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Dirty Little Secrets: Inferring Fossil-Fuel Subsidies from Patterns in Emission Intensities[1]

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Abstract

I develop a unique database of international fossil-fuel subsidies by examining country-specific patterns in carbon emission-to-GDP ratios, known as emission-intensities. For most - but not all - countries, intensities tend to be hump-shaped with income. I construct a model of structural-transformation that generates this hump-shaped intensity and then show that deviations from this pattern must be driven by distortions to sectoral-productivity and/or fossil-fuel prices. Finally, I use the calibrated-model to measure these distortions for 170 countries for 1980-2010. This methodology reveals that fossil-fuel price-distortions are large, increasing and often hidden. Furthermore, they are major contributors to higher carbon-emissions and lower GDP.

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1 Introduction

An astonishing feature of international energy and climate policy is that fossil-fuels - often seen as the primary contributor to climate change - receive enormous government support.[2] Eliminating these distortionary policies could in principle improve efficiency, provide a reprieve to strained government budgets whilst also lowering carbon emissions.[3] Surprisingly, no comprehensive database of directly measured, comparable fossil-fuel subsidies exists at the international level. As argued by Koplow (2009), this is both because of political pressure from the direct beneficiaries of subsidies and because of the immense complexity of the task given the profusion and diversity of subsidy programs across countries.[4] Indirect measures of subsidies - such as the ones constructed by the IMF (2013) or the IEA (2012) - are based on the price-gap approach. This methodology allows researchers to infer national subsidies by comparing measured energy prices with an international benchmark price. The key limitation of this technique is that it does not account for government actions which support carbon energy without changing its final price (Koplow, 2009).[5] Furthermