than one) will result in an aggregate oil-labor elasticity of substitution that falls from above one to below one, as structural transformation takes place. In this way, aggregate oil intensity will first rise - up to a point - and then fall.

Oil production I model oil production by assuming an inelastically growing oil supply. This is done for simplicity and to keep the focus of the model on the demand effects of structural transformation on the oil price. I motivate this assumption by the stable growth of oil output observed over the past three decades. Each consumer in country $i = O$ is endowed with a fraction, $\frac{1}{L_O}$, of an inelastically growing stream of oil each period which he sells to the world:

$$O_t^O = g_O^t B_O, \tag{2.7}$$

where, B_O is an initial efficiency parameter. The total amount of available oil in the economy grows at a fixed and constant rate. Although the above production function might seem restrictive, the above can be viewed as a specialization of a model where labor combines with exogenously growing oil reserves to produce oil. In such a version of the model, the share of oil reserves would be 1 (see Appendix 2.9.3). In this sense, oil reserves are a fixed factor in oil production.

Market Clearing Finally, goods, labor and oil markets clear according to the following conditions:

$$\sum_{j=C,D,O} \bar{L}^j A^j_{i,t} = (g^i_A)^t B^i_A F_A[L^i_{A,t}, O^i_{A,t}] \tag{2.8}$$

$$\sum_{j=C,D,O} \bar{L}^j I^j_{i,t} = (g^i_I)^t B^i_I F_I[L^i_{I,t}, O^i_{I,t}] \tag{2.9}$$

$$\sum_{j=C,D,O} \bar{L}^j S^j_{i,t} = (g^i_S)^t B^i_S F_S[L^i_{S,t}, O^i_{S,t}] \tag{2.10}$$

$$L^i_{A,t} + L^i_{I,t} + L^i_{S,t} = \bar{L}^i \tag{2.11}$$

$$O^O_t = \sum_{i=C,D} \sum_s O^i_{s,t} = g^t_O B_O. \tag{2.12}$$

Notice, that the size of the labor force across countries can potentially vary according to $\bar{L}^i$ for $i = A, D, O$. Thus, at each point in time, the total demand for good $s = A, I, S$ made in country i by country j will be given by $\bar{L}^j s^j_{i,t}$ - the size of the labor force multiplied by the per-capita consumption.

Competitive Equilibrium For every t, a competitive equilibrium is: (1) A set of consumption good prices $\{p^i_{s,t}\}_{s=A,I,S}$ and wages $\{w^i_t\}$ for $i = C, D$ as well as oil prices $\{p_{O,t}\}$; (2) household allocations $\{s^i_t\}_{s=A,I,S}$, for $i = C, D, O$; and (3) firm allocations $\{L^i_{s_t}\}_{s=A,I,S}$ and $\{O^i_{s_t}\}_{s=A,I,S}$ for $i = C, D$, such that: (a) Given prices, (1), households' allocations, (2), solve the households problem (2.3); (b) Given prices, (1), firms' allocations, (2), solve the firms problem in Equation (2.6) ; and (c) good, labor and oil markets clear. Standard arguments ensure that an equilibrium exists and is unique.

2.4 Calibration of the Model

The model is calibrated to match several facts pertaining to China/India and the OECD over the 1970-2003 period[20] . In particular, the above model is calibrated to match: 1) the structure of employment in China/India and the OECD in 1970; 2) the structure of oil consumption in China/India and the OECD in 1970; and 3) observed sectoral TFP growth in China/India and the OECD for the years 1970-2003. The calibration is undertaken in three steps[21] . First, sector and country specific labor growth rates and initial productivity levels as well as labor force sizes are calculated from the data $(g_s^i, B_s^i, \bar{L}^i)$. Next, the parameters governing the structural transformation are chosen $(\bar{A}, \alpha_A, \alpha_M, \rho)$. Finally, parameters affecting sector specific oil intensities are chosen (η_s, ξ_s) as well as the parameters effecting trade in oil and goods (ν_s^i, γ).

Productivity and Labor Force Parameters Ideally, I would obtain total factor productivity by finding the following residual in the data:

$$B_{s,t}^i = \frac{Y_{s,t}^i}{\left(\eta_s {O_{s,t}^i}^{\xi_s} + (1-\eta_s){L_{s,t}^i}^{\xi_s}\right)^{\frac{1}{\xi_s}}}, \tag{2.13}$$

where $Y_{s,t}^i$ is a country i's sector s gross output, $O_{s,t}^i$ is its oil use and $L_{s,t}^i$ is its labor force. Data on sectoral oil use and gross output however, is available only for limited countries and only for two years for China and India - 1995 and 2005. Consequently, I choose $B_{s,t}^i$ in the model to match labor productivity data (for details see Appendix 2.9.4). Calculating the sequences of TFP in this way, I can find the annualized growth rate of the productivity, for all countries and for all sectors[22] .

The output growth rate of the oil sector is calculated from world oil production data for the year 1970-2003, with the initial level of oil normalized to 1. The labor force in O is set to be small relative to the Chinese/Indian labor force - it is chosen to be 5% of Chinese/Indian labor force. Finally, I normalize the labor force in D to 1, and set

[20] The OECD here is taken to be Australia, Austria, Belgium, Canada, Denmark, Finland, France, Greece, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Turkey, UK, US. These countries are chosen due to data availability.

[21] Technically, this division is artificial since all the parameters are calibrated simultaneously. The division however, is made to ease exposition.

[22] This is done by solving, $g_s^i = \left(\frac{B_{s,2003}^i}{B_{s,1970}^i}\right)^{\frac{1}{2003-1970}}$.

Parameter	Values China	OECD	Oil Prod.	Target
$B^i_{A,1970}$	0.12	5.05	–	Initial Prod. in A
$B^i_{I,1970}$	0.51	17.14	–	Initial Prod. in I
$B^i_{S,1970}$	0.50	20.68	–	Initial Prod. in S
g^i_A	1.028	1.029	–	Prod. growth in A
g^i_I	1.051	1.020	–	Prod. growth in I
g^i_S	1.036	1.011	–	Prod. growth in S
g^i_O	–	–	1.014	World oil output growth
$\bar{L}^i$	2.35	1	0.05	Size of Labor force, 1970

Table 2.3: TFP, TFP growth rates and labor force parameter values and targets in a multi-country model.

the size of the labor force in C to match the size of the labor force in China and India relative to the OECD in 1970. The results from the first step of the calibration are given in Table 2.3.

Structural Transformation Parameters Parameters $\bar{A}$, α_A, α_I and ρ are chosen to match China/India's and the OECD's employment distribution across sectors in 1970[23] . The first two parameters influence employment levels in agriculture in the two regions. A high subsistence level in agriculture, $\bar{A}$, means that China/India - with their relatively low TFP in agriculture - must devote a large share of their labor force to agriculture. For the OECD, where the TFP in agriculture is significantly higher, this parameter plays a smaller role (with high agricultural TFP it is easy to achieve the subsistence level in the OECD). Instead, employment in agriculture is primarily determined by the utility parameter, α_A - the more consumers enjoy agriculture, the higher the employment in agriculture in the OECD. The utility weight on industry, α_I, plays a similar role in influencing industrial employment in China/India. The more consumer's enjoy industrial goods, the higher the industrial employment in China/India. Finally, the employment in industry in the OECD is determined by the parameter ρ, which governs the elasticity of substitution between agriculture, industry and services. Given the OECD's higher TFP in industry and services in 1970, consumers in the OECD

[23] Since the number of workers is fixed in each country, by matching employment shares in two sectors, I automatically match employment in the third sector.

will consume more industry and more service goods than consumers in China/India. Exactly *how* much more of each type of good is consumed in the OECD, is influenced by the elasticity of substitution between goods in the utility. This, in turn, influences the quantity of workers employed in industry. The results from the second step of the calibration are given in the first part of Table 2.4[24] .

Oil Intensity Parameters I choose oil parameters, ξ_s and η_s to match the share in world oil consumption of every sector (in each country) in 1970 [25] . It follows from the firm's first order conditions that at any point in time, the sectoral oil-labor ratio in each country is given by:

$$\frac{O^i_{s,t}}{L^i_{s,t}} = \left(\frac{\eta_s}{1-\eta_s}\right)^{\frac{1}{1-\xi_s}} \left(\frac{w^i_t}{p^O_t}\right)^{\frac{1}{1-\xi_s}} . \tag{2.14}$$

Since the oil price in both countries is the same, the oil labor ratio at each point in time, depends only on the relative wage of each country. Since sectoral employment in each country in 1970 is pinned down by the structural transformation parameters, by choosing oil-labor elasticity and share parameters, I can set the oil consumption of each sector in each country in 1970. At every point in time, a country with a higher per-capita income (recall that in C and D, all income is wage income) will use more oil per worker in every sector. The sector specific elasticity of substitution between oil and labor, $\sigma_s = \frac{1}{1-\xi_s}$, determines *how* much more oil per worker richer countries use. With Cobb-Douglas production functions (with an elasticity of substitution between oil and labor of 1), a country with a higher nominal wage will have a proportionally higher oil-labor ratio. With lower elasticities of substitution, richer countries will have less

[24] Notice, that since the model is being matched to the employment shares in China/India and the OECD in 1970, it doesn't exactly match the evolution of employment shares over time in either country, however it does a fair job of approximating shares in both countries over time. There is a trade off in how well the model matches structural transformation in any given country versus how well it matches the structural transformation in both countries - the better match the model makes in one country the worse it fares in matching the other country.

[25] The strategy of matching oil consumption at one point in time in two countries, rather than at two points in time in one country arises from the inability of the model to match exactly the structural transformation at all points in time in both countries. There is a trade off between our ability to match the structural transformation in one country exactly whilst failing to match the structural transformation of the other, and doing a fair job of matching structural transformation in both countries. Since I choose the latter strategy, it would be incorrect to calibrate the oil parameters across time rather than across countries.

Parameter	Values	Target
$\bar{A}$	0.08	Empl. in Agr. in C
α_A	0.001	Empl. in Agr. in D
α_I	0.09	Empl. in Ind. in C
$1/(1-\rho)$	0.34	Empl. in Ind. in D
$1/(1-\xi_A)$	1.61	Trend of Agr. Oil Int.
$1/(1-\xi_I)$	0.72	Trend of Ind. Oil Int.
$1/(1-\xi_S)$	0.57	Trend of Ser. Oil Int.
η_A	0.017	Long Run Agr. Oil Int.
η_I	0.044	Long Run Ind. Oil Int.
η_S	0.021	Long Run Ser. Oil Int.
ν_A^i	0.89	Trade share in Agr., $i = C, D$
ν_I^i	0.66	Trade share in Ind., $i = C, D$
ν_S^i	0.91	Trade share in Ser., $i = C, D$
$1/(1-\gamma)$	1.9	Change in share in world oil consumption

Table 2.4: Preference, production and trade parameter values and targets in a multi-country model.

than proportionally larger oil to labor ratios, whilst with higher elasticities, they will have a more than proportionally larger oil to labor ratios.

Since total world oil supply is exogenous, only five of the six oil parameters are needed to match the shares of all sectors in world oil consumption at a point in time. As such, the elasticity of substitution between oil and labor is set to lie in the mid-range of the values estimated by Berndt and Wood (1975) and Griffin and Gregory (1976), $\sigma_M = 0.72$. Due to a lack of data on oil consumption by sector in 1970 for all countries in the sample, I use the cross-sectional properties of sectoral oil intensity at different stages of structural transformation to infer sectoral oil consumption (see Appendix 2.9.5). The results from the third step of the calibration are given in the second part of Table 2.4.

The calibration has the intuitive implication that industry uses the most oil ($\eta_I = 0.044$), followed by services ($\eta_S = 0.021$) and agriculture ($\eta_A = 0.017$). It also implies that oil and labor are (gross) substitutes in agriculture and (gross) complements in industry and services - with the lowest elasticity in the service sector. How robust is this result? I check, by re-estimating these elasticities using equation (2.14) (for details see Appendix 2.9.6). I use 1995 cross-sectional data and estimate the elasticity of substitution between oil and labor to be approximately 1.3 for agriculture, 0.63 for industry and 0.47 for services. The calibrated values lie in the empirically estimated ranges.

Broadly speaking, the approach for estimating these values in the literature is similar to mine. For example, Berndt and Wood (1975) use time-series data (1947-71) to estimate the factor share functions (arising from a transcendental logarithmic production function) in US manufacturing for four inputs - capital, labor, energy and materials - using iterative three-stage least squares. Griffin and Gregory (1976) perform a similar analysis for cross-country manufacturing data. How do my values compare to the values obtained in the literature? For agriculture, Shankar et al. (2003) estimate the Allen partial elasticity of substitution between energy and labor to be 4.58 in Hungary. This is higher than in our calibration, but of the same order of magnitude. Furthermore, the authors use a short time period and one that included significant political upheaval in Hungary. Next, in industry numerous studies find Allen partial elasticities of substitution between energy and labor to be less than one. Berndt and Wood (1975) estimates this elasticity for the US to be 0.65. Griffin and Gregory (1976) estimates the elasticity for numerous advanced European countries and for the US to be between 0.72 and 0.87. Kemfert (1998) as well as Kemfert and Welsch (2000) estimate this elasticity for Germany to be 0.871. These values are again of similar magnitude to the value 0.72 found in my calibration. Finally Koschel (2000) finds elasticity in the German service sector to be 0.28. This again roughly matches the magnitude in our model estimates.

This pattern of constant *sectoral* oil-labor elasticities will result in a falling *aggregate* oil-labor elasticity of substitution. As the size of the high elasticity, agriculture sector declines and that of the low elasticity, industry and service sectors rises, aggregate oil-labor elasticity of substitution will fall from above one to below one. This is consistent with the findings in the literature. In particular, Daragay (1992) estimates a significant reduction in the energy-GDP elasticity in the UK from 1.0 to 0.9 for 1973 and 1988, which he primarily explains by a decline in the relationship between industrial energy consumption and GDP.

Trade Parameters The home bias parameters in $i = C, D$ are chosen to match trade flows between these countries. The home bias parameters in O are set to 0.5 - the oil producer shows no preference for C's or D's good. Finally, I choose the elasticity of substitution between C's and D's goods to match the change in the share in world oil consumption of China/India and the OECD over the 1970-2003 period. The results from the third step of the calibration are given in the third part of Table 2.4.

Aggregate Oil Intensity, Oil Prices and World Oil Shares The calibration gives further insight into the two channels driving the inverted-U shape of the aggregate oil intensity curve visible in the data.

First, the pattern of oil use across sectors ($\eta_I > \eta_S > \eta_A$) implies that as the economy moves away from producing predominantly agriculture to producing predominantly industry and service goods, aggregate oil intensity rises because of the higher oil use of these two sectors. As structural transformation continues and the economy moves from the high oil use industry sector to the (relatively) lower oil use service sector, aggregate oil intensity falls.

Second, the pattern in the sector specific elasticities of substitution between oil and labor ($\sigma_A > 1 > \sigma_I > \sigma_S$) acts to enforce the first effect. As the economy moves away from agriculture (a sector with an elasticity of substitution that is greater than one) to industry and services (sectors with elasticities of substitution that are less than one), the aggregate elasticity of substitution falls from above to below one. Since in each country, labor is supplied inelastically in the aggregate, but the world supply of oil *grows* inelastically, oil - over time - becomes relatively more abundant. An initially high elasticity of substitution between oil and labor implies that the aggregate share of the factor becoming relatively abundant - oil - rises. As the elasticity drops below one, and it becomes more difficult to substitute between oil and labor, the aggregate share of the factor becoming relatively scarce - labor - rises. Consequently, at this stage, the aggregate share of oil falls.

Notice, that these effects operate on country-specific aggregate oil intensities through both the price *and* quantity channels. The price channel is straightforward. Since the output of oil grows inelastically, at the aggregate level, oil markets can only clear when, if faced with higher or lower international oil demand, oil prices either rise or fall respectively. As world demand for oil first rises and then falls world oil prices that follow an inverted-U shape[26] . The quantity channel is a bit more subtle. Even though at the world level, oil supply grows inelastically, from a single country's perspective oil supply *is* elastic. Consequently, if China/India's demand for oil grows faster than world oil output, prices are not the only channel to clear the market domestically. China/India *can* physically consume more oil if the OECD consumes less. Although, over time, the world is consuming an inelastically growing quantity of oil, China and India's share in world oil consumption is increasing. Taken together, these effects account for: 1) An inverted-U shaped aggregate oil intensity 2) An inverted-U shaped oil price curve 3) China and India's rising share in world oil consumption.

2.5 Quantitative Analysis of Model

In this section I first examine the path of structural transformation in China/India and the OECD implied by the model. Next, I consider how sectoral oil intensities change over time. Then, I consider how changing structure and sectoral oil intensities influence aggregate oil intensities in the model. Finally, I show how changing oil intensities result in changing world oil consumption shares and a hump shape oil price.

The model is run from 1970 to 2050. This requires assumptions on future sectoral productivity growth rates in both regions, and the future growth rates of oil output beyond the 1970-2003 period. Initially, I make the following assumptions about growth rates: 1) productivity growth rates in the OECD stay at their 1970-2003 levels, 2) productivity growth rates in China/India stay at their 1970-2003 levels until the level of sector specific TFP in the OECD is reached, at which point they drop to those in the OECD[27] and 3) the growth rate of oil output remains at the level of the 1970-2003 period[28] .

[26] Although world demand for oil first rises then falls, the world *quantity* demanded does not - since in equilibrium world quantity demanded is always the same as world quantity supplied, and world quantity supplied of oil grows inelastically.

[27] Notice, that this assumption is made to prevent China/India's TFP becoming too large relative to that of the OECD, however it never gets used in the model. In particular, despite the higher TFP growth rates, China/India's TFP does NOT catch up to the TFP in the OECD by 2050. Thus, effectively, in the time period under consideration China/india's TFP is assumed to at the same rate as it did over the 1970-2003 period. This process is chosen for simplicity and a more complicated technology diffusion process does not effect the results significantly.

[28] In effect, I take the optimistic view that the world will not "run out of oil". Improvements in either extraction or location technology will ensure an inelastically growing oil supply in the coming

The top two panels of Figure 2.10 show the changing shares of employment in China/India and the OECD over time. In China/India, employment share in agriculture falls, forms an inverted-U in industry and rises in services. In the OECD, a similar pattern emerges for agriculture and services. Since the OECD has higher TFP levels, it is further along the structural transformation. As such, the share of employment in industry is falling - it is on the downward part of the inverted-U industry employment curve.

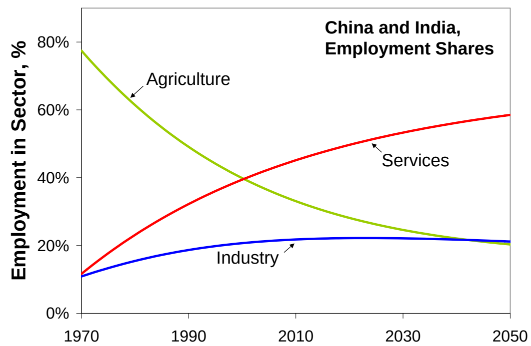
The middle two panels of Figure 2.10 show sector specific oil intensities. Oil intensity is rising in agriculture, but falling in industry and services. This development is analogous to the development of oil intensities in the data shown in Figure 2.7. Intuitively, as agriculture becomes more mechanized, oil intensity in agriculture rises. As technology in non-agriculture improves, industry and services require less oil and oil intensity in those sectors drops.

The bottom two panels of Figure 2.10 show the aggregate oil intensities over time in China/India and the OECD. As China/India undergoes its structural transformation from beginning to end, aggregate oil intensity in China/India first rises and then falls forming an inverted-U. As the OECD finishes its structural transformation, we only see the second part of the inverted-U - falling aggregate oil intensity in the OECD.

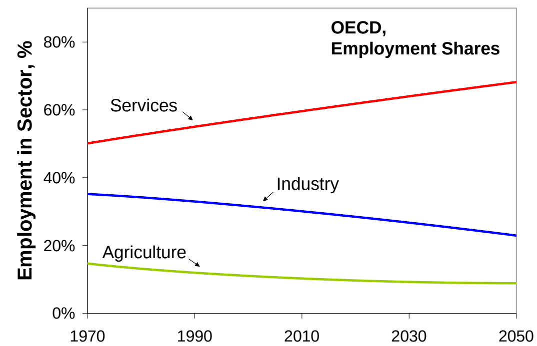
The top four panels of Figure 2.10, help explain the patterns in aggregate oil intensity visible in the bottom two panels. Initially in China/India, as the economy shifts away from agriculture towards industry and services, aggregate oil intensity rises, since sectoral oil intensity in industry and services is significantly higher than in agriculture. This effect is reinforced by rising oil intensity in the largest sector - agriculture. Later in both China/India and the OECD, the structural transformation becomes dominated by a shift away from industry towards services. Since oil intensity in services is lower than in industry, aggregate oil intensity falls. This effect is reinforced by falling oil intensities in the largest two sectors - industry and services.

Figure 2.11(a) shows how changing aggregate oil intensity affects the share in world consumption of specific countries. Since the output of oil is growing inelastically, as China/India spend a rising share of their income on oil and the OECD spends a falling share of income on oil, China/India's share in world oil consumption increases and

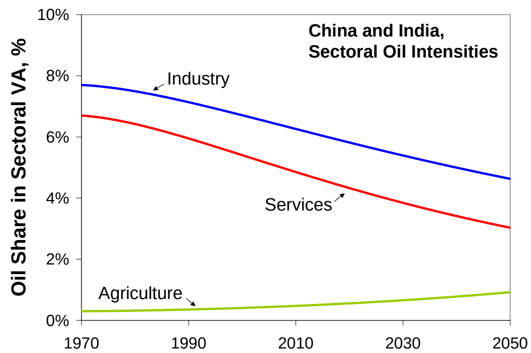
decades.



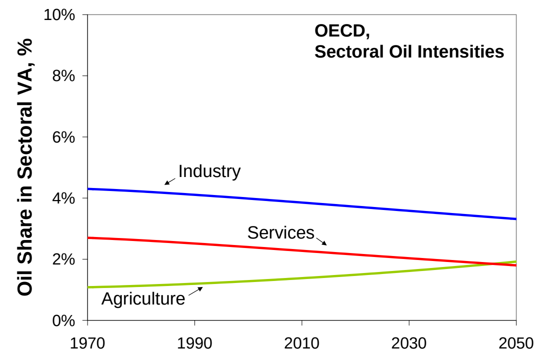
(a) China/India, Employment Shares



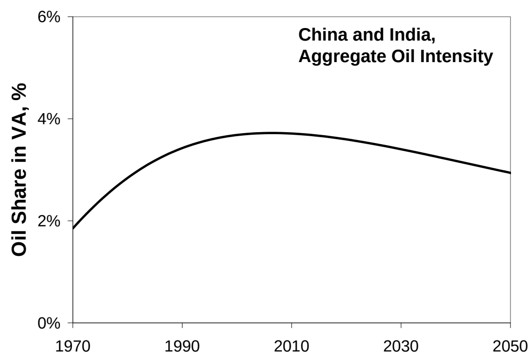
(b) OECD, Employment Shares



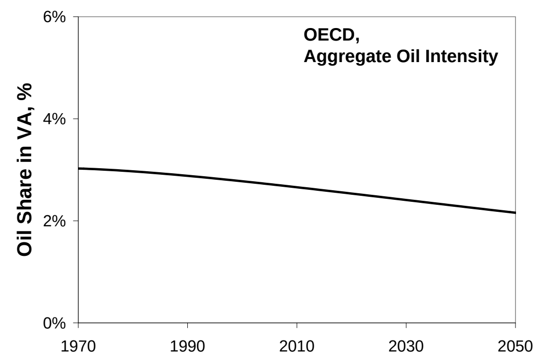
(c) China/India, Sectoral Oil Intensities



(d) OECD, Sectoral Oil Intensities

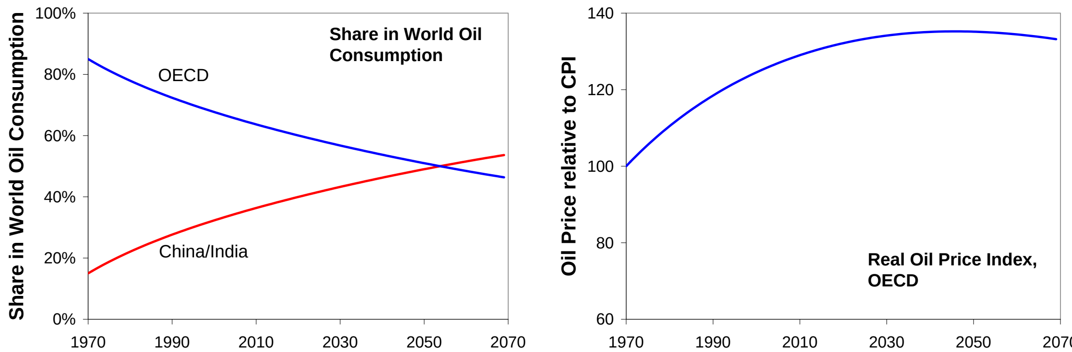


(e) China/India, Aggregate Oil Intensities



(f) OECD, Aggregate Oil Intensities

Figure 2.10: Simulation result for employment shares, sectoral oil intensities and aggregate oil intensities.



(a) Oil Consumption Shares

(b) OECD Oil Price

Figure 2.11: Share of oil consumption by region and OECD oil price.

the OECD's share falls. When China/India enters the second phase of the inverted-U aggregate oil intensity curve, both the shares spent on oil in the OECD and China/India are falling which results in shares that slowly begin to level off.

Finally, Figure 2.11(b) shows the wide hump in oil prices that arises from the hump in aggregate oil intensity in China/India[29] . As China/India spends first a higher then a smaller fraction of its income on oil it induces the world's aggregate oil intensity to follow a hump shape as well. This causes oil prices to rise and fall around the world and more oil to moves towards China. The model predicts that prices will rise approximately 35% until the mid 2040's, as China undergoes its structural transformation. The model however, also predicts that as China finishes its structural transformation, it will spend a falling share of its income on oil, resulting in prices that will eventually start to decline.

2.6 Counterfactuals

In this section I perform two counterfactuals that gauge the effect of China and India's growth and structural transformation on oil prices and underline the importance of modeling oil prices within a multi sector framework, rather than in a regular one sector growth model.

In the first counterfactual I switch off productivity growth in China and India in

[29] The price here, refers to the oil price in the model relative the to the OECD's time zero, fixed basket consumer price index.

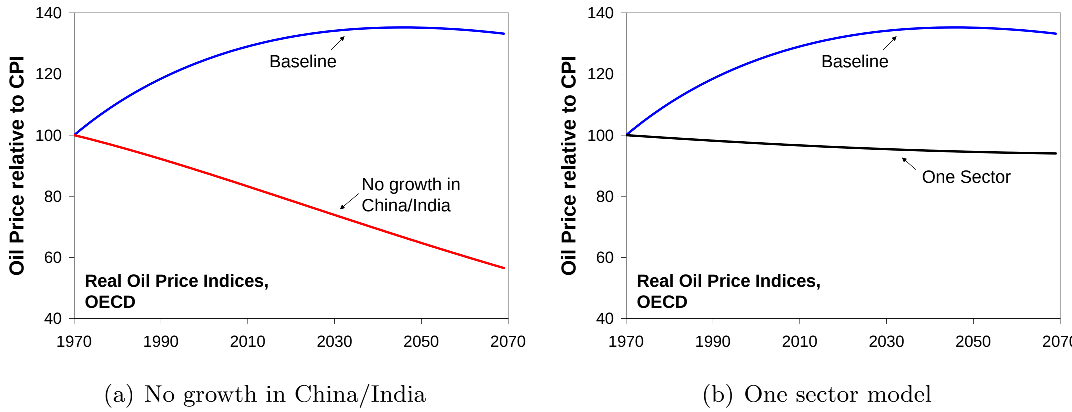


Figure 2.12: Counterfactual experiments.

all sectors and compare the resulting price index to the price index obtained in the baseline model. The result is shown in Figure 2.12(a). This experiment allows me to measure the total effect that growth and structural transformation in China and India have had on oil prices. From the graph, it becomes clear that if China and India had not undergone structural transformation at the speed that they did, oil prices would have declined since the 1970's. Comparing the two curves, the China/India effect results in oil prices in the model that are more than 100% higher at their peak in 2046 than they would be without the China/India effect. Furthermore, according to the model, the oil price in the OECD is 50% higher in 2007, than if China and India had not structurally transformed at the speed that they did. In this sense, the model explains 25% of the 200% observed increase in oil prices over the 1970-2007 period[30] .

Second, I replace all sector specific parameters with weighted sectoral averages of those values. In particular, I weigh country specific parameters (TFP growth rates and initial TFP levels) by the period zero current price share of each sector relative to each country's current price GDP. In particular, I set $g_s^C = 1.031$ and $B_{s,1970}^C = 0.21$ in all three sectors in China/India and I set $g_s^D = 1.017$ and $B_{s,1970}^D = 17.13$ in all three sectors in the OECD. Next, I replace all parameters that are common across countries but differ across sectors (production and trade parameters) by the sector

[30] Notice, that even though these curves show oil price indices, they can also be viewed as normalized price *levels* since both models are the same in time zero.

specific parameters weighed by the period zero current price shares of each sector in the OECD. In particular, I set $\sigma_s = 1/(1-\xi_s) = 0.68$, $\eta_s = 0.029$ and $\nu_s = 0.82$. All other parameters remain the same as in the baseline. Since all parameters are now identical across sectors, the model is essentially a standard, open economy, one sector growth model. The above procedure effectively turns off structural transformation, whilst keeping growth effects. The resulting price index, is shown in Figure 2.12(b). from this, it becomes clear that that omitting structural transformation misses a crucial non-linearity in prices. Without structural transformation, oil prices would have fallen.[31]

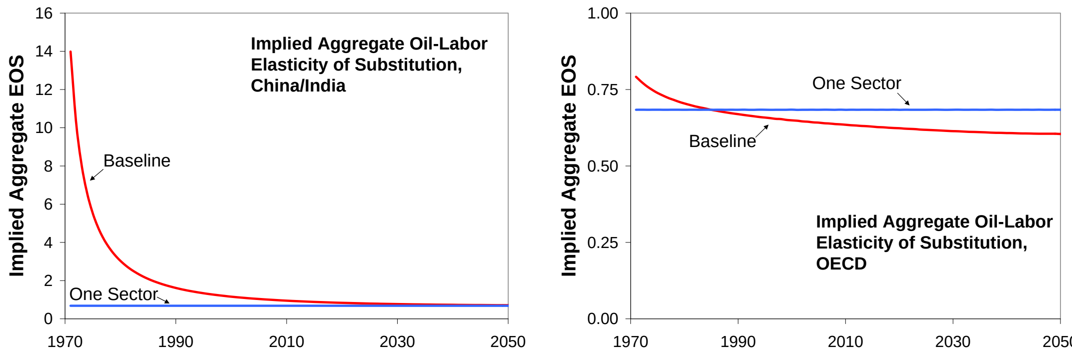
To see the source of this non-linearity, I demonstrate how aggregate elasticity of substitution between oil and labor in the baseline and in the one sector model change over time. In particular, taking the log of equation (2.14), I obtain a relationship that can be estimated from the data:

$$\log\left(\frac{O^i_{s,t}}{L^i_{s,t}}\right) = \sigma_s \log\left(\frac{\eta_s}{1-\eta_s}\right) + \sigma_s \log\left(\frac{w^i_t}{p^O_t}\right). \tag{2.15}$$

In the above, $\sigma_s = \frac{1}{1-\xi_s}$, is the elasticity of substitution between oil and labor in sector s. Notice, that if there was only one sector in the economy, then σ_s would be the aggregate elasticity of substitution between oil and labor. In particular, if an econometrician was given a sequence of relative wage and oil-labor ratio data derived from the baseline and the one sector model and asked to estimate σ_s at each point in time under the assumption that the data come from a one sector economy, his estimates would reflect the aggregate elasticity of substitution between oil and labor at each point in time. Aggregate elasticities of substitution estimated in this way for China/India and the OECD in both models at each point in time are shown in Figure 2.15.

The econometrician in the one sector model would find that the elasticity of substitution between oil and labor is constant over time and across countries and is equal to $\sigma_s = 0.68$. This is quite unsurprising, since in the one sector model, the aggregate elasticity of substitution does not change. On the other hand, the econometrician in the baseline world, would find that the estimates of elasticity of substitution vary widely

[31] Notice, that since the models are different in the initial period, they can no longer be viewed as normalized price *levels*. However, it is still correct to compare the price dynamic over time between the two scenarios.



(a) China/India (b) OECD

Figure 2.13: Implied aggregate oil-labor elasticities of substitution in China/India and the OECD in the baseline and one sector models.

over time and between countries. In particular, in China/India, the elasticity of substitution is very high initially (above one) and drops over time (to below one). In the OECD, the elasticity of substitution is also dropping but remains strictly below one the entire period.

Why is aggregate elasticity of substitution changing in the baseline model but constant in the one sector model? Since each sector has a different elasticity of substitution, as the relative size of sectors change, the aggregate elasticity of substitution also changes. The model is thus capable of generating endogenously changing elasticities of substitution - something that the one sector model cannot do. In China/India, when the elasticity of substitution is above one, oil intensities rise (recall that with the elasticity higher than one, the share of the factor growing more scarce - oil - rises). When the elasticity of substitution falls below one, oil intensities fall (with an elasticity lower than one, the share of the factor growing more scarce - oil - falls). In the OECD, since elasticities are always below one, oil intensity is always falling. In the one sector model however, elasticities are the same in both countries and always below one - this results in oil intensities that are falling in both countries. The baseline model predicts a hump shape oil price that follows the hump shape of emission intensity, whereas a model that omits structural transformation predicts falling oil prices and hence gives misleading implications about the long-term oil price dynamics. The lesson here is that to understand the impact of growth on the oil price, it is crucial to take a more disaggregated

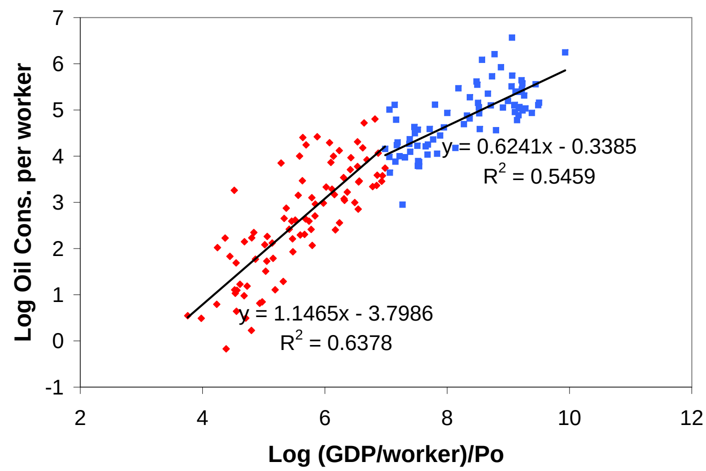


Figure 2.14: Evidence for falling aggregate oil-labor elasticity of substitution.

view than is standard in macroeconomics.

2.7 Evidence

Finally, I present evidence for aggregate oil-labor elasticities of substitution that fall from above to below one. In particular, I estimate equation (2.15) using cross-sectional 2000 data for all the world's countries, under the assumption that the data come from a one sector economy. Figure, 2.14 shows a log-log scatter plot of aggregate oil consumption per worker versus GDP per worker relative to the 2000 oil price[32] . GDP and labor force data comes from WDI (2007) whilst oil consumption data comes from the EIA (2009). The data has been divided into two groups of equal number of points, and regression lines have been drawn through each groups of the data. The slope of each regression line is an estimate of the aggregate elasticity of substitution between oil and labor at every level of wage-oil price ratio. Since, all countries face the same oil price, from the figure it is apparent that as income rises, elasticity of substitution fall from above to below one just as the model predicts.

[32] In the model wages correspond to value added per capita. Since value added per capita data is not available for a wide selection of countries, I use GDP per capita instead.

2.8 Conclusion

As structural transformation progresses, aggregate oil intensity first rises and then falls - forming an inverted-U shape. This can result in oil prices that follow a similar pattern over structural transformation. As large countries such as China and India enter the most oil intensive phases of their structural transformation, oil prices will rise. The increase however, is not necessarily permanent. In the medium to long run, the pressure on oil prices will ease, as the structural transformation in these countries comes to an end and oil intensity falls. Using a standard growth model model misses this non-linearity and can give misleading implications about the long-term oil price. To understand the impact of growth on the oil price, it is necessary to take a more disaggregated view than is standard in macroeconomics.

This paper is the the first to identify an inverted-U aggregate oil intensity curve in the data, the first to build a model that theoretically justifies its existence and the first to consider the long term price path implications of such a curve. The main contribution of the paper however, is to take a systematic approach to a contentious topic - China and India's impact on the oil price. In particular, the model developed here predicts that as long as the structural transformation in China/India and other developing nations follows past patterns, the upward pressure on oil prices from China and India will continue for many decades. Interestingly however, the model also predicts that in the more distant future, oil prices can return to lower levels as the economies of these countries become service dominated - hence China and India's impact on the oil price is not necessarily permanent.

2.9 Appendix

2.9.1 Aggregate Oil Intensity

I construct a panel data set that consists of the worlds largest 100 countries (by population in the year 2000) over the 1980-2005 period. Each data point is composed of: 1) a time period, 2) the share of employment in agriculture and 3) the aggregate oil intensity. The data for the shares of employment in agriculture comes from the WDI. The aggregate oil intensity of the economy is constructed by calculating the current year

Agg. Oil Intensity vs. Agr. Share in GDP

COEFFICIENT	(1) Aggregate Oil Int. (OLS)	(2) Aggregate Oil Int. (LAV)
agrShare	0.128***	0.094***
	(0.0066)	(0.0056)
agrShareSq	-0.165***	-0.114***
	(0.0095)	(0.0080)
Constant	0.0091***	0.0081***
	(0.0008)	(0.0006)
Observations	1172	1172
R^2	0.2496	
Pseudo R^2		0.1731

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2.5: Regression of aggregate oil intensity versus the agriculture share in value added for a panel of 150 countries over the period 1995-2005.

value of oil consumed in an economy (in dollar terms), divided by the current year GDP of the country (in dollar terms). Total country-specific oil consumption (in Quadrillions of BTU) and current oil price (dollars per million BTU) data come from the EIA. The oil price used is the 30-year moving average. The shape of the curve remains unchanged if observed oil price data is used. but using unsmoothed oil price data results in oil intensities that are significantly higher due to the high oil prices shock in the early 1980's. Current value GDP (in dollar terms) comes from the WDI.

Next, I perform robustness exercises to check for the existence of an inverted-U aggregate oil intensity curve in the data. I estimate the following equation using Ordinary Least Squares and Quantile Regression (also known as Least Absolute Value):

$$AggrOilShare_{i,t} = \beta_1 agrShare_{i,t} + \beta_2 agrShare^2_{i,t} + \varepsilon_{i,t}. \qquad (2.16)$$

The results are given in Table 2.5. All coefficients are highly significant and do not differ greatly across regression types. The R^2 values are approximately 7% and 4%. Table 2.1, in the main body of the text, presents the results for the following regression:

$$AggrOilShare_{i,t} = \beta_1 agrShare_{i,t} + \beta_2 agrShare_{i,t}^2 + \sum_{j=1996}^{2005} \beta_{2008-j} D_{i,t}^j + \varepsilon_{i,t}, \quad (2.17)$$

where $D_{i,t}^j$ is a dummy variable that takes the value one if $j = t$ and zero otherwise. All coefficients remain highly significant. Adding dummies (unsurprisingly) increases the R^2 of the regressions.

2.9.2 Matching sectoral oil intensities

The oil intensity of sector s - the share of oil relative to the value added of the sector - can be written as a function of sector specific oil-labor ratios, $\frac{O_s}{L_s}$, oil-labor elasticity of substitution parameters, ξ_s and the oil share parameters, η_s:

$$\begin{aligned} \frac{p_O O_s}{V_s} &= \frac{p_O O_s}{w_s L_s} \\ &= \frac{p_s F_{s,O} O_s}{p_s F_{s,L} L_s} \\ &= \frac{\eta_s O_s^{\xi_s}}{(1-\eta_s) L_s^{\xi_s}} \end{aligned} \quad (2.18)$$

The first equality follows from the fact that oil is imported and is hence an intermediate input. Value added in a sector is consequently identical to wage income in that sector. The second equality follows from the profit maximization problem of a sector s firm, since its production function is given by $g_s^t B_s F_s[L_{s,t}, O_{s,t}]$ where, $F_s[L, O] = (\eta_s O^{\xi_s} + (1-\eta_s) L^{\xi_s})^{\frac{1}{\xi_s}}$. Notice also that $F_{s,L}$ and $F_{s,O}$ refer to the derivatives of F with respect to labor and oil respectively. Thus, the share of oil in value added in sector s is given by:

$$\frac{p_O O_s}{V_s} = \frac{\eta_s}{1-\eta_s} \left(\frac{O_s}{L_s} \right)^{\xi_s}. \quad (2.19)$$

Since this relationship holds at every point in time, I can choose η_s and ξ_s, to match sectoral oil intensity at the beginning and end of of a structural transformation in each sector. In particular, ξ_s will determine how fast sectoral oil intensity changes (i.e. its slope) and η_s will determine the overall level of oil intensity (i.e. the long run oil intensity of the sector).

What elasticity parameters allow us to match the cross-sectional oil intensities implied by the data (i.e. rising oil intensities in agriculture and falling oil intensities in industry and services)? As structural transformation progresses, the amount of labor in each sector changes relatively slowly. The total amount of oil in the economy, on the other hand, is growing at a fixed exogenous rate. The ratio, $\frac{O_s}{L_s}$, will thus eventually be increasing in all sectors. Setting $\xi_A > 0$ in agriculture and $\xi_I, \xi_S < 0$ in industry and services (and the appropriate η_s's) allows us to match observed cross-sectional oil intensities.

2.9.3 Oil Production Function

The oil production function, equation (2.7) re-written here:

$$O_t^O = g_O^t B_O,$$

can be seen as a specialization of a Cobb-Douglas technology that combines labor, (L_O), and oil reserves, (R), to produce oil:

$$\sum_{s=A,I,S} O_{s,t} = \bar{g}_O^t \bar{B}_O (g_R^t R)^\varepsilon L_{O,t}^{1-\varepsilon}. \tag{2.20}$$

In the above, ε is the share of oil reserves in oil production, g_R is the exogenous growth rate of oil reserves (or alternatively oil reserve location techniques), $\bar{g}_O^t$ is the exogenous growth rate of refinement technology and $\bar{B}_O$ is an initial efficiency parameter. Labor in the oil producing country is supplied inelastically and hence, $L_{O,t} = L_O$. I can thus re-write the production function as:

$$\sum_{s=A,I,S} O_{s,t} = (\bar{g}_O g_R^\varepsilon)^t (\bar{B}_O R^\varepsilon L_O^{1-\varepsilon}). \tag{2.21}$$

By setting $g_O = \bar{g}_O g_R^\varepsilon$ and $B_O = \bar{B}_O R^\varepsilon L_O^{1-\varepsilon}$, I obtain my original production function given by equation (2.7). Thus, the growth rate of oil output depends on the (exogenous) innovation in the oil production industry and on (exogenous) growth in oil reserves[33] .

The assumption of the above production function, is that oil extraction does not impact the total quantity of oil reserves, $g_R^t R$. This assumption is made primarily for

[33] No explicit assumption is made whether g_R is greater or smaller than one, rather g_O is chosen to match world oil production data. If we assume positive oil output growth, this can either mean that both g_O and g_R are greater than one, or that g_O is sufficiently large to overcome depleting oil reserves.

simplicity, and can be thought of as signifying that oil reserves are very large in comparison to extraction. Alternatively, this assumption can be interpreted through the prism of the (somewhat-controversial) abiotic theory of oil production. This theory promoted by Gold (1992) and recently documented by Proskurowski et al. (2008), suggests that coal and crude oil deposits arise from the decomposition of microbes living at extreme depths under the surface of the earth and drawing their energy from natural super-heated subterranean gas flows. In other words, this theory claims that oil - rather than being produced from the decomposition of exhaustible fossils - arises from tectonic forces and is continuously being replenished by the decomposition of new microbes.

Finally, if I choose to incorporate the more general version of the production function directly into the model, the consumer's problem in the oil producing country, will qualitatively change. Consumers will now own the oil reserves and the inelastically supplied labor, rather than owning a flow of oil output. As such, the consumer's income will no longer come from sales of oil, but rather from the supply of oil reserves and labor to oil producing firms as well as the profits of those firms. Quantitatively however, this proves to be identical to the original problem, since firms earn zero-profits.

2.9.4 Total Factor Productivity Calibration

Ideally, I would obtain total factor productivity by finding the following residual in the data:

$$B^i_{s,t} = \frac{Y^i_{s,t}}{\left(\eta_s {O^i_{s,t}}^{\xi_s} + (1-\eta_s){L^i_{s,t}}^{\xi_s}\right)^{\frac{1}{\xi_s}}}, \tag{2.22}$$

where $Y^i_{s,t}$ is a country i's sector s gross output, $O^i_{s,t}$ is its oil use and $L^i_{s,t}$ is its labor force. Data on sectoral oil use and gross output however, is available only for limited countries and only for two years - 1995 and 2005 . Consequently, I estimate sectoral productivity growth data using labor productivity data.

Labor productivity in the data is given by:

$$\bar{D}^i_{s,t} = \frac{V^i_{s,t}}{L^i_{s,t}}, \tag{2.23}$$

where $V^i_{s,t}$ is the value added of sector s in country i at time t in constant prices. Notice, that since the above does not involve sectoral oil consumption, the sequences of labor productivities for each country i and for each sector s, is known. Denote these sequences (normalized by Chinese GDP/worker in 2003) as $\{\bar{D}^i_{s,t}\}_{t=1970}^{2003}$.

Returning to the model, suppose that all parameters where known, and in particular suppose we had guessed a sequence of TFP parameters, $\{B^i_{s,t}\}_t$. Solving the model, we could calculate the implied labor productivity (in the model) as $D^i_{s,t}$:

$$D^i_{s,t} = D^i_{s,t}(B^i_{s,t}) \equiv \frac{p^i_{s,0} B^i_{s,t} \left(\eta_s {O^i_{s,t}}^{\xi_s} + (1-\eta_s) {L^i_{s,t}}^{\xi_s} \right)^{\frac{1}{\xi_s}} - p^O_0 O^i_{s,t}}{L^i_{s,t}}, \tag{2.24}$$

where the term in the numerator is the value added of a sector s in country i at time t in period 0 prices (notice that this is just the gross output of sector s less intermediate inputs - the oil used in the sector). The objective is thus to choose TFP levels, $B^i_{s,t}$, so that the model's implied labor productivity, matches observed labor productivity:

$$D^i_{s,t}(B^i_{s,t}) = \bar{D}^i_{s,t}. \tag{2.25}$$

The above, is simply an extra equation, that must be solved for countries $i = C, D$ and sectors $s = A, I, S$ at every point in time t, together with the first order conditions for the extra unknown, $B^i_{s,t}$. Calculating the sequences of TFP in this way, I can find the annualized growth rate of the productivity, for all countries and for all sectors.

2.9.5 Oil Consumption Calibration

In this section, I estimate oil consumption by sector in China/India and the OECD in 1970. In order to do this (and for lack of sectoral oil consumption data in China/India and the OECD), I use the regression presented in equation 2.2 and Table 2.2. These regressions describe what fraction of a sector's value added is devoted to oil at any point in the structural transformation and they are robust over time. According to these regressions, countries that employ 80% of their work force in agriculture - approximately the share employed by China/India in 1970 - spend 1% of their agriculture value-added, 8% of their industry value-added and 7% of their service value added on oil. Since I have data on the value-added of Chinese/Indian agriculture, industry and services in 1970, this allows me to estimate the total value of oil used by each sector in 1970 - $p_{O,1970} O^C_{s,1970}$. This allows me to calculate what fraction of total oil consumption in China/India was consumed by which sector, $\frac{p_{O,1970} O^C_{s,1970}}{\sum_s p_{O,1970} O^C_{s,1970}} = \frac{O^C_{s,1970}}{\sum_s O^C_{s,1970}}$. Given data on a country's total oil consumption, I can then estimate the quantity of oil consumed by each sector in each country and hence its share in total world oil consumption

Since I model the entire world as only the OECD and China/India, I need to make an assumption on how the oil that is not consumed by either the OECD (as defined in the text) or China/India in the data, is allocated across countries C and D in the model. In the data, China/India and the OECD (as defined in the text) consumed only 68% of the world's total oil consumption in 1970. Furthermore, this number did not stay constant over time, but fell to 60% by 2003 BP. This implies that I cannot assume that the growth rate of oil consumption in China/India and the OECD is the same as the growth rate of world oil output without adjusting the data. Consequently, I divide world oil consumption in the data into two groups: 1) The OECD and the Former Soviet Union[34] and 2) China/India and other emerging economies[35]. I match the oil consumed by the first group in the data to $D's$ oil consumption in the model and the oil consumption by the second group in the data to C's oil consumption in the model. This adjustment ensures that total oil consumption of C and D in the model grows at the same rate as world oil consumption in the data (by construction).

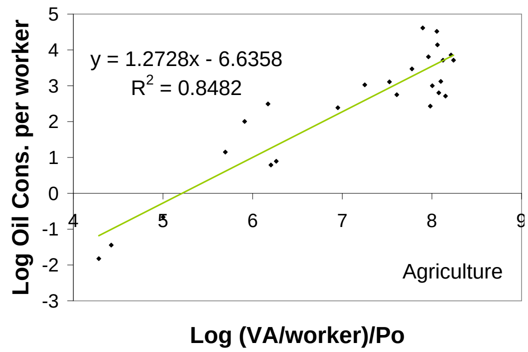
2.9.6 Estimating Sectoral Oil-Labor Elasticities

In this section, I estimate equation (2.14) using cross-sectional 1995 data for OECD countries, Brazil, Russia, India, China, Indonesia and South Africa. The sectoral oil consumption data is obtained from the Input-Output tables constructed by the OECD (2006). In my model, wages correspond to value added per capita. This data is taken from UN (2008). Finally, 1995 oil prices are taken from BP (2008). Taking the log of equation (2.14), I obtain:

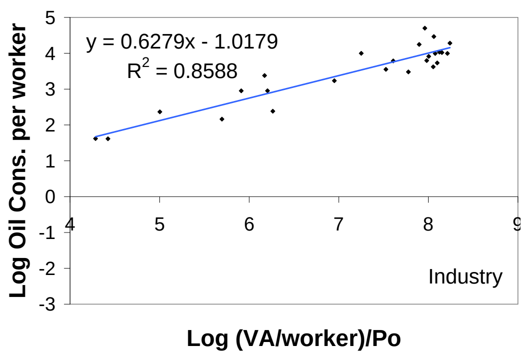
$$\log\left(\frac{O^i_{s,t}}{L^i_{s,t}}\right) = \sigma_s \log\left(\frac{\eta_s}{1-\eta_s}\right) + \sigma_s \log\left(\frac{w^i_t}{p^O_t}\right),$$

[34] For the purposes of dividing world oil output, the OECD consists of Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Republic of Ireland, Italy, Japan, Luxembourg, Mexico, Netherlands, Norway, New Zealand, Poland, Portugal, Slovakia, South Korea, Spain, Sweden, Switzerland, Turkey, United Kingdom and the USA. The Former Soviet Union consists of: Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine and Uzbekistan.

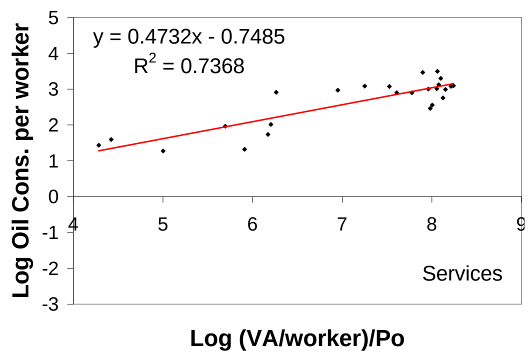
[35] These are all the other countries that are not in any of the other groups.



(a) Agriculture



(b) Industry



(c) Services

Figure 2.15: Regression results

where $\sigma_s = \frac{1}{1-\xi_s}$. I estimate this equation using OLS and the results are shown in Figure 2.15. The slope parameter of each regression is the elasticity of substitution between oil and labor in a particular sector.

Chapter 3

A comment on "The Green Solow Model"

3.1 Introduction

Most man made emissions are directly related to the production process. More output is usually associated with higher emissions, unless production of additional units of output becomes cleaner. The simplest way to capture this relationship is with the following equation:

$$P_t = N_t Y_t, \tag{3.1}$$

where, at a given point in time, P_t are the total emissions of an economy, Y_t is the total output of the economy and N_t is the quantity of emissions released per unit of output (this term is also often referred to as the emission intensity). Taking logarithms of the above equation and differentiating with respect to time, I obtain a relationship between the growth rate of emissions, $g_{P,t}$, the growth rate of GDP, $g_{Y,t}$, and the growth rate of emission intensity $g_{N,t}$:

$$g_{P,t} = g_{Y,t} + g_{N,t}. \tag{3.2}$$

In Brock and Taylor's (2004) analysis, the EKC arises solely from the dynamics generated by capital accumulation and hence from changing $g_{Y,t}$, whilst emission intensity is assumed to fall at a constant rate (due to technological improvements in abatement technology), resulting in a constant $g_{N,t}$. As $g_{Y,t}$ falls over time, $g_{P,t}$ can first be positive (emissions will be growing) and then negative (emissions will be falling) resulting in a EKC-type emission profile.

In what follows I briefly elaborate on the Green-Solow framework. I then show why this model cannot be the right way to think about emissions profiles of countries: in the data $g_{Y,t}$ is relatively constant over time, whilst $g_{N,t}$ changes significantly over time. Whilst convergence effects can certainly contribute to falling emissions, the changing emission intensity effect dominates the growth effect by an order of magnitude. Finally, I construct a simple example were structural transformation from agriculture to non-agriculture acts as the mechanism capable of matching observed changes in $g_{N,t}$.

3.2 The Green-Solow Model

Brock and Taylor (2004) present a very simple extension of the traditional Solow model. For simplicity, both savings rates and abatement choices are assumed to be exogenously set. Output is assumed to be produced using capital (K_t) and labor (L_t) by a constant returns to scale and strictly concave production function, $F(K_t, B_tL_t)$, where B_t is the productivity of labor. Capital is accumulated at a constant savings rate s and depreciates at a fixed rate δ. Pollution is assumed to be generated directly by output. If left unabated, a unit of output will generate Ω_t units of pollution at every point in time. However, the economy can devote a constant (and exogenous) fraction of output, $0 \leq \theta \leq 1$, to abate pollution. After abatement, a unit of output generates $a(\theta)\Omega_t$ units of pollution, where $a(\theta)$ is an abatement function that is assumed to satisfy $a(0) = 1$ as well as $a'(\theta) < 0$ and $a''(\theta) > 0$. Thus, abatement has a positive but diminishing marginal impact on pollution reduction. The labor force, L_t, is assumed to grow at a constant rate n. Labor productivity, B_t, is assumed to grow at a constant and exogenous growth rate g. There also exists exogenous technological progress in abatement, that lowers Ω_t at a constant rate $g_A > 0$. The model is given by:

$$Y_t = (1 - \theta)F(K_t, B_tL_t)$$

$$\dot{K}_t = sY_t - \delta K_t$$

$$P_t = a(\theta)\Omega_t F(K_t, B_tL_t)$$

$$\dot{L}_t = nL_t,\ \dot{B}_t = gB_t,\ \dot{\Omega}_t = -g_A\Omega_t,$$

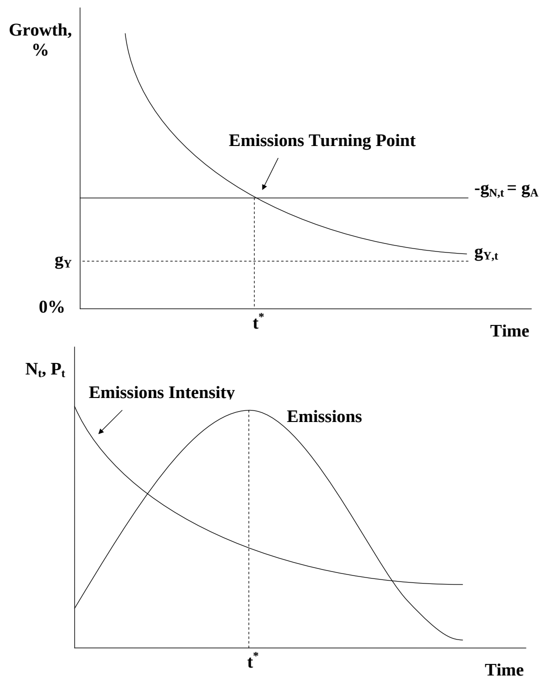


Figure 3.1: The EKC according to Brock and Taylor (2004)

where a dot above a variable represents the partial derivative with respect to time. In particular, notice that emission intensity, $N_t \equiv P_t/F(K_t, B_tL_t)$, is simply declining at the constant exogenous rate of technological progress in abatement, g_A.

The main departure from the standard Solow model is the assumption that pollution is co-produced with every unit of output. A second departure, is the assumption that some fraction of income can be devoted to abatement. Notice however, that neither of these assumptions fundamentally influence the dynamics of the standard Solow model. The production of pollution does not effect growth of output, whilst the abatement technology will effect the level of GDP but not its growth path. In particular, the model can be solved like the regular Solow model. The model is thus re-written in terms of effective units per capita as follows:

$$y_t = (1-\theta)f(k_t)$$

$$\dot{k}_t = s(1-\theta)f(k_t) - (\delta + n + g)k_t$$

$$p_t = \Omega_t a(\theta) f(k_t),$$

where $k_t = K_t/B_tL_t$, $y_t = Y_t/B_tL_t$, $p_t = P_t/B_tL_t$ and $f(k_t) = F(k_t, 1)$. Next, assume that the Inada conditions hold for F - in particular, for simplicity assume that $F(K, L) = K^{\alpha}L^{1-\alpha}$. Then, given a fixed θ, it follows immediately that starting from any $k(0) > 0$, the economy converges to a unique capital per effective worker level, k^*, just as in the Solow model. On the balanced growth path aggregate GDP, consumption and capital all grow at rate $g_Y = g_C = g_K = g+n$, whilst their corresponding per capita magnitudes grow at rate $g_y = g_c = g_k = g$. Finally, pollution grows according to $g_P = g + n - g_A$. Off the BGP, the growth rate of the economy and emissions depends on the level of capital stock. In particular, it is easy to show that:

$$\frac{\dot{k}_t}{k_t} = sk_t^{\alpha-1}(1-\theta) - (\delta + n + g) \tag{3.3}$$

and

$$g_{P,t} \equiv \frac{\dot{P}_t}{P_t} = g_{Y,t} - g_A = (g + n + \alpha\frac{\dot{k}_t}{k_t}) - g_A, \tag{3.4}$$

where $g_{Y,t} = g + n + \alpha\frac{\dot{k}_t}{k_t}$, is the growth rate of output off the BGP. As in the standard Solow, model, if the effective-units economy starts with a capital stock less than the steady state level ($0 < k_0 < k^*$), the economy accumulates capital ($\frac{\dot{k}_t}{k_t} > 0$) until it converges to the steady state ($\lim_{t\to\infty} k_t = k^*$), at which point the economy stops accumulating capital ($\lim_{t\to\infty} \frac{\dot{k}_t}{k_t} = 0$). Consequently, the economy is growing faster off the BGP than it does on the BGP (i.e. $g_{Y,t} > g_Y$). Furthermore, if (for given parameter values) it is assumed that $g_P = g + n - g_A < 0$, then with low enough initial capital stock, there exists a t^* such that for $t < t^*$, $g_{P,t} = g_{Y,t} - g_A > 0$, whilst for $t > t^*$, $g_{P,t} = g_{Y,t} - g_A < 0$. Emissions follow an EKC type profile, peaking at t^*.

This process is demonstrated in Figure 3.1. Countries starting at low levels of capital, grow faster than they do on their BGP. For countries with low enough levels of initial capital, improvements in emission intensity are not enough to outweigh the extra pollution caused by faster growth of GDP - this results in rising total emissions ($g_{P,t} = g_{Y,t} - g_A > 0$, for $t < t^*$). As capital is accumulated, GDP growth eventually slows enough for improvements in emissions intensity to outweigh the additional pollution created during the production of output - resulting in falling emissions ($g_{P,t} = g_{Y,t} - g_{A,t} < 0$, for $t > t^*$). Depending on the chosen parameters, capital accumulation and constant growth in abatement technology can result in an EKC (although whether an EKC is observed depends fundamentally on parameters).

The dynamics of the EKC in the Green-Solow framework ultimately depend on the dynamics of GDP growth and in particular the slow down associated with convergence to a balanced growth path. Notice that emission intensity however, is assumed to decline at a constant and exogenous rate. In what follows I show that - in the data - the influence of dynamics of GDP are secondary in determining the shape of the EKC relative to the dynamics of the emission intensity growth rates.

3.3 Stylized Facts

3.3.1 Development of Emission Intensity

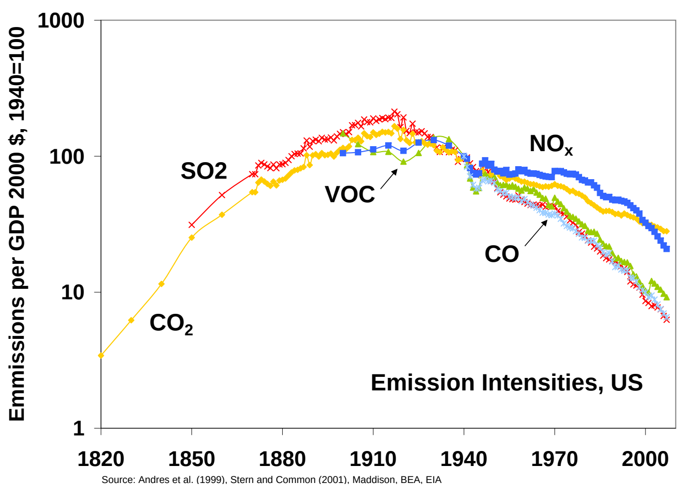


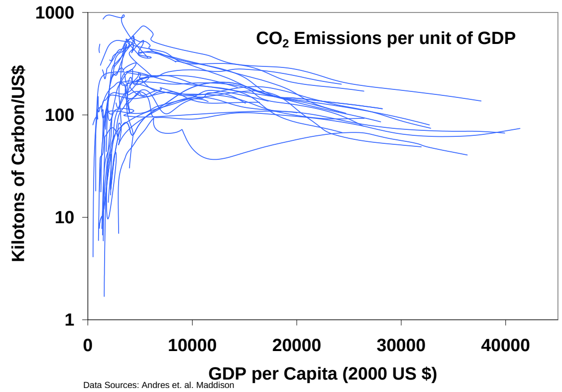
Figure 3.2: US emission intensities, 1820-2007.

Brock and Taylor (2004) motivate their assumption of emission intensity declining at a constant rate by considering US data for the 1950-1998 period. Figure 3.2 shows their emission intensity data, except that it is extended backwards and forwards in time and it includes the emissions intensity of carbon dioxide. Thus, the figure shows indices of US emissions of various pollutants (with 1940=100) per dollar of US GDP (in 2000 US dollars). I have adopted a log-scale for ease of reading. The intensities under consideration are nitrogen oxides (NO_x) for 1900-2007, carbon dioxide (CO_2) for 1820-2007, carbon monoxide (CO) for 1940-2007, sulphur dioxide (SO_2) for 1850-2007 and volatile organic compounds (VOC) for 1900-2007. When considering a longer period of time it becomes clear that emission intensities are *not* declining at a constant rate. In particular, emission intensities trace out a inverted-U, which implies that growth rates of emission intensities change over time. In particular, they fall from above zero (when emission intensity is rising) to below zero (when emission intensity is falling).

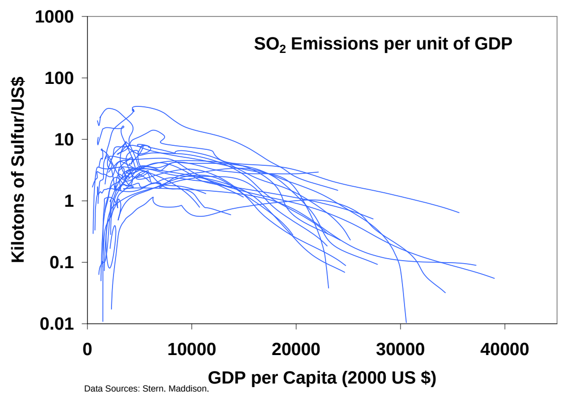
The inverted-U shape is not restricted to the United States. Figure 4.1 plots total CO_2 emissions per dollars of GDP for 26 OECD countries versus each country's GDP per capita, for the years 1820-2007[1] . Emissions of CO_2 are measured in thousands of metric tons of carbon and the data comes from Andres et al. (1999). Figure 3.3(b) plots total SO_2 emissions per dollars of GDP for 26 OECD countries versus each country's GDP per capita, for the years 1850-2002[2] . Emissions of SO_2 are measured in thousands of metric tons of sulphur and the data comes from Stern (2005). Real GDP and real GDP per capita are expressed in 2000 US-dollars. GDP and GDP per capita for the year 2000 is obtained from *World Development Indicators* (2009). The growth rates for both series for all countries are obtained from Maddison (2007) for the years 1820-2006. The 2006-2007 growth rate is obtained from *World Development Indicators* (2009). These growth rates are then applied to the GDP and GDP per capita level data and extended backward and forward. Both the emissions data and the GDP per capita data is smoothed using an HP filter, with smoothing parameter $\lambda = 100$. Although there is some variance in the levels of emissions intensity across countries, in general emission intensity of both CO_2 and SO_2 rises until a country's GDP per capita reaches approximately 4500-5000 US dollars, and then slowly begins to fall. Notice that this

[1] The countries and the years under consideration are: Canada (1870-2007), Mexico (1900-2007), United States (1870-2007), Japan (1875-2007), Korea, Rep. (1945-2007), Australia (1875-2007), New Zealand (1878-2007), Austria (1870-2007), Belgium (1846-2007), Denmark (1843-2007), Finland (1860-2007), France (1820-2007), Germany (1850-2007), Greece (1921-2007), Hungary (1924-1942; 1946-2007), Ireland (1924-2007), Italy (1861-2007), Netherlands (1846-2007), Norway (1835-2007), Poland (1929-1938; 1950-2007), Portugal (1870-2007), Spain (1850-2007), Sweden (1839-2007), Switzerland (1858-2007), Turkey (1923-2007) and the United Kingdom (1830-2007). The Czech and Slovak Republics, Iceland and Luxembourg were not considered due to the lack of data.

[2] The countries and the years under consideration are: Canada (1870-2002), Mexico (1900-2003), United States (1870-2003), Japan (1870-2002), Korea, Rep. (1946-2000), Australia (1850-2002), New Zealand (1878-2002), Austria (1870-2002), Belgium (1850-2002), Denmark (1850-2002), Finland (1860-2002), France (1850-2002), Germany (1850-2002), Greece (1921-2002), Hungary (1924-1942; 1946-2002), Ireland (1924-2002), Italy (1861-2002), Netherlands (1850-2002), Norway (1850-2002), Poland (1929-1938; 1950-2002), Portugal (1865-2002), Spain (1850-2002), Sweden (1850-2002), Switzerland (1850-2002), Turkey (1923-2000) and the United Kingdom (1850-2002).



(a) OECD Carbon Dioxide Emission Intensity, 1820-2007



(b) OECD Sulfur Dioxide Emission Intensity, 1850-2000

Figure 3.3: CO_2 and SO_2 emission intensities in the OECD.

pattern holds for both “advanced countries” such as the UK, France or Denmark; for countries that have recently becomes “advanced”, such as Spain, Korea or Portugal; and for the least developed countries in the group such as Turkey, Hungary or Mexico.

3.3.2 Emission Intensity vs. Growth Dynamics

The above figures imply that growth rates of emission intensities fall from above to below zero in a wide range of countries. I argue that this changing dynamic in emission intensity growth rates is key to influencing the formation of an EKC. In particular, in this section I show that the changing emission intensity growth rates are of far greater importance than changing GDP growth rates when it comes to influencing emissions.

Table 3.1, shows three sets of regressions that describe how GDP, CO_2 emission intensity and SO_2 emission intensity growth rates vary over time (starting with $t = 0$). In particular, each column shows the following country specific regressions:

$$g_t = \alpha t + \beta + \epsilon. \tag{3.5}$$

The slope parameter, α, describes the average annual change in growth rates over the period in question. Notice that the slope parameters of the GDP regressions are very close to zero - growth rates in the OECD are nearly constant over time (approximately 2.639% per annum); they increase - on average - by only 0.004 percentage points per year. The growth rates of emission intensities however, are declining over time. Emission intensity growth rates are decreasing - on average - by 0.074 percentage points per year for carbon dioxide and by 0.14 percentage points per year for sulfur dioxide. The rate of change of these growth rates is an order of magnitude bigger than the rate of increase of GDP per capita - emission intensity in CO_2 declines 20 ($\approx 0.074/0.04$) time faster whilst emission intensity in SO_2 declines nearly 40 ($\approx 0.14/0.04$) times faster than the rate of change of GDP growth. Thus, the impact on emissions from changes in GDP growth is relatively small compared to changes in the growth rates of emission intensities. Since most OECD countries exhibit near constant long run GDP growth and many still exhibit the EKC profile of emissions in most pollutant types, the above data suggests that the main source of the EKC is falling pollution intensity growth rates, rather than falling GDP growth rates caused by convergence to a balanced growth path.

The message from this is that in order to understand the existence of an EKC, it is necessary to understand why emissions intensity growth rates fall over time - in other words, any theory of the EKC has to explain why countries exhibit an inverted-U emissions intensity curve. In the next section I argue that one possible mechanism driving the pattern is structural transformation.

3.4 Why do emission intensity growth rates fall?

A theory explaining the emission profiles of a country would have to generate an inverted-U emission intensity profile. In particular, it would have to generate an emission intensity growth rate that fell over time, from above to below zero. One possible

	(1) GDP		(2) CO_2 Intensity		(3) SO_2 Intensity	
	slope	inter	slope	inter	slope	inter
Canada	0.002	3.509	-0.087	6.881	-0.105	6.099
Mexico	0.020	2.733	-0.081	6.295	-0.044	1.743
United	-0.007	3.898	-0.041	2.287	-0.069	2.956
Japan	0.019	2.536	-0.091	7.689	-0.139	8.504
Korea	0.008	7.374	-0.430	15.973	-0.821	24.502
Australia	0.009	2.709	-0.067	5.842	-0.029	2.210
New Zealand	-0.002	3.065	-0.037	2.834	-0.068	3.535
Austria	0.015	1.351	-0.018	0.548	-0.101	3.765
Belgium	0.004	1.844	-0.032	1.840	-0.071	3.930
Denmark	0.004	2.291	-0.049	4.480	-0.128	8.541
Finland	0.010	2.316	-0.027	4.012	-0.110	8.903
France	0.017	0.799	-0.045	3.262	-0.082	5.459
Germany	0.002	2.183	-0.061	4.968	-0.179	10.156
Greece	0.024	2.258	-0.073	6.215	-0.106	7.704
Hungary	-0.130	6.618	-0.156	4.272	-0.253	3.894
Ireland	0.084	-0.009	-0.065	1.764	-0.136	3.059
Italy	0.017	1.234	-0.059	6.308	-0.246	21.642
Netherlands	0.014	1.579	-0.023	1.588	-0.076	3.979
Norway	0.012	2.053	-0.052	4.789	-0.136	10.204
Poland	-0.066	4.815	-0.123	2.037	-0.269	4.183
Portugal	0.026	1.044	-0.057	5.458	-0.037	3.192
Spain	0.024	0.681	-0.062	6.829	-0.061	4.820
Sweden	0.006	2.094	-0.077	7.112	-0.144	11.320
Switzerland	0.003	2.275	-0.067	6.195	-0.121	7.995
Turkey	-0.019	5.665	-0.014	1.813	-0.026	2.087
United States	0.004	1.689	-0.028	1.229	-0.073	3.550
Average	**0.004**	2.639	**-0.074**	4.712	**-0.140**	6.844

Table 3.1: Changes in GDP growth and emission intensity growth over time in the OECD. Each column shows country specific regressions that quantify how particular growth rates change over time: $g_t = \alpha t + \beta + \epsilon$. The slope parameter, α, describes the average annual change in growth rates over the period in question.

driver of this could be structural transformation: the shift of an economy away from agriculture, towards industry and services - both in terms of value added of particular sectors and in terms of employment in particular sectors.

To see how structural transformation can result in an inverted-U emission intensity, assume that the economy consists of two sectors - agriculture (A) and non-agriculture (C). Assume that at each point in time, the emissions of each sector i ($P_{i,t}$) and of the aggregate economy (P_t), are proportional to the scale of activity in each sector and the economy. Thus, for each sector, assume that $P_{i,t} = n_{i,t}Y_{i,t}$, where $n_{i,t}$ is the emission intensity of sector i and for the aggregate economy, assume that $P_t = N_tY_t$, as in equation 3.1. Furthermore, assume that emission intensity in each of the sectors declines at the same constant rate, $g_A > 0$, and hence $\dot{n}_{i,t} = -g_A n_{i,t}$. As in Brock and Taylor (2004), this can be thought of as (equal) technological progress in abatement technology in each sector. Finally, suppose that non-agriculture is an inherently dirty sector, whilst agriculture is clean[3] - thus each sector's emission intensity is $n_{i,t}$, with $n_{C,t} > n_{A,t}$.

Given these assumptions, aggregate emission intensity is simply a sum of emission intensities in each sector ($n_{i,t}$), weighted by the share of value added of each sector in total value added ($s_{i,t} = \frac{Y_{i,t}}{Y_t}$):

$$N_t = \frac{P_t}{Y_t} = \sum_i \left(\frac{P_{i_t}}{Y_{i_t}} \frac{Y_{i,t}}{Y_t}\right) = \sum_i n_{i,t}s_{i,t}. \tag{3.6}$$

Taking logs and differentiating the above expression with respect to time, the growth rate of emission intensity is given by:

$$g_{N_t} = -g_A + \frac{\dot{s}_{C,t}(n_{C,t} - n_{A,t})}{s_{C,t}(n_{C,t} - n_{A,t}) + n_{A,t}}, \tag{3.7}$$

where I have made use of the fact that $s_{A,t} + s_{C,t} = 1$ and hence $\dot{s}_{A,t} = -\dot{s}_{C,t}$. The above equation provides a decomposition of the growth rate of emission intensity into two effects, first described by Grossman and Krueger (1991) - the technique effect and the composition effect. The technique effect, captured by $-g_A$, measures how improvements in technology influence pollution intensity over time. This is the effect that operates in

[3] One characteristic of agriculture, especially at the early stages of development, is its use of cleaner energy (i.e. renewable combustibles) versus non-agriculture's use of dirtier energy (i.e. fossil fuels).

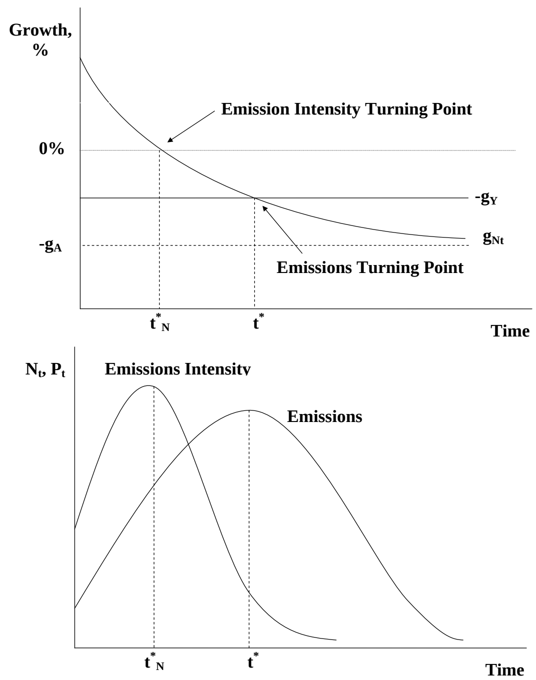


Figure 3.4: The EKC driven by structural transformation

Brock and Taylor (2004): improvements in abatement technology can result in falling emission intensity.

The composition effect, measures how changes in the structure of the economy influence pollution intensity over time. As the economy shifts away from agriculture, the share of (dirty) non-agriculture in value added rises (i.e. $\dot{s}_{C,t} > 0$) and hence the effect is initially positive. If it is large enough - it can outweigh the technique effect, resulting in rising emission intensity. As the economy becomes dominated by non-agriculture, the rate at which the share of non-agriculture in GDP increases goes to zero[4] . Thus, over time, the technique effect dominates and emission intensities fall. Depending on parameters, this setup can generate an inverted-U emission intensity curve (and hence emission intensity growth rates that fall from above to below zero) and an EKC type profile for emissions.

The above mechanism is demonstrated in Figure 3.4. In the face of the evidence

[4] That is, if we assume that the share of non-agriculture converges smoothly to 1, then $\lim_{t\to\infty} \dot{s}_{C,t} = 0$.

of the previous section, growth of GDP, g_Y, is assumed to be (roughly) constant[5] . Assuming that the composition effect dominates initially, the growth rate of emission intensity, $g_{N,t}$, falls over time from above, to below zero according to equation 3.7. As emission intensity growth rates fall towards zero, emission intensity rises. When emission intensity growth rates are equal to zero at time t^*_N, emission intensity reaches a maximum. Total emissions, however, keep rising as improvements in emission intensity are still not large enough to outweigh the extra pollution created by GDP growth. Emissions only reach a turning point at time t^*, once improvements in emission intensity become larger than the growth rate of GDP. After this point, total emissions begin to fall. As long as emission intensity (in absolute value) falls below GDP growth (i.e. as long as $g_Y - g_A < 0$), the emission profile will always follow an EKC.

3.5 Conclusion

Brock and Taylor (2004) provide a valuable contribution to the study of emissions associated with economic activity, by placing the theory neatly within the context of the well understood Solow growth model. However, despite the elegance of this approach, a Green-Solow model is not necessarily the right framework to think about the emissions of an economy over time. Falling GDP growth rates caused by convergence, are not the key driver behind emission dynamics. Rather, changes in emission intensity are key. Any model that wishes to generate an EKC, must concentrate on explaining falling emission intensity growth rates and in particular, the inverted-U shaped emission intensity that is followed by many pollutants and in many countries. I provide a suggestion of one such possible mechanism - structural transformation and provide a very simple framework where an inverted-U emission intensity curve can arise from the changing structure of an economy.

[5] GDP growth does not necessarily have to be constant over time. The point is that that the variation in trend GDP growth rates is significantly smaller than the variation in trend emission intensity growth rates, rendering GDP growth a less important mechanism in driving the EKC.

Chapter 4

Structural Transformation and Pollution

4.1 Introduction

Table 4.1 shows the average annual growth rates of CO_2 emissions, GDP and primary energy consumption over the 1950-2000 period for high and low income countries.[1] Emissions grow faster than GDP in poorer countries and slower than GDP in richer countries. Emission growth rates in richer countries are also lower (in absolute terms) than in poorer countries. These observation prompt three questions: 1) What is driving this relationship? 2) Will emission growth rates fall below GDP growth rates as poor countries grow richer? and 3) Can we expect emission growth rates in rich countries to continue falling?

Since most man-made CO_2 emissions arise as a direct consequence of energy production, any explanation of the above facts will have to account for changing energy demand over a country's development process. Growth rates in energy use and GDP,

[1] High income countries are defined to be: the OECD in 1990 (Australia, Austria, Belgium, Canada, Denmark, Finland, France Germany, Greece, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States), the Former Soviet Union (Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan) and Central and Eastern Europe (Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia). All remaining countries are classified as low-income countries. This particular grouping is chosen, as data for energy consumption is available over the 1950-2000 period in this format.

	GDP growth	CO_2 growth	Energy growth
Low Income	4.8%	5.8%	2.8%
High Income	3.5%	1.9%	2.7%

Table 4.1: Annualized growth rates of GDP, CO_2 emissions and total primary energy consumption in high and low income countries (1950-2000). (Source: Maddison; Anders et. al.; Grubler.)

however, do not display the pattern found between growth in emissions and GDP. Table 4.1 shows that energy growth rates, in general, tend to be lower than growth rates of GDP in both rich *and* poor countries. Something other than changing energy use must be driving the relationship between GDP and emission growth rates. In this paper I argue that structural transformation is key to understanding both of these relationships.

Structural transformation is usually defined as a shift in the composition of an economy away from agriculture towards industry and services, that accompanies growth.[2]

In this paper, I argue that structural transformation has two further facets. In particular, the changing composition of the economy influences: 1) the mix of fuel used to produce energy and 2) the energy characteristics of a unit of output and hence an economy's demand for energy.

I construct and calibrate a simple two-sector general equilibrium model that generates a structural transformation: a shift of labor out of agriculture into non-agriculture. Labor moves due to an assumption of non-homothetic preferences for agriculture as in Gollin et al. (2002), Echevarria (1997), Duarte and Restuccia (2007) or Rogerson (2007). In the model, energy productivity grows in both sectors, causing energy intensity (the ratio of energy use to total GDP) to fall as a country develops (i.e. GDP grows faster than energy use). Energy used in agriculture however, is "clean" (biomass fuel - such as firewood - is carbon-neutral), whilst energy used in non-agriculture is "dirty" (fossil fuels are the main source anthropogenic carbon dioxide in the atmosphere). As an economy shifts from producing predominantly agriculture to non-agriculture, it begins to use a dirtier fuel mix, which results in emissions rising faster than GDP (even as energy use continues to grow at a slower rate than GDP). As the economy becomes dominated by non-agriculture, improvements in energy productivity induce energy intensity

[2] Both in terms of employment shares and value-added per sector shares.

to fall, which in turn results in falling emission intensity (i.e. emissions grow faster than GDP). Furthermore, energy and non-energy inputs in non-agriculture, exhibit a degree of complimentarity. Improvements in energy intensity thus induce non-agriculture to use relatively more non-energy inputs than energy as productivity rises.

In poor countries, the main determinant of emission growth rates will be the changing fuel mix. In rich countries, the main determinant of emission growth rates will be the degree of substitutability between energy and non-energy inputs in production as well as improvements in energy efficiency. Structural transformation increases emission intensity by inducing a dirtier fuel mix. As structural transformation comes to a close, falling energy intensity outweighs the effect of the changing fuel mix, causing emission intensity to fall.

I show that a model of structural transformation provides a useful theory of why emissions grow faster than GDP in poor countries, but slower than GDP in rich countries; why emission growth rates slow over time; and why improvements in energy efficiency are generally insufficient to induce falling emissions. I also show that, in as far as low agricultural productivity delays the beginning of structural transformation, it is key in influencing the emission profile of countries over development. Finally, I find that countries starting structural transformation earlier, tend to have higher emission intensities at each level of GDP/capita than countries that start structural transformation later. This may explain why countries such as the United States or the United Kingdom have higher emission intensities than countries at similar income levels, but ones that started industrialize later (such as Japan, South Korea, France or Denmark). Finally, omitting structural transformation from the model misses these dynamics in emissions growth rates, and can lead to misleading predictions with respect to total emissions.

4.2 Stylized Facts

This section establishes three facts:

1. For a wide panel of countries, CO_2 emission intensities follow an inverted-U shape whilst energy intensities are roughly declining over income.

2. Rising emission intensity is predominantly driven by a change in the fuel mix from renewable combustibles towards fossil fuels; Falling emission intensity is predominantly driven by falling energy intensity.

3. Structural transformation is a key driver of the change in fuel mix.

Emission Intensity Fossil fuel energy production accounts for approximately 80% of all anthropogenic carbon dioxide emissions (Schimel et al., 1996).[3] Since historical energy production is well documented, this allows for the estimation of long run emissions of both types of pollutants using historical energy consumption and production data.

Andres et al. (1999) make use of historical energy statistics and estimate fossil fuel CO_2 emissions from 1751 to the present for a wide selection of countries. In this exercise, they obtain historical coal, brown coal, peat, and crude oil production data by nation and year for the period 1751-1950 from Etemad et al. (1991) and fossil fuel trade data over this period from Mitchell(1983, 1992, 1993, 1995).[4] This production and trade data is used to calculate fossil fuel consumption over the 1751-1950 period. Carbon dioxide emissions are imputed following the method first developed by Marland and Rotty (1984) and Boden et al. (1995). The 1950-2007 CO_2 emission estimates reported by Andres et al. (1999) are derived primarily from energy consumption statistics published by the United Nations UN (2006) using the methods of Marland and Rotty (1984). The data is now maintained and updated by the Carbon Dioxide Information Analysis Center.[5]

Figure 4.1 plots total CO_2 emissions per dollars of GDP for 26 OECD countries versus each country's GDP per capita, for the years 1820-2007.[6] Emissions of CO_2

[3] The remaining twenty percent mostly consists of changes in land use - such as deforestation or urbanization.

[4] Mitchell's work tabulates solid and liquid fuel imports and exports by nation and year.

[5] The data is available for download at http://cdiac.ornl.gov/trends/emis/overview.html.

[6] The countries and the years under consideration are: Canada (1870-2007), Mexico (1900-2007), United States (1870-2007), Japan (1875-2007), Korea, Rep. (1945-2007), Australia (1875-2007), New Zealand (1878-2007), Austria (1870-2007), Belgium (1846-2007), Denmark (1843-2007), Finland (1860-2007), France (1820-2007), Germany (1850-2007), Greece (1921-2007), Hungary (1924-1942; 1946-2007), Ireland (1924-2007), Italy (1861-2007), Netherlands (1846-2007), Norway (1835-2007), Poland (1929-1938; 1950-2007), Portugal (1870-2007), Spain (1850-2007), Sweden (1839-2007), Switzerland (1858-2007), Turkey (1923-2007) and the United Kingdom (1830-2007). The Czech and Slovak Republics, Iceland and Luxembourg were not considered due to the lack of data.

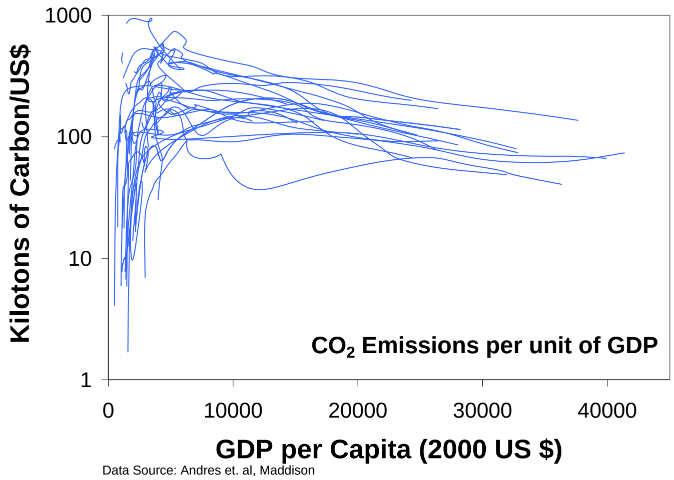
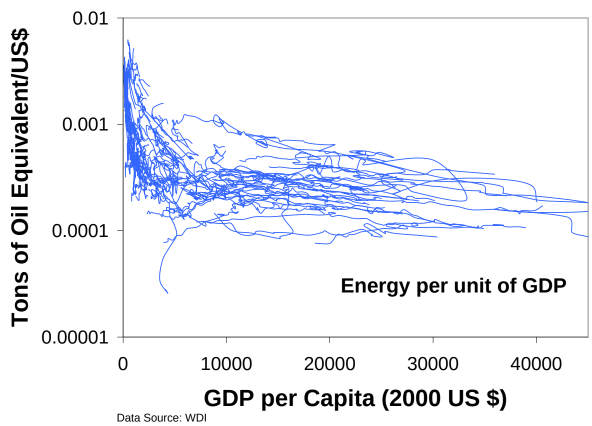


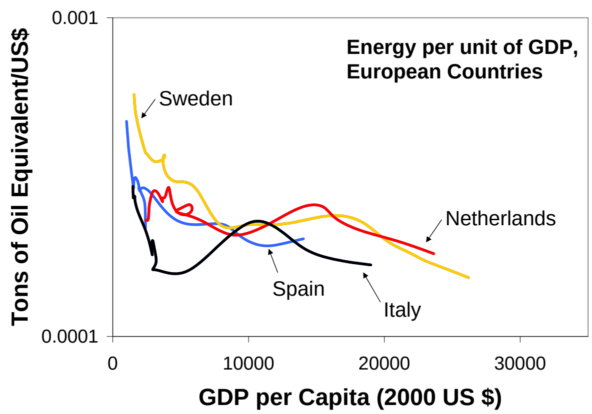
Figure 4.1: OECD carbon dioxide emission intensity, 1751-2007

are measured in thousands of metric tons of carbon and the data comes from Andres et al. (1999). Real GDP and real GDP per capita are expressed in 2000 US-dollars. GDP and GDP per capita for the year 2000 is obtained from *World Development Indicators* (2009) The growth rates for both series for all countries are obtained from Maddison (2007) for the years 1820-2006. The 2006-2007 growth rate is obtained from *World Development Indicators* (2009). These growth rates are then applied to the GDP and GDP per capita level data and extended backward and forward. Both the emissions data and the GDP per capita data is smoothed using an HP filter, with smoothing parameter $\lambda = 100$. Although there is some variance in the levels of emissions intensity across countries, in general emission intensity of CO_2 rise until a country's GDP per capita reaches approximately 4500-5000 US dollars, and then slowly begins to fall. Notice that this pattern holds for both "advanced countries" such as the UK, France or Denmark; for countries that have recently becomes "advanced", such as Spain, Korea or Portugal; and for the least developed countries in the group such as Turkey, Hungary or Mexico. This figure implies that emissions are growing faster than GDP in poorer countries and slower than GDP in richer countries.

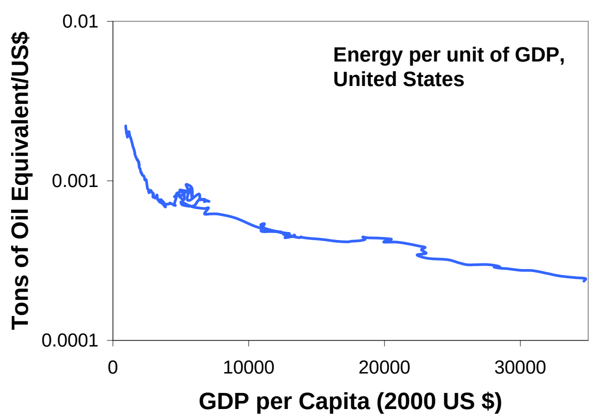
Energy Intensity A country's energy use includes fossil fuel based energy, renewable non-combustibles (such as wind, hydro or nuclear power) and renewable combustibles (such as wood or biomass). Whereas much historical data exists for the first two types



(a) Energy intensity in the world (1960-2006)



(b) Energy intensity of selected European countries, 1850-2000



(c) Energy intensity of the US, 1800-2001

Figure 4.2: Energy intensity of world (1960-2006), selected EU countries (1850-2000) and US (1800-2001).

(and indeed, that is the data largely used to derive emissions), there is less historical data that includes renewable combustibles. As such, Figure 4.2(a) presents energy intensity panel data from *World Development Indicators* (2009) for the year 1960-2006 for all countries (over two hundred countries) and years available rather than just focusing on historical OECD data. Energy here is defined as the use of primary energy before transformation to other end-use fuels and is in kilotons of oil equivalent. GDP and GDP per capita data is also obtained from *World Development Indicators* (2009) and is in 2000 US dollars. A clear falling trend emerges over income.

Although historical data for all OECD countries is not available, it is available for some countries. Gales et al. (2007) construct the first national series of energy consumption data to include the full set of traditional energy carriers such as firewood, charcoal, human and animal traction, and stationary (nonelectric) hydropower along with modern sources for the years 1800-2000 for Sweden, Holland, Italy and Spain. They find a downward historical trend in emission intensity. Figure 4.2(b) shows emission intensities calculated using their data and plotted against GDP per capita.[7] Finally, I construct a time series of historical energy intensity of the United States[8] for the period 1800-2001 using energy data reported by Wright (2006) and Grubler (2003) and plot the results in Figure 4.2(c). Historical energy intensities in both the EU and the US are declining with GDP per capita. Both the panel and the time series data, seem to indicate that output of energy is growing at a slower rate than GDP in both rich *and* poor countries.

The Role of Fuel Mix and Energy Intensity Changes in the composition of the energy basket have an important effect on CO_2 emissions, since different energy carriers emit carbon dioxide to varying degrees. The burning of biomass materials for energy, only releases the carbon accumulated by the plant-matter during its lifecycle. Since such emissions do not add to the atmospheric concentrations of carbon dioxide, most international protocols - including that of the Intergovernmental Panel on Climate Change (IPCC) - consider biomass emissions to be neutral. The US Energy Information

[7] The countries are: Sweden (1839-2000), Netherlands (1846-2000), Italy (1861-2000), Spain (1850-1935; 1940-2000)

[8] Energy consumption here, consists of wood, coal, petroleum, natural gas, hydroelectric power, nuclear electric power and geothermal energy, and is hence not directly comparable to the Gales et al. (2007) data.

Administration, also follows the IPCC guidelines and recommends that "reporters may wish to use an emission factor of zero for wood, wood waste, and other biomass fuels".[9]

The burning of fossil fuels for current energy use however, releases large quantities of CO_2 that had previously been removed from the biosphere over millions of years, in the form of coal, oil or natural gas.[10] Thus burning fossil fuels releases stored carbon into the biosphere, whereas burning biomass recycles carbon that is already in the biosphere.

At the same time, output is becoming more energy efficient as goods and production techniques require less and less energy to operate. For example, in 1946, the Electronic Numerical Integrator and Automatic Computer (ENIAC), one of the world's first super computers, consumed two hundred thousand Watts of energy an hour and performed 100,000 operations per second. Today, the Lenovo T400 Thinkpad, the laptop on which this paper is written, sips eight Watts of energy an hour and performs 2.2 million operations per second - in this example, energy intensity has fallen from 2 Watts an operation to 0.00000364 Watts per operation - an over 550,000 fold improvement, or an average annual increase in energy efficiency of nearly 20%! Whilst this may be an extreme example, many everyday production processes and goods have seen similarly significant improvements in energy efficiency.

I perform a decomposition of CO_2 emission intensity in the United States, were I show that initially the changing fuel mix effect dominates, whilst more recently, improvements in energy efficiency are key: as the main energy source of fuel changes from predominantly combustible renewables (like wood or biomass) to predominantly fossil fuels, emission intensities rise; When this transformation is complete, improvements in energy efficiency induce falling emission intensity. In order to perform this decomposition, I assume that the entire source of emissions is derived from energy use and that each type of energy source (i.e. wood, biomass, coal, oil etc.), i, emits a fixed quantity of pollution, η_i. These are good assumptions for CO_2: first, a large majority of carbon dioxide emissions arise from energy production; second, from a chemical point of view, the combustion of a fixed amount of a particular fossil fuel must release a given fixed

[9] For details see, EIA (2001).

[10] The world is a closed system, so technically releasing the carbon dioxide stored in coal, oil and natural gas also does not add to the total quantity of carbon on the planet. The difference is that fossilized carbon and sulfur have been 'fixed' for millions of years and are being released quickly, whereas the biofuel carbon and sulfur was fixed (for example) last year and is being released this year.

amount of carbon dioxide as a by-product (especially as, historically, very little regulation has been applied to carbon emissions). Given these assumption, the following identity relates emission intensities to energy intensities:

$$\frac{P_t}{Y_t} = \frac{E_t}{Y_t}\left(\sum_i \eta_i \frac{E_{i,t}}{E_t}\right), \tag{4.1}$$

where, P_t, is total emissions of CO_2; Y_t, is constant price GDP; E_t, is total energy use and $E_{i,t}$, energy produced by type i feul. Using this identity, I decompose changes in emission intensity into changes in energy intensity and changes in the fuel mix in the United States, using energy data from Wright (2006) for the 1850-2001. Energy use is subdivided into: wood (w), coal (c), petroleum (p), natural gas (ng), hydroelectric (h), nuclear electric (n) and geothermal energy (g). Besides assuming that wood is carbon neutral, I also assume that hydroelectric power, nuclear electric power and geothermal energy do not release any carbon dioxide. As such, it is assumed that: $\eta_w = \eta_h = \eta_n = \eta_g = 0$. Next, following EPA (2004), I take the emission factors of the other fuels to be $\eta_{ng} = 14.5$, $\eta_p = 20.3$ and $\eta_c = 25.8$ kilotons per trillion BTU. Given these emission factors, I can calculate total emissions of CO_2, P_t, over the $1850 - 2001$ period[11] and using previous GDP data, I can also calculate emission intensity, $\frac{P_t}{Y_t}$. Next I perform two decompositions: First, I assume that energy intensity is held constant at 1917 levels (the year emission intensity reached it's peak in the US) and calculate the resulting emission intensity; Second - I assume that the fuel mix is held constant at 1917 levels and calculate the resulting emission intensity. These two decompositions, along with observed emission intensity are plotted in Figure 4.3 versus time (since GDP per capita in the US grows at roughly 2% a year, the shape of the picture is unchanged when plotted against GDP per capita - however plotting the data against time presents a clearer image).

Observed emission intensity follows an inverted-U, emission intensity with energy intensity held constant rises initially and then remains roughly constant, whilst emission

[11] The data obtained in this way are similar to the CO_2 emissions calculated by Andres et al. (1999) for most of the time period under consideration. Over the 1850-1960 period, my estimates are roughly a constant two percent higher. Over the 1960-1975 period the discrepancy between the two data sets increases and stabilizes at around 8% by 1975. The difference between the data sets arises from the greater extent of disaggregation used by Andres et al. (1999) - especially within the petroleum category. This discrepancy however, does not effect my qualitative findings and it's quantitative impact is small.

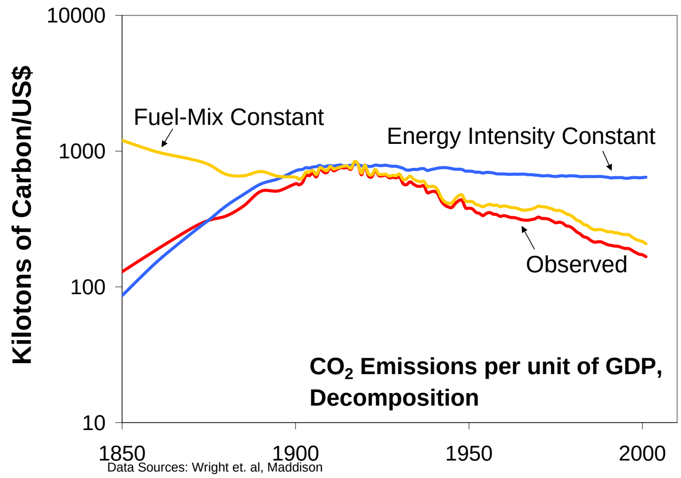


Figure 4.3: US emission intensity decomposition, 1850-2001.

intensity with the fuel mix held constant declines over the whole period. This indicates that the sharp initial rise in emission intensity in the US is caused by a change in the fuel mix. The size of the increase, is somewhat tempered by falling energy intensity. The declining part of emission intensity curve however, is predominantly caused by falling energy intensity. The difference between the observed intensity and the intensity with fuel-mix held constant is very small. This indicates that switching to cleaner fuels such as nuclear, hydro and geothermal or switching from dirty coal to cleaner oil or natural gas, has only had a marginal effect on emission intensities over the last century. The main driver of falling emission intensities, has been improvements in energy efficiency - that is improvements in technology that have allowed the economy to use less energy, whilst providing the same output.

Figure 4.4 shows how the energy mix has changed over time in the US. Whilst hydroelectric power and nuclear power have made slight inroads into the US energy markets over the 20th century, the most significant change in the fuel mix - by far - occurred at the end of the 19th century as the economy shifted from using predominantly fuel wood to using predominantly fossil fuels (coal, oil and natural gas) as it's main source of energy. A similar pattern is revealed in the cross sectional data. Figure 4.5, presents the change in the fuel mix from renewable combustibles to fossil fuels in a panel of all the world's countries for the period 1960-2006, versus GDP per capita. The data is

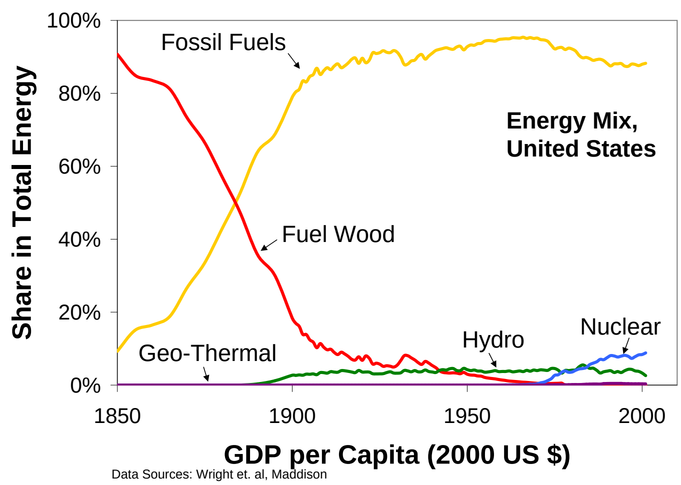
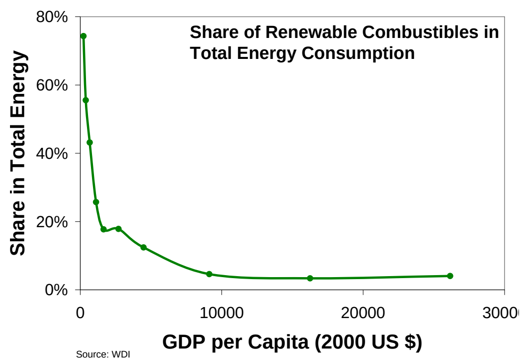


Figure 4.4: US energy mix, 1850-2001.

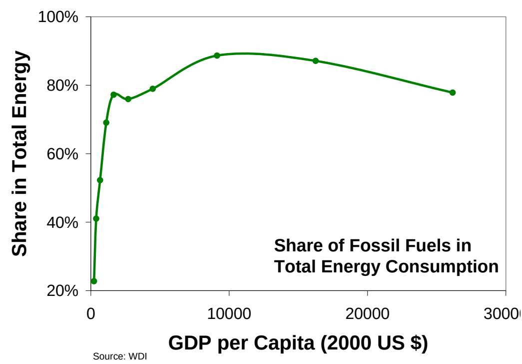
obtained from the *World Development Indicators* (2009) data. To keep the image clean, the data is sorted according to GDP per capita, divided into deciles and only the decile averages are presented. In the poorest countries, three quarters of all energy comes from renewable combustibles whilst 22% comes from fossil fuels. In the middle income and rich world only 4%-5% of energy comes from renewable combustibles, whilst 78%-89% comes from fossil fuels. Although richer countries on average tend to substitute away from fossil fuels more than the US, the decline in fossil fuel share as countries move from being middle income to rich is an order of magnitude smaller than the increase in fossil fuel share from when countries move from being poor to middle income.

Structural Transformation and Changing Fuel Mix Next, I argue that structural transformation - and in particular the shift from agriculture to non-agriculture - is responsible for a changing fuel mix.

Countries, where a large share of the labor force is employed in agriculture, derive their energy predominantly from materials such as wood, biomass or muscle power (which in turn is powered by food). This occurs, since these fuels are relatively abundant in an agricultural and rural setting. The production technology of agricultural products in such economies also relies heavily on human and animal traction - thus production in a traditional agricultural sector by it's very nature, requires large quantities of fodder, wood or other biomass fuels which are produced directly within the sector itself. Over



(a) Renewable Combustibles as a Share of Total Energy



(b) Fossil Fuels as a Share of Total Energy

Figure 4.5: World energy mix; Decile averages for all countries(1960-2006).]

time, agriculture does begins to use an increasing share of modern fuels[12] however, by the time these form a significant source of energy, agriculture's share in GDP will be small and hence the share of energy consumed by the agricultural sector itself will also be small.[13] Thus, the share of energy consumed by agriculture, is large when agriculture consumes predominantly renewable combustibles.

Countries that have a small share of labor in non-agriculture, derive most of their energy needs from non-biomass fuels such as coal, oil or natural gas. Many industrial processes and services require modern types of energy. For instance industries that use, produce or process metals require dependable fuel supplies and the greater flexibility associated with fuels like coal or oil, than renewable combustibles. Fossil fuels also provide a degree of control, ease and energy density that allow for greater quantities of effective power - coal, for instance, burns hotter than wood since it is more compact and has more combustible material. Many modern services also require a constant flow of energy which can - to a large extent - only be supplied by fossil fuels - an obvious example being the informational technology sector, or international transport which needs coal or oil for reliable service. Finally, most factories and services are localized in urban areas, were access to biomass is limited. In as far as industrialization results in a

[12] Stefanski (2009), for instance, finds that the share of oil in agriculture value added is increasing with income

[13] For example, in the OECD over the 1990-2007 period, the share of agriculture's consumption of energy in total energy consumed was only 3% *SourceOECD* (2009).

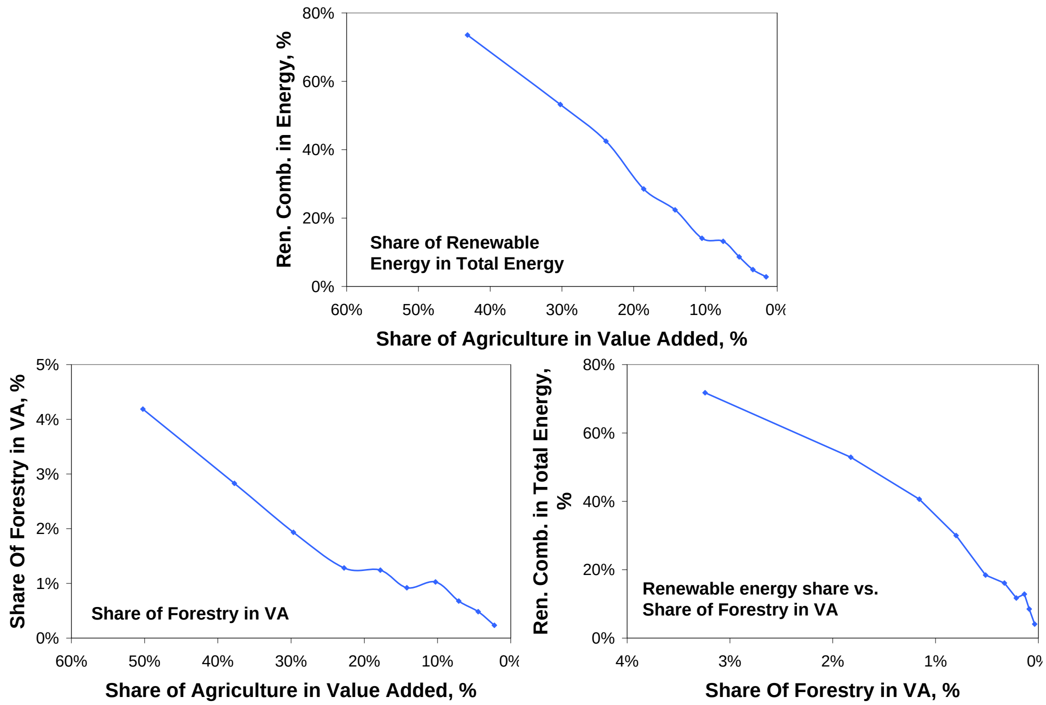


Figure 4.6: Structural transformation and renewable combustibles

change in the type of output that is produced by an economy, structural transformation will induce urbanization, which can, in turn, result in fuel-switching. Thus energy used within non-agriculture is predominantly modern, consists mostly of fossil fuel and as such these goods are produced in the non-agricultural sector. As the composition of the broader economy shifts from agriculture towards the industry and service sectors, the production of energy will also shift from the agricultural sector to the non-agricultural sector. This, will induce a change in the mix of fuel used to generate energy - from renewable biomass materials to (predominantly) fossil fuels such as coal, oil or gas.

Figure 4.6 shows three graphs that relate the use of renewable combustibles to structural transformation for a panel of all the world's countries for the years 1960-2005 obtained from the *World Development Indicators* (2009). The top graph show a simple relationship between the consumption of renewable combustibles as a fraction of total energy consumption versus the share of value added produced in agriculture. The share of value added in agriculture can be viewed as yardstick of structural transformation

- the further along the structural transformation a country is, the less workers are employed in agriculture. Each point of the panel data (in the top graph) consists of a time-country pair of share of agriculture in value added and share of renewable combustibles in total energy consumption. The panel data is sorted from highest share of agriculture in value added, to lowest and divided into deciles. These are then plotted in the top panel. From the graph it becomes clear that the lower the share of agriculture in value added, the lower the share of renewable combustibles in total energy consumption - as structural transformation progresses, countries obtain a falling share of their energy needs from renewable combustibles. Why does this occur? This is strongly related to the fact that renewable combustibles are a product of the agricultural sector itself and that the fuel produced by a given sector tends to be largely consumed by the sector in which it was produced.

The bottom left panel of Figure 4.6, shows a similar decile relationship between the share of the forestry sector (ISIC sector 02) in value added and the share of agriculture in value added for a panel of all the world's countries for the years 1990-2000 obtained from Lebedys (2004) (for the forestry data) and the *World Development Indicators* (2009) (for the agriculture data). The Food and Agriculture Organization of the UN defines the forestry sector as, "covering the production of standing timber as well as the extraction and gathering of wild growing forest materials except for mushrooms, truffles, berries and nuts. Besides the production of timber, forestry results in products that undergo little processing, such as wood for fuel". From the figure we see that as the share of agriculture in value added falls, the share of the forestry sector also falls. Since, to a large extent, the forestry sector is the main source of fuelwood in an economy, the bottom right panel shows that as the share of the forestry sector declines, the share of renewable combustibles also falls. Thus a decline in the share of renewable combustibles is deeply linked to the overall falling share of agriculture in output.

4.3 One Sector Model

In this section I present a one sector model to demonstrate that, it cannot match observed patterns of both emission and energy intensity.

Consumer's Problem On the demand side, the model consists of a utility maximizing representative consumer who at each point in time, t, inelastically supplies a unit of labor in exchange for wage income, w_t. This income is then used to purchase a consumption good, c_t, to maximize

$$\sum_{t=0}^{\infty} \beta^t u(c_t), \tag{4.2}$$

where $0 < \beta < 1$, is the discount factor. It is assumed that the period utility function, $u(c_t)$, is continuous, twice continuously differentiable, strictly increasing (i.e. $u'(c) > 0$) and strictly concave (i.e. $u''(c) < 0$) and satisfies the Inada conditions:

$$\lim_{c \to 0^-} = +\infty \tag{4.3}$$

$$\lim_{c \to +\infty^+} = 0. \tag{4.4}$$

The above conditions guarantee that an agent always chooses an interior solution. No other source of income exists for the consumer and the labor-leisure tradeoff is not considered.

Firm's Problem On the supply side, there is a single representative firm that hires labor from the consumer. A part of the total labor hired, L_t^e, is used to produce an intermediate good called energy, E_t, whilst the remainder, L_t^y, is used to produce a final good, Y_t, which is then sold to the consumer. The firm has access to two types of technologies. The first, combines labor and energy to produce the final good according to the following CES production function:

$$Y_t = \left(\alpha(g_l^t L_t^y)^\chi + (1-\alpha)(g_E^t E_t)^\chi\right)^{\frac{1}{\chi}}. \tag{4.5}$$

In the above equation, α is the weight of labor in the production function and the parameter χ determines the elasticity of substitution between labor and energy, $\sigma_{EL} = \frac{1}{1-\chi}$. Labor productivity and energy productivity are assumed to grow at exogenous rates given by g_l and g_E respectively,[14] The second technology, uses labor to produce

[14] The implication of the later assumption is that, for a positive elasticity of substitution and given a fixed L^y, to produce a constant quantity of output, energy use can go to zero over time. In reality

energy according to the following production function:

$$E_t = g_l^t L_t^e. \tag{4.6}$$

For simplicity, labor productivity in energy and output production are assumed to be the same. At each point in time t, given that p_t is the price of output and w_t is the wage paid to workers, the firm then chooses L_t^e and L_t^y to solve the following problem:

$$\max p_t Y_t - w_t(L_t^e + L_t^y), \tag{4.7}$$

subject to equations (4.5) – (4.6). A side effect of production however, is the emissions of pollution. Each unit of energy consumed in the production of output is assumed to release a proportional amount of pollution, P_t:

$$P_t = \eta E_t \tag{4.8}$$

where, η is the coefficient of proportionality and captures the total amount of pollution released per unit of energy.

Market Clearing Finally, in every period t, all goods and labor markets clear, so that:

$$c_t = Y_t \tag{4.9}$$

$$L_t^y + L_t^e = 1. \tag{4.10}$$

Competitive Equilibrium For every period t, a competitive equilibrium is: (1) A price of the consumption good $\{p_t\}$ and a wage rate $\{w_t\}$ (2) household allocations: $\{c_t\}$, and (3) firm allocations $\{L_t^y, L_t^e, Y_t\}$, such that: (a) Given prices, (1), households' allocations, (2), solve the households problem; (b) Given prices, (1), firms' allocations, (2), solve the firms problem in Equation (4.7) ; and (c) goods and labor markets clear. Standard arguments ensure that an equilibrium exists and is unique.

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there is a physical lower bound on the minimum energy required to perform any quantity of work. As such, energy productivity cannot technically increase at an exogenous constant rate indefinitely. For the purpose of simplicity, in this paper I assume that the energy efficiency at time $t = 0$, is low and that continued improvements in efficiency at a constant exogenous growth rate are physically viable for extended periods of time.

Discussion of the Model The above method of modeling pollution makes four basic assumptions. First, it is assumed that the consumption of energy - rather than production of output - is the source of all emissions. Since the data shows that almost the entire anthropogenic source of carbon dioxide is energy production, this assumption is more realistic than in models that assume emissions are directly proportional to output.

Second, it is assumed that pollution and energy are perfect complements in output - a unit of energy always releases ηE units of pollution. Since in the model there are no cost to firms of emitting pollution (like, for instance, rising prices of emissions or tightening government emission standards), there are no incentives for the firms to substitute away from energy towards other factors. In this setup, even if firms had the option of spending resources to make cleaner products, they would never do so. This way of modeling emissions is probably a good approximation of the observed reality (especially in the past), since active regulation of pollution is a fairly recent event, which postdates the drop in emission intensities observed in all OECD countries. Thus, regulations may have contributed to falling emissions intensity, but the process driving down emission intensities was already in play long before active regulation.

Third, it is assumed that the coefficient of proportionality, η, remains constant over time. This assumption is made purposefully in order to illustrate how crucial compositional effects are, in influencing emission intensity and pollution emissions over time. By setting η to a constant, I am implicitly assuming that the mix of fuels used to generate energy does not change over time. The idea is that if the fuel mix stays constant, each additional unit of energy will always produce the same quantity of pollution, ceteris paribus. Making this assumption will allow me to demonstrate that a change in the mix of fuels is crucial in order to generate the inverted-U emission intensity observed in the data.

Finally, I assume that there is no progress in the emission technology. In Brock and Taylor (2004), for instance, emissions are assumed to decline exogenously at a constant rate, g_P, (i.e. $P_t = \frac{\eta Y_t}{g_P^t}$). In their setup however, emissions are proportional to output so this assumption is more appropriate, since improvements in their "abatement" or emission technology can be interpreted as improvements in energy efficiency. Here, since emissions are proportional to the quantity of energy used, this assumption is less justifiable. From a chemical point of view, a fixed basket of fuel will always produce a similar quantity of CO_2 pollution no matter if its burnt today or in the future: the unavoidable and inevitable products from the chemical process of combustion of carbon based fuels are heat, water and carbon dioxide.

Technological progress in emission technology could potentially stem from our ability to store large quantities of carbon dioxide. This, however, has not been done on any major scale in the past and poses some very serious technical challenges in the future (such as were captured carbon dioxide would be stored or the large energy cost involved in capturing it). Any such form of scheme would ultimately requires some form of government intervention to induce producers to devote resources to storing carbon from combustion. Since I am focusing on the role of structural transformation on emission intensities and total emissions, I want to abstract from government intervention and other non-transformation related mechanisms as much as possible. In this sense, the above assumptions presents a "worst-case" scenario. The only way that pollution emissions can fall is if output becomes energy efficient quickly enough, causing energy use to decrease. In practice, output can always become cleaner if government intervenes and mandates cleaner output however, this to a large extent, is an exogenous process outside the above model.

4.3.1 Solution to the One Sector Problem

Since no intertemporal decisions are made, this is essentially a sequence of repeated static problems. Given positive prices, the consumer will always chooses to supply a unit of labor and uses all their wage income to purchase the entire output of the consumption good produced by the firm. The problem thus effectively consists of the firm choosing how much labor it will allocate to energy production versus output production. Substituting equations (4.5) and (4.6) into (4.7) and taking the first order conditions of (4.7) with respect to L_t^y and L_t^e, allows us to write the ratio of these first order conditions as:

$$\frac{L_t^y}{L_t^e} = \left(\frac{\alpha}{1-\alpha}\right)^{\frac{1}{1-\chi}} (g_E^t)^{\frac{\chi}{\chi-1}} \equiv x_t. \tag{4.11}$$

If the elasticity of substitution between energy and labor, $\sigma_{EL} = \frac{1}{1-\chi}$, is one (i.e. if, $\chi = 0$ and the production function in (4.5) is Cobb-Douglas), the share of labor allocated to energy and production will be constant over time. If $\sigma_{EL} > 1$, and hence energy and labor are gross substitutes, labor is going to move from output production towards energy production. If $\sigma_{EL} < 1$, and hence energy and labor are gross complements, labor is going to move from energy production towards output production. The rate at which labor moves between energy and output production depends on the exogenous growth rate of energy productivity and the degree of substitutability between the two factors. If energy and labor are substitutes, then as energy productivity increases, relatively more energy will be used in the production process. If energy and labor are complements, then as energy productivity increases, less labor will be used in the production process.

Since the total amount of labor in the economy is fixed to one, we can solve for the employment in the energy sector:

$$L_t^e = \frac{1}{1+x_t}. \tag{4.12}$$

This determines the aggregate energy use of the economy over time:

$$E_t = g_l^t L_t^e = \frac{g_l^t}{1+x_t}, \tag{4.13}$$

which in turn determines aggregate emissions of pollution:

$$P_t = \eta E_t = \frac{\eta g_l^t}{1+x_t}. \tag{4.14}$$

Equations (4.12)-(4.14) demonstrate the mechanism at work behind the changing energy use of an economy. Differential productivity growth in energy relative to labor is a source of change in $x_t = \frac{L_t^y}{L_t^e}$, which in turn induces changes in employment, energy use and pollution emissions. Since energy is produced using labor, the productivity of a unit of labor allocated to energy production is greater than the productivity of a unit of labor allocated directly to output production since output is additionally becoming more energy efficient over time. This will induce factor reallocation between the energy and output sectors (through movements in x) as long as χ is not equal to zero. If $g_E > 1$, a low elasticity of substitution, $\chi < 0$, ensures that labor moves from the energy sector to the output sector, whilst a high elasticity of substitution, $\chi < 0$, ensures that labor moves from the energy sector to the output sector. If $\chi = 0$ or $g_E = 1$, no reallocation of factors will take place.

Notice that the only way emissions can decrease over time, is for energy use, E_t to decrease. This can occur if labor moves out of the energy sector into the output sector, which in turn can only happen if $\chi < 0$ and $g_E > 1$. In particular, it is easy to show that:

$$\lim_{t\to\infty} \frac{P_{t+1}}{P_t} = \begin{cases} g_E^{\frac{\chi}{1-\chi}} g_l & \text{if } \chi < 0 \\ g_l & \text{if } \chi \geq 0 \end{cases} \tag{4.15}$$

If, $\chi > 0$, in the limit, emissions will always grow at the rate of labor productivity as there will always be incentives to substitute towards energy. The only way that energy use (and hence emissions) can decrease is if $\chi < 0$, and energy efficiency grows quickly enough to outweigh economic growth. In particular, emissions will be falling in the limit if and only if $g_E > g_l^{\frac{\chi-1}{\chi}}$. The lower the χ, the higher the g_E and the lower the g_l, the more likely emissions are to fall in the limit.

Finally, normalizing the price of output to one in each period, it can be shown that GDP in this economy is given by:

$$Y_t = g_l^t D_t, \tag{4.16}$$

where, $D_t = \left(\alpha(\frac{x_t}{1+x_t})^\chi + (1-\alpha)(\frac{g_E^t}{1+x_t})^\chi\right)^{\frac{1}{\chi}}$. Thus the growth rate in the economy depends on exogenous labor productivity growth, and an endogenous factor, D_t. This second term captures the role of energy in production. Notice that for $0 < \alpha < 1$ and $\chi < 1$ it is true that $0 < D_0 < 1$. If, $\chi > 0$, it can be shown that $\lim_{t\to\infty} \frac{D_t+1}{D_t} = g_E^t$. Since labor and energy are substitutes in production, as energy efficiency improves, labor moves towards energy production. In the long run, when all labor is devoted to energy production, output grows at the combined rate of labor and energy productivity. If $\chi < 0$, it can be shown that $\frac{\partial D}{\partial t} > 0$ and that $\lim_{t\to\infty} D_t = \alpha^{\frac{1}{\chi}}$. In the case that $\chi < 0$, energy and labor are complimentary. This means that the economy is forced to devote labor to energy production in order to produce output - this makes initial output lower than it would be, if no energy were necessary (i.e. $0 < D_0 < 1$). As energy efficiency improves over time (i.e. as g_E^t grows), and output begins to require less and less energy, labor that would have otherwise been used to produce energy is freed up and can be devoted to producing output - thus D_t grows over time. This process continues until all labor has moved out of energy production and is located in energy production. Thus, the economy initially grows fast, as labor moves into output production from energy production, but slows down to the growth rate of labor productivity in the long run, when all labor has been transferred out of energy production. If $\chi = 0$, the term D_t, grows at a constant rate $g_E^{1-\alpha}$ over time.

Emission and Pollution Intensities How do the energy and emissions intensities of the economy change over time? Normalizing the price of output to one in each period, and using equation (4.11), the energy intensity of the economy, $e_t = E_t/Y_t$, is given by:

$$e_t = \left(\alpha(x_t)^\chi + (1-\alpha)(g_E^t)^\chi\right)^{-\frac{1}{\chi}}. \tag{4.17}$$

It is easy to show that if $\chi \leq 0$ then energy intensity of the economy is always decreasing and when $0 < \chi < 1$, energy intensity follows an inverted U shape with time.[15] Emission intensity, p_t, is just a constant multiple of energy intensity, $p_t = P_t/Y_t = \eta E_t/Y_t = \eta e_t$ and hence has the same shape as energy intensity. For a given g_E and α, choosing a small enough elasticity parameter (i.e. $\chi \leq 0$), results in an energy intensity *and* an emission intensity that decrease monotonically over time. Choosing a large enough elasticity parameter (i.e. $0 < \chi < 1$), results in an energy intensity *and* an emission intensity that follow an inverted-U shape over time. The one sector model can thus *either* match energy intensity (i.e. falling energy intensity) *or* it cannot match emission intensity (i.e. a hump shaped emission intensity), but it cannot match both. Thus the one sector model cannot generate the pattern of emission and energy growth rates observed in the data.

The reason for this is that η, the coefficient of proportionality between energy use and pollution, is constant over time. Since one unit of energy is assumed to be produced using the same mix of fuel, it always emits the same quantity of pollution. Emission intensity will thus always be proportional to energy intensity and hence it will have the same shape. To match the data more closely and get an accurate prediction of pollution over a country's development, a theory is needed that can explain why a unit of energy produces different quantities of pollution at different stages of development. The discussion in the data section indicates that structural transformation plays a crucial role in influencing the mix of fuels used and hence the aggregate pollution-energy ratio.

[15] More specifically, there exists a t^*, such that if $t < t^*$, $\frac{\partial e_t}{\partial t} > 0$; if $t > t^*$, $\frac{\partial e_t}{\partial t} < 0$ and if $t = t^*$, $\frac{\partial e_t}{\partial t} = 0$

As such, in the next section I construct a multi-sector version of the model where structural transformation will be key to driving a changing energy mix and hence a changing energy-pollution ratio, a falling energy intensity and an inverted-U emission intensity.

4.4 A Two Sector Model

In this section I present a two sector model that incorporates a structural transformation, to demonstrate that it can match observed patterns of both emission and energy intensity. Structural transformation occurs due to the assumption of a non-homotheticity in utility for agricultural products - a subsistence level of agriculture must be consumed by individuals each period. Initially, this forces a large share of the labor force to be devoted to producing agriculture. As productivity in the agricultural sector improves, the subsistence level can be achieved by devoting a smaller and smaller share of the labor force to agriculture. Asymptotically, employment share in agriculture shrinks to zero, and the model becomes identical to the (asymptotic limit of the) one-sector model presented in the previous section.

Consumer's Problem On the demand side, the model consists of a utility maximizing representative consumer who at each point in time, t, inelastically supplies a unit of labor in exchange for wage income, w_t. This income is then used by the consumer to purchase two consumption goods: an agricultural good, a_t , and a non-agricultural good (industry-service composite), c_t. The consumer has preferences over consumption goods given by the following extreme functional form:

$$\sum_{t=0}^{\infty} \beta^t U(a_t, c_t), \tag{4.18}$$

where $0 < \beta < 1$, is the discount factor. The period utility function, $U(a_t, c_t)$, is adopted from Gollin et al. (2002) and given by:

$$U(a_t, c_t) = \begin{cases} \bar{a} + u(c_t) & \text{if } a_t > \bar{a} \\ a_t & \text{if } a_t \leq \bar{a}. \end{cases} \tag{4.19}$$

A consumer that has low incomes cares only about agricultural consumption, whilst a high income consumer becomes satiated with agricultural products when $a_t = \bar{a}$ and devotes the remainder of their income to non-agriculture. The assumption on $u(c_t)$ are the same as in the one-sector model: it is assumed to be continuous, twice continuously differentiable, strictly increasing, strictly concave and to satisfy the Inada conditions. The reason for adopting this simple type of preferences is analytic tractability.

Since no dynamic decisions are made in the model, the consumer's problem is a sequence of static problems and consists of solving for the optimal allocation of income between agricultural and non-agricultural goods at each point in time given by:

$$\max U(a_t, c_t) \tag{4.20}$$

$$\text{s.t. } p_t^a a_t + p_t^c c_t = w_t,$$

where, p_t^a is the price of agricultural products and p_t^c is the price of non-agriculture.

Agricultural Firm's Problem The agricultural firm hires labor from the consumer. The energy needs of the agriculture sector are assumed to be produced within that sector. The firm has access to two types of technologies: an output and an energy technology. A part of the labor hired by the firm, $L_{A,t}^e$, is assigned to produce an intermediate good called energy, $E_{A,t}$, whilst the remainder, $L_{A,t}^y$, is used to produce a final good, A_t, which is then sold to the consumer. The output technology, combines labor and energy to produce the final good according to the following production function:

$$A_t = (g_{l,A}^t L_{A,t}^y)^{\alpha_A} (g_E^t E_{A,t})^{(1-\alpha_A)}. \tag{4.21}$$

In the above equation, α_A is the labor share. Labor productivity, $g_{l,A}$, and energy productivity, g_E, are assumed to grow at exogenous rates. It ia assumed that labor productivity can vary across sectors, but energy productivity is the same. This assumption will be loosened later.

The energy technology, uses labor to produce energy according to the following production function:

$$E_{A,t} = g_{l,A}^t L_{A,t}^e. \tag{4.22}$$

For simplicity, labor productivity in energy and output production are assumed to be the same. At each point in time t, given the price of output, p_t^A, and the wage, w_t, the agricultural firm chooses $L^e_{A,t}$ and $L^y_{A,t}$ to solve the following problem:

$$\max p^A_t A_t - w_t(L^e_{A,t} + L^y_{A,t}), \tag{4.23}$$

subject to equations (4.21) – (4.22). An additional effect of production however, is the emission of pollution. Each unit of energy consumed in the production of sector A output is assumed to release a proportional amount of pollution, $P_{A,t}$:

$$P_{A,t} = \eta_A E_{A,t} \tag{4.24}$$

where, η_A, is the coefficient of proportionality and captures the total amount of pollution released per unit of energy in the agriculture sector.

Non-Agricultural Firm's Problem The non-agricultural firm hires labor from the consumer. The energy needs of the agriculture sector are assumed to be produced within that sector. The firm has access to two types of technologies: an output and an energy technology. A part of the labor hired by the firm, $L^e_{C,t}$, is assigned to produce an intermediate good called energy, $E_{C,t}$, whilst the remainder, $L^y_{C,t}$, is used to produce a final good, C_t, which is then sold to the consumer. The output technology, combines labor and energy to produce the final good according to the following CES production function:

$$C_t = \left(\alpha_C(g^t_{l,C}L^y_{C,t})^{\chi_C} + (1-\alpha_C)(g^t_E E_{C,t})^{\chi_C}\right)^{\frac{1}{\chi_C}}. \tag{4.25}$$

In the above equation, α_C is the weight of labor in production, whilst χ_C determines the elasticity of substitution between labor and energy, $\sigma^s_{EL} = \frac{1}{1-\chi_s}$. Labor productivity and energy productivity are assumed to grow at exogenous rates given by $g_{l,C}$ and g_E respectively.

The energy technology, uses labor to produce energy according to the following production function:

$$E_{C,t} = g^t_{l,C} L^e_{C,t}. \tag{4.26}$$

For simplicity, labor productivity in energy and output production are assumed to be the same. At each point in time t, given the price of output, p^c_t, and the wage, w_t, the non-agricultural firm chooses $L^e_{C,t}$ and $L^y_{C,t}$ to solve the following problem:

$$\max p^c_t C_t - w_t(L^e_{C,t} + L^y_{C,t}), \tag{4.27}$$

subject to equations (4.25) – (4.26). An additional effect of production however, is the emission of pollution. Each unit of energy consumed in the production of output is assumed to release a proportional amount of pollution, $P_{C,t}$:

$$P_{C,t} = \eta_C E_{C,t} \tag{4.28}$$

where, η_C, is the coefficient of proportionality and captures the total amount of pollution released per unit of energy in non-agriculture sector.

Competitive Equilibrium For every period t, a competitive equilibrium is: (1) Price of agriculture and consumption goods $\{p_t^a, p_t^c\}$ and a wage rate $\{w_t\}$ (2) household allocations: $\{a_t, c_t\}$, and (3) firm allocations $\{L_{s,t}^y, L_{s,t}^e, s_t\}_{s=A,C}$, such that: (a) Given prices, (1), households' allocations, (2), solve the households problem in Equations (4.20); (b) Given prices, (1), firms' allocations, (2), solve the firms' problems in Equations (4.23) and (4.27) ; and (c) good and labor markets clear. Standard arguments ensure that an equilibrium exists and is unique.

Discussion of the Model In addition to the assumptions of the one sector model, I make two further assumptions - mostly for simplicity. First, it is assumed that each sector's entire energy is produced within the given sector. This assumption is made because of the strong positive relationship between the share of energy produced by renewable combustible energy sources and the extent of structural transformation. In the data section, it is argued that countries with a large share of output in agriculture, derive a large share of their energy needs from renewable combustible fuels like wood or biomass. This relationship arises due to the strong positive correlation between the share of agriculture in value added and the share of forestry in value added, as well as a strong positive relationship between the share of forestry in value added and the share of renewable combustibles in total energy sources. Since most renewable combustible materials are produced in the agricultural sector, a falling share of the agricultural sector in value added will result in a falling share of renewable combustibles in energy production.

How realistic is this assumption? In countries at the early stages of structural transformation, some of the energy used in non-agriculture is likely to come from renewable combustibles - technologies may be primitive and use wood or biomass as fuel. Hence, at the beginning of the structural transformation, the model may overestimate the increase in emissions and emission intensity, caused by the shift from agriculture to industry. In countries at the tail end of structural transformation, much of the energy used in agriculture is likely to come from non-agriculture - modern production techniques involve tractors, combine harvesters and large quantities of fertilizer. The model may overestimate the decline in emissions and emission intensity, at this point. The potential impact of these two effects however, is mitigated by the small size of the respective sectors when the particular effects are likely to be in play. Thus, in poor countries, non-agriculture forms a small part of GDP - hence renewable energy consumption in non-agriculture forms an even smaller part in total energy consumption. Similarly, in advanced countries, agriculture forms a small share of GDP - hence the non-renewable share of energy used by agriculture in total energy, forms an even smaller part in total energy consumption - the average share of total (non-renewable) energy consumed by the agricultural sector in OECD countries between 1990 and 2004, is only 3% of total energy consumption. The quantitative and qualitative impact of this simplification is thus in all likelihood small. Finally, direct substitution between modern and traditional energy sources, would take us too far afield from the goal of the paper which is to investigate the role that structural transformation plays in influencing emission intensity.

Second, it is assumed that within sector pollution-energy ratios, η_s, are constant. This relates directly to the previous point - the energy mix used in each sector is assumed to stay the same over the development process. Again, this assumption is made for simplicity and to concentrate on the effect of structural transformation on emission intensity. Notice however, that even though sectoral pollution-energy ratios will be constant, the aggregate pollution energy ratio will change, as the economy changes its structure. Thus the change in aggregate fuel mix will occur as a direct consequence of structural transformation - from the shift in the type of goods produced by the economy.

4.4.1 Solution to the Two Sector Problem

Since no intertemporal decisions are made, the two sector problem - like the one sector problem - is essentially a sequence of repeated static problems. Given positive prices, the consumer will always chooses to supply a unit of labor and uses all their wage income to purchase agricultural and non-agricultural goods. Due to the simple preferences, the model is solved in two steps. First, employment, energy and pollution emissions of agricultural sector are found. Then, this information is used to solve for the employment, energy and pollution emissions of the non-agricultural sector in a way that is analogous to the one sector problem.

To solve for employment in agriculture, notice that the agricultural firm needs to choose how much of it's total hired labor it will allocate to energy production versus output production. Substituting equations (4.21) and (4.22) into (4.23) and taking the first order conditions of (4.23) with respect to $L^y_{A,t}$ and $L^e_{A,t}$, allows us to write the ratio of these first order conditions for the agricultural firm as:

$$\frac{L^y_{A,t}}{L^e_{A,t}} = \frac{\alpha}{1-\alpha}. \tag{4.29}$$

Given that the agricultural firm hires $L_{A,t}$ workers at a given point in time, this expression can be solved for a relationship analogous to equation (4.12), relating total employment in a sector to employment in energy and output production given by:

$$L^e_{A,t} = (1-\alpha_A)L_{A,t} \tag{4.30}$$

and

$$L^y_{A,t} = \alpha_A L_{A,t}. \tag{4.31}$$

Thus, a constant fraction of workers hired by the agricultural sector is used to generate energy and output. How many workers are used in each sub-sector depends on the the share parameters in the production function of agriculture. Given the simple specification of preferences, the consumer will demand a fixed quantity of agricultural output each period, $\bar{a}$. The market clearing condition for agricultural goods and the relationships derived in equations (4.30) and (4.31), allow us to solve for employment in the agricultural sector:

$$L_{A,t} = \frac{\bar{a}\bar{c}}{g^t_{l,A}(g_E^{1-\alpha_A})^t}, \tag{4.32}$$

where $\bar{c} = 1/\alpha_A^{\alpha_A}(1-\alpha_A)^{1-\alpha_A}$. Employment in agriculture falls, at a rate that depends on the labor and energy productivities of the agricultural sector. Intuitively, as agriculture becomes more productive, less workers are needed to produced the required subsistence level. These workers move out of the agriculture sector and into the non-agriculture sector. The initial employment in agriculture depends on $\bar{a}$ and $\bar{c}$. Notice however, that given $\bar{c}$, $\bar{a}$ can be chosen to match any initial employment.

Given the above solution for total employment in agriculture, employment in the energy and output sub-sectors is given by:

$$L^e_{A,t} = (1-\alpha_A)\frac{\bar{a}\bar{c}}{g^t_{l,A}(g_E^{1-\alpha_A})^t} \tag{4.33}$$

and

$$L^y_{A,t} = \alpha_A\frac{\bar{a}\bar{c}}{g^t_{l,A}(g_E^{1-\alpha_A})^t}. \tag{4.34}$$

This employment information can be used to determine the energy use of agriculture over time:

$$E_{A,t} = g^t_{l,A}L^e_{A,t} = (1-\alpha_A)\frac{\bar{a}\bar{c}}{(g_E^{1-\alpha_A})^t}, \tag{4.35}$$

which in turn determines emission of pollution from agriculture:

$$P_{A,t} = \eta_A E_{A,t} = \eta_A(1-\alpha_A)\frac{\bar{a}\bar{c}}{(g_E^{1-\alpha_A})^t}. \tag{4.36}$$

Notice that energy and emissions of the agricultural sector will fall, only if employment in the energy sub-sector of agriculture falls fast enough to outweigh rising labor productivity in the energy sub-sector - as labor becomes more productive, more energy will be produced unless the total amount of labor engaged in producing energy falls fast enough to outweigh the increase in productivity. Since employment in energy is proportional to employment in agriculture, energy use and pollution of the agricultural sector will fall only if employment in overall agriculture falls faster than the growth rate of labor productivity. Consequently, energy use and pollution of the agricultural sector will fall at a rate of $g_E^{1-\alpha_A}$. Thus, there are two mechanisms working together to check agriculture's demand for energy - first, the size of agricultural sector is falling as labor moves out of the sector into non-agriculture. Second, the sector is becoming more energy efficient over time. Consequently, the long-run rate of decline of emissions in the agricultural sector can be written as:

$$g_{P,A} \equiv \lim_{t\to\infty}\frac{P_{A,t+1}}{P_{A,t}} = \frac{1}{g_E^{1-\alpha_A}}. \tag{4.37}$$

Given the above, it is now possible to solve for employment in non-agriculture. Any worker that is not employed by the agricultural sector, is employed by non-agriculture. Given that that the total labor force is normalized to one, employment in non-agriculture is:

$$L_{C,t} = 1 - L_{A,t} = 1 - \frac{\bar{a}\bar{c}}{g_{l,A}^{t}(g_E^{1-\alpha_A})^t}. \tag{4.38}$$

To determine employment in the energy and output sub-sectors, substitute equations (4.25) and (4.26) into (4.27) and take the first order conditions of (4.27) with respect to $L_{C,t}^{y}$ and $L_{C,t}^{e}$. This allows us to write the ratio of these first order conditions as:

$$\frac{L_{C,t}^{y}}{L_{C,t}^{e}} = \left(\frac{\alpha_C}{1-\alpha_C}\right)^{\frac{1}{1-\chi_C}} (g_E^t)^{\frac{\chi_C}{\chi_C - 1}} \equiv x_{C,t}. \tag{4.39}$$

Since the non-agriculture firm hires $L_{C,t}$ workers, this expression can be solved for a relationship analogous to equation (4.12), relating total employment in non-agriculture to employment in the energy and output sub-sectors:

$$L_{C,t}^{e} = \frac{L_{C,t}}{1 + x_{C,t}} \tag{4.40}$$

and

$$L_{C,t}^{y} = \left(\frac{x_{C,t}}{1 + x_{C,t}}\right) L_{C,t}. \tag{4.41}$$

This can then be used to determine the energy consumption of non-agriculture over time:

$$E_{C,t} = g_{l,C}^{t} L_{C,t}^{e} = \frac{g_{l,C}^{t} L_{C,t}}{1 + x_{C,t}}, \tag{4.42}$$

which in turn determines emission of pollution from non-agriculture:

$$P_{C,t} = \eta E_{C,t} = \eta \frac{g_{l,C}^{t} L_{C,t}}{1 + x_{C,t}}. \tag{4.43}$$

Equations (4.40)-(4.43) demonstrate the mechanism at work behind the changing energy use of an economy and are parallel to equations (4.12)-(4.14) of the one sector problem. Productivity growth in energy is a source of change in $x_{C,t}$. As long as χ_C is not equal to zero, as energy becomes relatively more productive than labor, employment will move between the energy and output sectors. As in the one sector model, given $g_E > 1$, a low elasticity of substitution ($\chi_C < 0$) ensures that labor moves from the energy sector to the output sector, whilst a high elasticity of substitution ($\chi_C > 0$) ensures that labor moves from the energy sector to the output sector. If $\chi_C = 0$ or $g_E = 1$, no reallocation of factors will take place. As labor moves across sub-sectors, $x_{C,t}$ will change resulting in changing energy use and emissions. In the multi-sector model however, there is an additional effect caused by structural transformation - labor is shifting from agriculture to non-agriculture. The increasing quantity of labor employed in non-agriculture results in upward pressure on the output of energy and emissions in the non-agricultural sector.

As the structural transformation progresses and the economy becomes dominated by non-agriculture (i.e. as $L_{C,t} \to 1$), the influence of this effect wanes and energy use and emission of non-agriculture become increasingly driven by changes in allocation of labor between energy and output production (i.e. changes in $x_{C,t}$) and labor productivity. Consequently, as in the one sector model, the only way emissions can decrease over time in the non-agricultural sector, is for energy use, $E_{C,t}$ to decrease. This can occur only if labor moves out of the energy sub-sector into the output sub-sector, which in turn can only happen if $\chi_C < 0$ and $g_E > 1$. In particular, it is easy to show that:

$$g_{P,C} \equiv \lim_{t\to\infty} \frac{P_{C,t+1}}{P_{C,t}} = \begin{cases} g_E^{\frac{\chi_C}{1-\chi_C}} g_{l,C} & \text{if } \chi_C < 0 \\ g_{l,C} & \text{if } \chi_C \geq 0 \end{cases} \tag{4.44}$$

If, $\chi > 0$, in the limit, emissions of the non-agriculture sector will always grow at the rate of labor productivity - just as in the one sector case. Emissions can fall only if energy use falls, which can happen only if $\chi_C < 0$, and energy efficiency grows quickly enough to outweigh growth in labor productivity. In particular, emissions in the non-agricultural sector will fall if and only if $g_E > g_{l,C}^{\frac{\chi_C - 1}{\chi_C}}$. The lower the χ_C, the higher the g_E and the lower the $g_{l,C}$, the more likely emissions are to fall in the limit, in the non-agricultural sector.

How does total pollution, $P_t = P_{C,t} + P_{A,t}$, evolve over time? Notice that

$$\frac{P_{t+1}}{P_t} = (1 - s_t) \frac{P_{A,t+1}}{P_{A,t}} + s_t \frac{P_{C,t+1}}{P_{C,t}}, \tag{4.45}$$

where $s_t = \frac{P_{C,t}}{P_{A,t}+P_{C,t}}$ is the share of non-agricultural emissions in total emissions and hence, $0 < s_t \leq 1$. In any given period, the growth rate of total emissions is a weighted average of growth rate of emissions in the agricultural and the non-agricultural sectors. It is easy to show that

$$\lim_{t\to\infty} s_t = \begin{cases} 1 & \text{if } g_{P,C} > g_{P,A} \\ 0 & \text{if } g_{P,C} < g_{P,A} \\ \bar{s} & \text{if } g_{P,C} = g_{P,A}, \end{cases} \tag{4.46}$$

where $0 < \bar{s} < 1$ is a constant.[16] Given this fact, as well as the long run growth rates of emissions in non-agriculture and agriculture in equations (4.37) and (4.44), the long run growth of pollution in the economy is given by:

$$g_P \equiv \lim_{t\to\infty} \frac{P_{t+1}}{P_t} = \begin{cases} g_{P,C} & \text{if } g_{P,C} > g_{P,A} \\ g_{P,A} & \text{if } g_{P,C} < g_{P,A} \\ g_{P,C} = g_{P,A} & \text{if } g_{P,C} = g_{P,A} \end{cases} . \tag{4.47}$$

Since $g_E > 1$, emissions in agriculture will always be falling (i.e. $g_{P,A} < 1$). Thus, in the limit, aggregate emissions will only fall if emissions in the non-agricultural sector are also falling. As in the one sector model, this can only happen if $\chi_C < 0$. In particular, aggregate emissions can fall in the limit if and only if $g_E > g_{l,c}^{\frac{\chi_C - 1}{\chi_C}}$. The rate at which aggregate emissions fall however, depends on how quickly emissions are falling in the non-agriculture sector. If emissions in non-agriculture are dropping slower than in agriculture, aggregate emissions will drop at the rate of emissions in non-agriculture. If emissions in agriculture are dropping slower than in non-agriculture, then aggregate emissions will drop at the rate of emissions in agriculture. Thus, in the long run, aggregate emissions fall (rise) at the same rate at which they fall (rise) in the sector were they are falling (rising) the slowest (fastest).

Finally, the GDP in this economy (at time zero prices) is given by:

$$GDP_t = p_0^a \bar{a} + p_0^c g_l^t D_{C,t} L_{C,t}, \tag{4.48}$$

[16] Notice, $\frac{P_{A,t}}{P_{C,t}} = \frac{(g_E^{1-\alpha_A} g_{l,C})^{-t} + (g_E^{1-\alpha_A})^{-t} (g_E^{\frac{-\chi_C}{1-\chi_C}})^{-t} g_{l,C}^{-t} (\frac{1-\alpha_I}{\alpha_I})^{\frac{-1}{1-\chi_C}}}{1 - \bar{a}\bar{c}(g_E^{1-\alpha_A} g_{l,A})^{-t}} \frac{\eta_A}{\eta_I} \bar{a}\bar{c}(1-\alpha_A)$. The convergence properties of this quotient depend on the term, $(g_E^{1-\alpha_A})^{-t}(g_E^{\frac{-\chi_C}{1-\chi_C}})^{-t} g_{l,C}^{-t}$. If $g_{P,C} > g_{P,A}$, this term converges to zero and s_t converges to 1, if $g_{P,C} < g_{P,A}$ the term converges to infinity and s_t converges to 0, if $g_{P,C} = g_{P,A}$ the term converges to a positive constant and s_t converges to $\bar{s}$.

where, $D_{C,t} = \left(\alpha_C(\frac{x_{C,t}}{1+x_{C,t}})^{\chi_C} + (1-\alpha_C)(\frac{g_E^t}{1+x_{C,t}})^{\chi_C}\right)^{\frac{1}{\chi_C}}$. Each period, the non-homothetic preference impose that $\bar{a}$ units of agricultural good be produced, thus output of agriculture is constant. The only source of growth in the economy is output growth of non-agriculture. There are three mechanisms driving growth in the non-agricultural sector (and hence overall growth). As in the one sector model, the growth rate in the economy depends on exogenous labor productivity growth, and the endogenous factor, D_t. However, there is now an additional endogenous effect on growth - structural transformation. As productivity in agriculture improves, less labor is required to produce the necessary quantity of agricultural output, $\bar{a}$. As this labor is freed, it can move into non-agriculture, where it can produce more non-agricultural output. Thus, as $L_{C,t}$ increases, output also increases. Since $\lim_{t\to\infty} L_{C,t} = 1$, this effect is temporary. Thus, when $\chi_C > 0$, there are two permanent effects on growth (exogenous labor productivity and exogenous energy productivity growth) and one temporary effect on growth (structural transformation). When $\chi_C < 0$, there are two temporary effects on growth (movement out of energy production and structural transformation) and one permanent effect on growth (exogenous labor productivity). If $\chi = 0$, there are only two effects on growth: one permanent (exogenous labor productivity) and one temporary (structural transformation).

Emission and Pollution Intensities How do the energy and emissions intensities of the two sector economy change over time? The energy intensity of the agricultural sector (at time zero prices), $e_{A,t} = \frac{E_{A,t}}{p_0^a A_t}$, is given by:

$$e_{A,t} = \frac{(1-\alpha_A)^{\alpha_A}(\alpha_A)^{-\alpha_A}}{p_0^a(g_E^t)^{1-\alpha_A}} \tag{4.49}$$

whilst the energy intensity of the non-agricultural sector (at time zero prices), $e_{C,t} = \frac{E_{C,t}}{p_0^c C_t}$, is given by:

$$e_{C,t} = (p_0^c)^{-1}\left(\alpha_C(x_{C,t})^{\chi_C} + (1-\alpha_C)(g_E^t)^{\chi_C}\right)^{-\frac{1}{\chi_C}}. \tag{4.50}$$

Energy intensity in agriculture is declining over time. As in the one sector model, it is easy to show that if $\chi_C \leq 0$ then energy intensity of the non-agricultural sector is decreasing over time. Furthermore, for a given g_E and α_C, there exists a cutoff elasticity parameter, $0 < \bar{\chi}_C < 1$ such that if $\chi_C \leq \bar{\chi}_C$, energy intensity will always be strictly decreasing, and if $\chi_C > \bar{\chi}_C$, energy intensity of non-agricultural sector will first rise and then fall, forming an inverted-U over time. The emission intensities of each sector, $p_{A,t}$ and $p_{C,t}$, are simply proportional to the energy intensities of each sector, $p_{A,t} = P_{A,t}/p_0^a A_t = \eta_A E_{A,t}/p_0^a A_t = \eta_A e_{A,t}$ as well as $p_{C,t} = P_{C,t}/p_0^c C_t = \eta_C E_{C,t}/p_0^c C_t = \eta_C e_{C,t}$, and hence have the same shape as sectoral energy intensities. Aggregate energy intensity (at time zero prices), $e_t = \frac{E_{A,t}+E_{C,t}}{p_0^a A_t + p_0^c C_t}$, is a weighted average of the sectoral energy intensities and is given by:

$$e_t = e_{A,t}(1 - d_t) + e_{C,t} d_t, \tag{4.51}$$

where $d_t = \frac{p_0^c C_t}{p_0^a A_t + p_0^c C_t}$ is the constant price share of non-agricultural sector in GDP and that $0 < d_t \leq 1$. Notice that since $A_t = \bar{a}$, $\lim_{t\to\infty} d_t = 1$. Initially, as the economy is dominated by agriculture, aggregate emission intensity is close to agriculture emissions intensity. As the economy shifts from agriculture to non-agriculture, aggregate energy intensity approaches non-agricultural energy intensity. Depending on parameters, aggregate energy intensity can take a form that is a linear combination of the sectoral energy intensities - it can be decreasing, it can rise and then fall or it can be sideways-s shaped.

Unlike in the one sector model, aggregate emission intensity is no longer directly proportional to aggregate energy intensity. Aggregate emission intensity (at time zero prices), $p_t = (P_{A,t} + P_{C,t})/(p_0^a A_t + p_0^c C_t)$, is a weighted average of sectoral emission intensities and is given by:

$$p_t = \eta_A e_{A,t}(1 - d_t) + \eta_C e_{C,t} d_t. \tag{4.52}$$

Although emission intensity does depend indirectly on energy intensity, the changing structure of the economy now plays a crucial role in breaking the proportionality between the emission and energy intensity. For illustrative purposes, suppose that $\eta_A = 0$ and $\eta_C > 0$. In this case, the profile of aggregate emission intensity over time is dependent on how energy intensity in non-agriculture changes ($e_{C,t}$), but also how the size of non-agriculture relative to the rest of the economy changes (d_t). Thus, even if $\chi_C < 0$ and $e_{C,t}$ is falling, the initial shift from agriculture to non-agriculture causes d_t to rise. If the increase in d_t is rapid enough, it can potentially outweigh falling energy intensity and result in aggregate emission intensity that first rises and then falls. Unlike the one sector model, the two sector model provides a framework that is capable of reproducing observed patterns of both energy and emission intensity in the data. The exact path of emission intensity however, will depend indirectly on energy, pollution and structural parameters. Testing the model requires carefully choosing reasonable parameters to see if these can reproduce observed patterns of energy and emission intensity in the data.

4.5 Numerical Experiments

The approach of the numerical experiments is to use UK data to discipline the model and then perform numerical experiments to investigate how emissions and emission intensities evolve in countries that are at different stages of their structural transformation (and hence started structural transformation at different points in time). Due to the structure of preferences, the calibration procedure can be roughly broken down into roughly three parts: First, I choose the agricultural parameters then the non-agricultural parameters and finally the remaining parameters.

4.5.1 Calibration

Calibration of Agriculture Parameters Next, I describe how I choose values for: the energy share parameter, $1 - \alpha_A$; the subsistence level, $\bar{a}$; and effective labor productivity growth rate, $g_A \equiv g_{l,A} g_E^{1-\alpha_A}$. In this exercise, I assume that the agricultural sector is effectively a traditional-agricultural sector (versus a modern agricultural sector). Notice, from equation (4.31), that $1 - \alpha_A = \frac{L^e_{A,t}}{L_{A,t}}$. Thus the parameter $1 - \alpha_A$, determines the fraction of agricultural labor devoted to energy production. Ideally, this parameter would be calibrated to the share of hours devoted to energy production in the pre-industrial agricultural sector in the United Kingdom. This data however, is unavailable for the UK. Instead, I use data for a country were the agricultural sector is conceivably similar to pre-industrial UK - Nepal.

Table 4.2 shows time allocation information for men, women and children for the year 1982 in Nepal. The table is constructed from numbers reported by Kumar and Hotchkiss (1988) and is based on data collected by the Nepalese Agriculture Projects Service Center; the Food and Agricultural Organization of the United Nations and the

	hrs/person/day			hrs/HH/day	
Activity	Men	Women	Children	Household†	HH Shares
Field Work	3.10	2.75	0.05	6.00	27.3%
Employment	0.80	0.13	···	0.93	4.2%
Fuel Collection	0.58	2.48	2.23	9.73	44.3%
Food Preparation	0.58	2.80	···	3.38	15.4%
Water Collection	0.10	1.15	0.23	1.93	8.8%
TOTAL	5.15	9.30	2.50	21.95	100.0%

Source: Kumar and Hotchkiss (1988), Table 5.
†Data constructed by assuming five people/household.

Table 4.2: Patterns of time allocation in Nepal for men, women, children and households.

International Food Policy Research Institute.[17] In particular, the first three columns of the table show the number of hours per person per day devoted to a particular activity.

The activities can be broadly divided into two groups: Agricultural Work and Support Activities. Agricultural work consists of field work and employment - these two categories measure how much time is spent in the field and working as an agricultural employee on someone else's field. Support Activities consist of Fuel Collection (fuelwood collection, grass collection, leaf fodder collection and grazing), Water Collection and Food Preparation (food processing and cooking). Kumar and Hotchkiss (1988) present the data disaggregated by season - the data in the above table however, is aggregated by taking inter-seasonal averages and hence represents an annual average. To see what fraction of total hours worked in agriculture is devoted to Fuel Collection, I construct hours spent per activity for a "typical" Nepalese household/agricultural producer. According to the Nepalese Central Bureau of Statistics.[18] , the average size of an agricultural household in Nepal is approximately 5 people - a man, a woman and three children.[19] Thus, to obtain the total hours devoted to each activity for an average household, the men, women and children columns are summed with the children's column weighed by a factor of three. This gives total hours per day spent by a typical

[17] "Nepal Energy and Nutrition Survey, 1982/83," Western Region, Nepal.
[18] http://www.cbs.gov.np/nlfs_%20report_demographic_characteristics.php.
[19] This was also the average household size in the UK in the 1870's (Find Citation)

Nepalese agricultural household/producer in each one of the above activities. From this, the fraction of time spent on Fuel Collection is approximately forty-four percent, which implies that, $\alpha_A = 0.56$.

Finally, I choose parameters $\bar{a}$ and $g_A \equiv g_{l,A} g_E^{1-\alpha_A}$ to match employment share in agriculture in the United Kingdom in 1870 and 1950. According to Maddison (1980), employment share in agriculture in the United Kingdom was 22.7% in 1870 and 5.1% in 1950. Given these values, and given the value of α_A found above, I use equation (4.32) (with $t = 0$ for 1870 and $t = 80$ for 1950) to find the these parameter values to be $\bar{a} = 0.114$ and $g_A = 1.01884$.

Calibration of Non-Agriculture Parameters Next, values are chosen for: the energy share parameter, α_C; the elasticity of substitution between energy and labor, $\sigma_{E,L} = \frac{1}{1-\chi_C}$; and the productivity of energy, g_E. These parameters are chosen to match the rate of decline of energy intensity between the period when CO_2 emission intensities in the UK reached their peaks (in 1882) and 1950 as well as the employment in energy production sectors (here taken to be the Mining/Quarrying sector and the Gas/Electricity/Water Sector) in the years 1921 and 1938.[20] According to Warde (2007), energy intensity in the UK declined at an average annual rate of -0.7% per year over this period. According to Ashworth (2005), employment in the energy producing sub-sectors of non-agriculture fell from 7% in 1921 to 6% in 1938.

These parameters are determined simultaneously and as such, the calibration is performed in two steps. For a given χ_C, equation (4.40) evaluated at time $t = 51$ and $t = 68$ (remember, $t = 0$ is 1870 and so $t = 51$ and $t = 68$ are 1921 and 1938 respectively) forms a system of two equations which can be solved for the two unknowns α_C and g_E. The parameter χ_C is then chosen to match the rate of decline in energy intensity between 1882 (i.e. at $t = 12$), the time when maximum emission intensity peaked in the UK, and 1950 (i.e. at $t = 80$). The following procedure results in the following parameter values: $\alpha_C = 0.94$, $g_E = 1.0388$ and $\chi_C = -0.342$, which implies that the elasticity of substitution between labor and energy is $\sigma_{E,L} = 0.745$. This last elasticity parameter is broadly consistent with previous literature and lies

[20] Ideally I would want to match employment in 1870 and 1950, however data for the utilities sector for this period is not available

in the mid-range of the values usually estimated for Allen partial elasticities between energy and labor in manufacturing. For example Berndt and Wood (1975) estimate the elasticity of substitution in US manufacturing between energy and labor to be 0.65. Griffin and Gregory (1976) estimates this elasticity for numerous advanced European countries and the US to be between 0.72 and 0.87. Kemfert (1998) as well as Kemfert and Welsch (2000) estimate this elasticity for Germany to be 0.871. Finally, Stefanski (2009) estimates an elasticity of substitution between oil and labor for a panel of OECD countries and finds it to be 0.72.[21]

Remaining Parameters Given the above values for g_E, g_A and α_A, I can find the parameter value for direct labor productivity growth in agriculture to be, $g_{l,A} = 1.00192$. Finally, I choose labor productivity growth in non-agriculture to match GDP per capita growth rates in the UK between 1997 and 2007. I do this, because, in the limit, GDP per capita of the economy grows at the rate of direct labor productivity, $g_{l,C}$.[22] According to the *World Development Indicators* (2009), GDP per capita growth in the UK between 1997 and 2007 was 1.023 percent. Thus, I am assuming that the UK is close to that limit and as such I set $g_{l,C} = 1.023$. Finally I set pollution parameters. As was discussed in the data section, emissions from biomass are assumed not to pollute (i.e. be carbon neutral). As such, I take $\eta_A = 0$. Given this fact I can set $\eta_C = 1 > 0$ without loss of generality.

4.5.2 Results for the United Kingdom

In this section I compare the outcome and predictions of the model on various dimensions to data. The dimensions that will be considered are: employment share, output per capita growth, energy intensity, pollution intensity and pollution levels.

Table 4.3, shows employment shares in the UK from 1851-2006. The data comes from three primary sources: Lewis (1978) for 1851-1861, Feinstein (1972) for 1861-1950

[21] Notice that the usual procedures to obtain these elasticities involves estimating share equations. So for example, Berndt and Wood (1975) use time-series data (1947-71) to estimate the factor share functions arising from a transcendental logarithmic production function in US manufacturing for four inputs capital, labor, energy and materials - using iterative three-stage least squares. Griffin and Gregory (1976) perform a similar analysis for cross-country manufacturing data.

[22] Given $\chi_C < 0$, $\lim_{t\to\infty} \frac{GDP_{t+1}}{GDP_t} = g_{l,C}$.

	Agriculture	Industry	Services
1851	32.0%	39.6%	29.2%
1861	26.9%	40.8%	32.3%
1871	22.2%	42.2%	35.6%
1881	18.9%	42.7%	38.4%
1891	15.8%	43.2%	41.0%
1901	13.0%	43.4%	43.7%
1911	11.8%	43.5%	44.7%
1930	7.6%	42.5%	49.9%
1950	5.1%	44.9%	50.0%
1990	2.0%	27.4%	70.6%
2000	1.4%	21.4%	78.9%
2006	1.2%	18.7%	82.6%

Source: Lewis (1978), Feinstein (1972), StatOECD

Table 4.3: Employment by sector in the UK, 1851-2006.

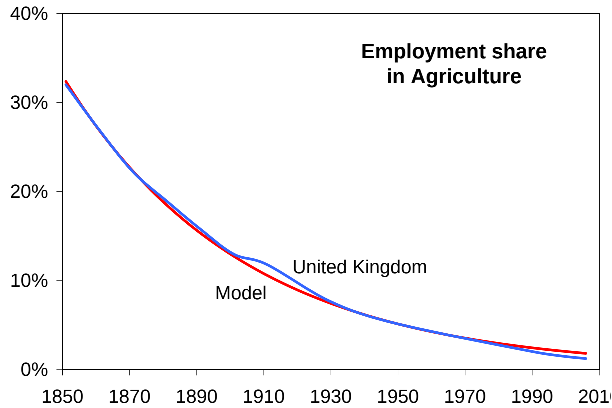
and the OECD for 1950-2006.[23] For 1851-1990, the data is compiled by Broadberry (1998) and Broadberry and Irwin (2004). For 1990-2006, I extend their data using OECD data from StatOECD. The employment share in agriculture from the data and the model is presented in Figure 4.7(a). Despite it's simplicity, the match between data and model is quite striking.

Figure 4.7(b), shows output per capita relative to its 1950/2000 level in the model and the data for the years 1820-2007. The model replicate Great Britain's growth experience over the period, although it overstates output per capita growth rates.

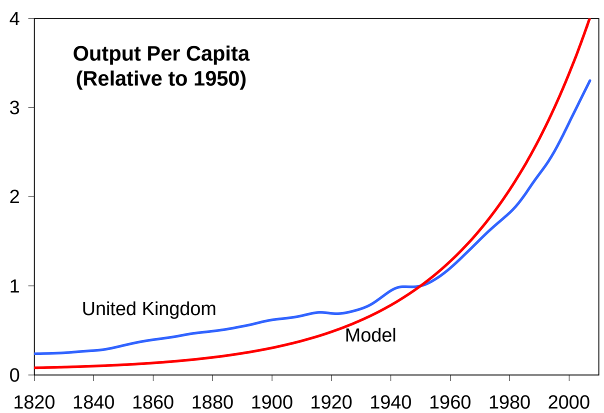
Figure 4.7(c), shows energy intensity and "modern-energy" intensity in the model for the years 1820-2007. Total energy intensity is declining over time, as it does in the data. Modern energy intensity - the energy intensity of non-agricultural energy - however, follows an inverted-U. Both of these facts are consistent with the data. Notice that the aggregate energy intensity between 1870 and the year modern energy peaks, declines approximately three times - this is in line with the average (total) energy-intensity decline in the countries studied by Gales et al. (2007) - Sweden, Holland, Italy and Spain.[24]

[23] The Feinstein (1972) data is take as the base and is extended backward and forward using growth rates calculated from Lewis and the OECD

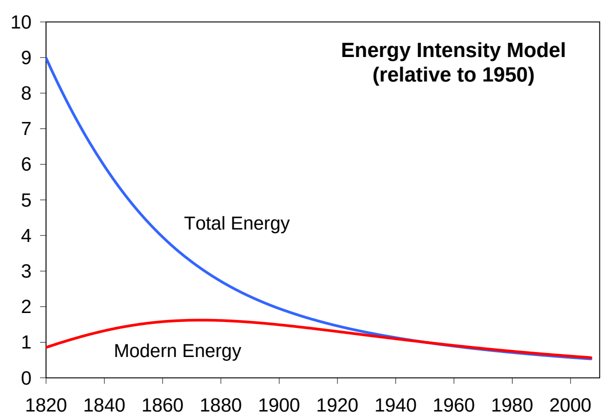
[24] Total energy data for the UK is available over this period, however I have had trouble obtaining



(a) Employment share in UK and model, 1851-2006.

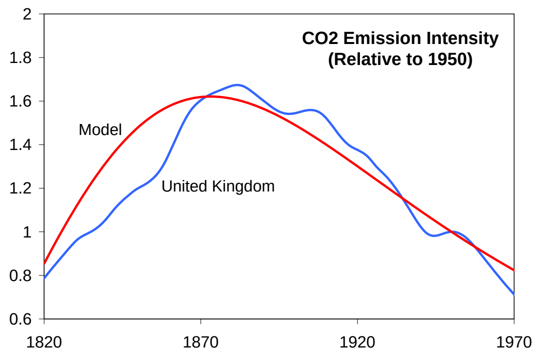


(b) Output per capita in UK and model, 1820-2006 (relative to 1950).

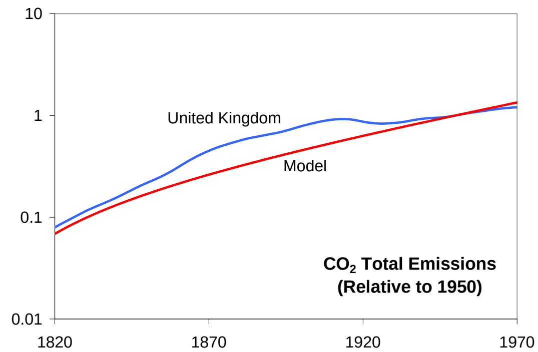


(c) Total and Modern Energy Intensity in Model, 1820-2000 (relative to 1950).

Figure 4.7: Employment share (1851-2006), output per capita (1820-2006), total and modern energy intensity in UK and model.



(a) Emission Intensity of CO_2, 1820-1970 (relative to 1950).



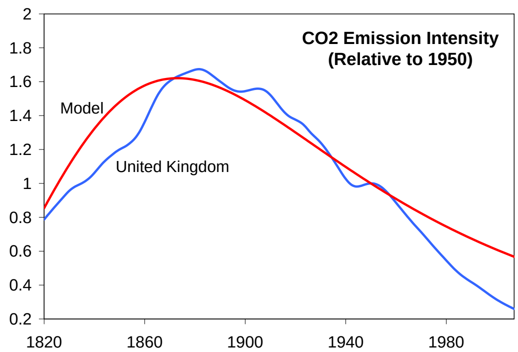
(b) Total Emissions of CO_2, 1820-1970 (relative to 1950).

Figure 4.8: Emission intensity and total emissions of CO_2 1820-1970 (relative to 1950).

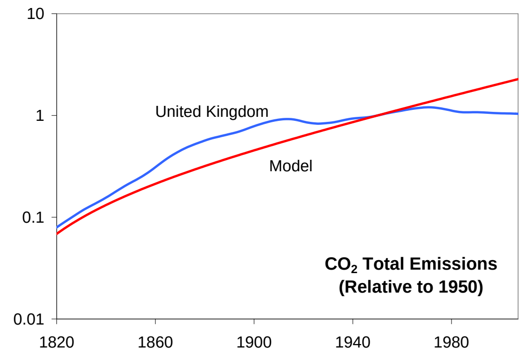
Finally, Figure 4.8(a) shows the emission intensity in the model and data (relative to 1950 emission intensity) for the years 1820-1970. In the data, emission intensity peaks in 1882, whilst in the model it peaks in 1873. Between 1870 and the peak (1882), emission intensity in the data increase by 113%, whilst in the model, it increases by 90% . Despite its simplicity, the model can account for 80% of the increase in emission intensity and predicts the peak to within 9 years of accuracy. Figure 4.8(a), shows total emissions in the data and the model between 1820 and 1970. Again, the match over the period is quite good.

Given the above calibration, in the limit, the growth rate of pollution will be $\lim_{t\to\infty} \frac{P_{t+1}}{P_t} = g_E^{\frac{\chi_C}{1-\chi_C}} g_{l,C} = 1.0135$, or 1.35% a year. Thus, in the limit, pollution grows at less than the growth rate of output, $g_Y = g_{l,C} = 1.023\%$, since the low elasticity of substitution between labor and energy and the positive productivity growth in energy consumption, induces labor to move from energy production to output production within the non-agricultural sector. However, this mechanism alone is not sufficient to induce falling pollution. Given the elasticity of substitution between energy and labor, $\sigma_{E,L} = \frac{1}{1-\chi_C} = 0.745$, for total emissions to fall in the long run, the growth rate of energy specific productivity should be at least 9.49% per year. Alternatively, given energy specific productivity growth, $g_E = 1.039$, the elasticity of substitution that would result in falling emissions must be lower than $\sigma_{E,L} = 0.39$. Both of these values seem

the data.



(a) Emission Intensity of CO_2, 1820-2007 (relative to 1950).



(b) Total Emissions of CO_2, 1820-2007 (relative to 1950).

Figure 4.9: Emission intensity and total emissions of CO_2 1820-2007 (relative to 1950).

somewhat implausible.[25]

Next, the emission intensity and total emissions are shown from 1820-2007 in Figure 4.9. The break between model and data after the mid-1960's is quite striking - emission intensity in the data begins to fall at a faster rate whilst total emissions begin to decline. Given the implausibly high energy intensity growth rates (or the low elasticity of substitution) necessary to generate falling emissions within the framework of the model, suggests that other factors may be at play. In the 1960's, energy production began to shift out of fossil fuel driven energy, towards cleaner nuclear and other renewable energy. Since this shift happened very slowly, this can bee seen - as best - as a contributing factor to falling emission intensity.

Probably a more important factor that contributed to the trend, is the change in structure within the non-agricultural sector itself - the shift in non-agriculture from industry to services. If the service sector has a lower elasticity of substitution than industry or devotes a smaller share of value added to energy consumption, then a shift in the economy from industry to services, will induce a fall in aggregate elasticity of substitution between energy and labor resulting in a faster shift out of the energy producing sub-sector, a faster decline in emission intensity and - potentially - a fall in emissions. This story is supported by Figure 4.10, which shows employment share by

[25] Although the aggregate elasticity of substitution between energy and non-energy inputs can fall further as the economy moves towards services.

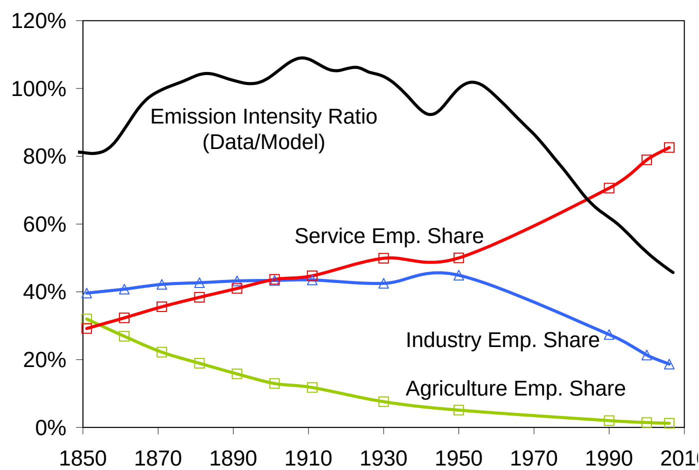


Figure 4.10: Structure of employment in the UK and emission intensity ratio (model/data), 1850-2006.

sector and the ratio of emission intensity in the data to the model. Until approximately the mid 1960's, the model does a good job of explaining the observed emission intensity in the data. Until this period, employment share in industry and services is increasing at roughly the same rate. However, after this point, employment share in services starts to increase sharply, whilst employment share in industry starts to fall. Thus, at the time when the model predicts higher than observed emission intensity, there is a significant change in the structure of non-agriculture in the data, away from industry towards services.[26]

For now, I purposefully abstract from substitution towards "clean-energy" in the non-agricultural sector and from the structural transformation that takes place within the non-agriculture sector to highlight the role played by structural transformation from agriculture to non-agriculture, improvements in energy efficiency and substitutability between energy and other factors. Work is in progress to incorporate the shift towards cleaner energy and the shift from industry to services into the model.[27]

[26] The changing fuel mix and structural transformation within the non-agricultural sector may also be related. The type of fuel used by the service sector, may in fact be cleaner than the fuel used by industry - cars and skyscrapers use oil and electricity, whilst industrial processes may depend more on dirty coal.

[27] Another factor causing emissions to fall in the data, may be the mechanism suggested by Brock and Taylor (2004) - technological progress in emission intensity. However, since the above data deals with emissions of carbon dioxide, a pollutant that is an inevitable co-product of the burning process

4.5.3 Generalizations and analysis

Next, I explore the implications of cross-country productivity differences on the evolution of cross-country income and economic structure and the implication of this changing structure for energy consumption, energy intensity, emission intensities and total emissions.

In the above analysis, the production functions in agriculture were assumed to be special cases of the following functions, for agriculture:

$$A_t = B_A(g_{l,A}^t L_{A,t}^y)^{\alpha_A}(g_E^t E_{A,t})^{(1-\alpha_A)}, \tag{4.53}$$

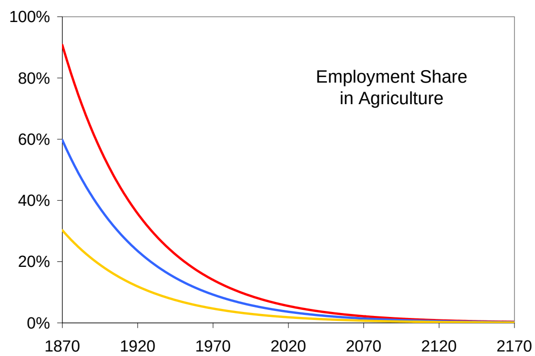
and for non-agriculture:

$$C_t = B_C \left(\alpha_C(g_{l,C}^t L_{C,t}^y)^{\chi_C} + (1-\alpha_C)(g_E^t E_{C,t})^{\chi_C}\right)^{\frac{1}{\chi_C}}, \tag{4.54}$$

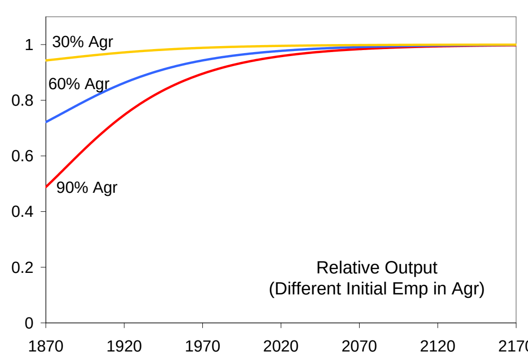
with $B_A = B_C = 1$. These productivities are a shorthand method of capturing a wide range of cross-country differences including, but not limited to, differences in taxation, educational attainment, endowments, technological differences, enforcement of property rights or regulations. In the baseline example for the UK, these productivities were assumed to be one, without loss of generality. In what follows, in order to investigate the role of structural transformation, I assume that all cross-country differences stem from differences in agriculture productivity (as in Gollin et al. (2002)), and hence effectively in how far countries are along their structural transformation. Countries with lower initial labor productivity in agriculture, will have a higher share of employment in agriculture than countries with a higher productivity. I assume that this is the only difference between countries.

Figure 4.11 shows employment shares and the output per capita relative to the GDP per capita of the UK, of three economies that have 90%, 60% and 30% of their labor force in agriculture in 1870, assuming that $B_C = 1$. Relative output per capita is measured in 2000 prices from the benchmark UK economy. The country with 90% initial employment share in agriculture has $B_A = 0.25$ and a GDP per capita of 49% of the UK in 1870. The country with 60% initial employment share in agriculture has $B_A = 0.38$ and a GDP per capita of 72% of the UK in 1870. The country with 30%

and hence has not and cannot be abated, this is probably less of an issue here.



(a) Share of Employment in Agriculture, three example economies.



(b) Relative Output, three example economies.

Figure 4.11: Three example economies

initial employment share in agriculture has $B_A = 0.75$ and a GDP per capita of 94% of the UK in 1870.

As productivity in agriculture grows, less labor is required to satiate agricultural needs. Labor freed by improvements in agricultural productivity moves into the non-agricultural sector where it can produce additional output, resulting in higher growth. Over time, as structural transformation comes to a close, the magnitude of this effect wanes, and growth in those countries slows as GDPs converge. Thus, countries that start with a lower level of productivity in agriculture, initially grow faster and eventually converge to the leader as labor moves from agriculture to non-agriculture (this is true because $B_C = 1$). Notice, however, that since the only difference between countries is assumed to be initial productivity levels in agriculture, the second temporary effect on growth (the reallocation of labor from energy to output production) that takes place in non-agriculture, will impact all economies equally.

Thus, all countries choose to divide their non-agriculture labor in the same proportions between energy production and output production at every point in time - at every point in time, each economy (regardless of its labor productivity in agriculture) allocates the fraction $\frac{1}{1+x_{C,t}}$ of its non-agricultural employment to energy production. Since energy efficiency improves equally across all countries, countries that started structural transformation in the past would have devoted a higher share of non-agriculture labor to energy production than countries that started structural transformation in the present.

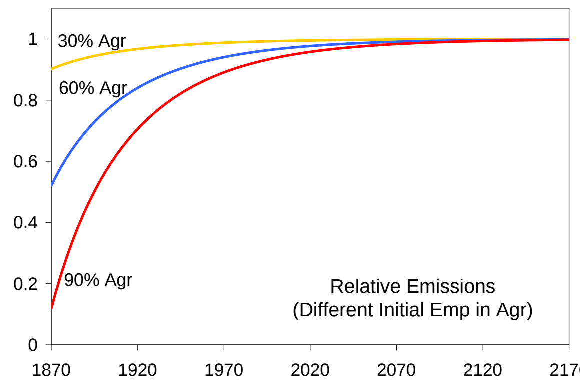
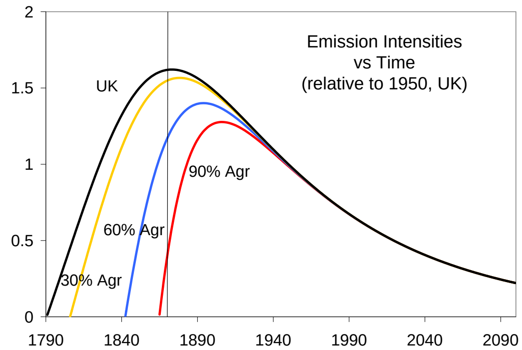


Figure 4.12: Relative emissions, three example economies.

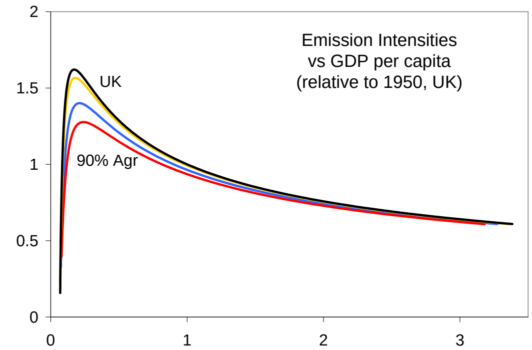
Thus even if in the past, 20% of employment was devoted to non-agriculture, a higher fraction of that 20% would be devoted to energy production in the past than if a country had 20% of employment devoted to non-agriculture today.

Next, Figure 4.12 shows emissions of the three economies relative to emissions in the United Kingdom. The country with 90% initial employment share in agriculture has emissions that are 12% of the UK in 1870. The country with 60% initial employment share in agriculture has emissions that are 52% of the UK in 1870. The country with 30% initial employment share in agriculture has emissions that are 90% of the UK in 1870. Thus, countries that start with a higher share of employment in 1870 (i.e. countries that started the industrialization process later), have lower initial emission levels. As structural transformation progresses and labor shifts from agriculture to non-agriculture, emissions in these countries grow faster than in the UK and emissions converge to emissions in the UK. The growth rates of emissions thus initially start high (with higher growth rates in countries that started the industrialization process later) and fall over time until they reach growth rates of emissions in the UK.[28] Notice that emissions are relatively lower than output in 1870, yet both output and emissions converge to the UK value. Thus emissions initially grow faster than output (how much faster depends on how late a country started its structural transformation). Over time, as countries grow richer and as structural transformation progresses, growth rates of emissions slow and fall below growth rates of GDP, since $g_Y = g_{l,C} > g_P$. In the above

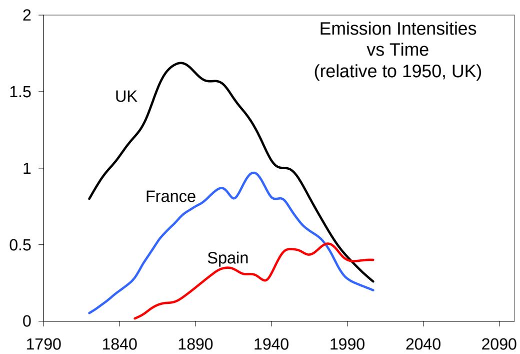
[28] Recall, that in the limit emissions in the UK grow at a constant rate given by $g_P = g_E^{\frac{\chi_C}{1-\chi_C}} g_{l,C}$.



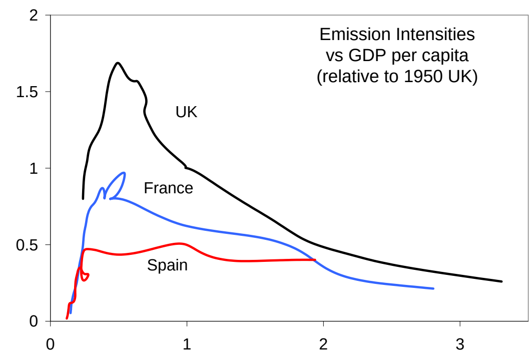
(a) Emission Intensities versus Time.



(b) Emission Intensities versus GDP per capita.



(c) Emission Intensities versus Time in the UK, France and Spain.



(d) Emission Intensities versus versus GDP per capita in the UK, France and Spain.

Figure 4.13: Emission intensities, three example economies.

calibration, emissions in rich countries continue to grow over time since $g_P > 1$.

Next, I combine output and emission data and consider resulting emission intensity data. The top two panels of Figure 4.13 show emission intensities versus time (top panel), GDP per capita (middle panel) and employment share in agriculture (bottom panel), for the UK and the three example economies. The top two graphs show emission intensities that have been extended back in time (relative to 1870), so that the first point in each graph corresponds to the point in time when each economy started it's structural transformation (i.e. had 100% share of employment in agriculture). As a comparison, the bottom two panels show the corresponding graphs for the United Kingdom, France and Spain - countries which roughly started their structural transformation fifty years apart (beginning, middle and end of the nineteenth century). Several facts emerge from these figures.

First, all countries exhibit an inverted-U emission intensity - initially the growth rates of emissions are higher than growth rates of GDP, and so the ratio of emissions to GDP rises. Subsequently, as the bulk of the economy moves into non-agriculture, improvements in energy productivity and the movement of labor out of energy production and into output production in the non-agricultural sector (caused by the complimentarity of energy and non-energy inputs in non-agriculture), results in falling emission intensities - output begins to grow faster than emissions. Notice, that the higher the share of employment in agriculture in a given country (in a given year), the lower the emission intensity - as a higher share of output is produced in the clean sector, the economy emits less pollution per unit of output. Also, the higher the share of employment in agriculture in a given country (in a given year), the faster the initial growth rate in intensity.

Second, countries that start their structural transformation earlier (and hence at every moment in time have a lower share of employment in non-agriculture), have higher levels of emission intensity at each level of GDP per capita. Since energy intensity is improving in all sectors all the time, countries that industrialize later, will have access to more energy efficient technologies than countries that started earlier, at every level of income, and will thus use less modern energy (and hence emit less pollution) at each level of income.

Fourth, emissions intensities rise proportionally more and keep rising for a longer period of time in countries that start their structural transformation earlier than in countries that start their structural transformation later.

Fifth, the later the country starts it's structural transformation in relation to the baseline country, the faster the initial increase in emission intensity.

Finally, notice that assuming no labor is employed in agriculture (i.e. $B_A \rightarrow \infty$, and hence structural transformation effectively does not take place), results in the model missing the inverted-U emission intensity curve. This results in emissions that are growing at a constant rate, rather than a rate that starts fast and slows over time. Omitting structural transformation from the model can thus seriously underestimate the impact of a poor country growing rich on its total emissions.

4.6 Conclusion

I argue that structural transformation is a major driver of the path of emissions over the development process of countries. As poor countries industrialize, output of their emissions will grow rapidly (faster than their GDP) as they move from clean bio-fuels to dirty fossil fuels. Eventually improvements in energy efficiency will limit the growth rates of emissions. In the long run, the key factor determining the path of pollution is the technological improvements in energy efficiency and the economy's ability to substitute between energy and non-energy inputs. I find that growth in emissions should slow significantly as countries become richer, but that this substitution effect is not strong enough in itself to induce emissions to fall for reasonable values of elasticity or technological progress. The falling growth rate of emissions however, may explain why richer countries could find it easier to limit emissions than poorer countries.

In this paper I argue that a model of structural transformation provides a useful theory of 1) why emissions grow faster than GDP in poor countries, but slower than GDP in rich countries; 2) why emission growth rates slow over time; and why 3) improvements in energy efficiency are generally insufficient to induce falling emissions. Additional implications of the model are that: 3) In as far as low agricultural productivity delays the beginning of structural transformation, it is key in influencing emission profile of countries over development; and that 4) countries that start structural transformation earlier, tend to have higher emission intensities at similar levels of GDP/capita than countries that start structural transformation later. Finally, omitting structural transformation from the model misses these dynamics in emissions growth rates, and can lead to misleading predictions with respect to total emissions.

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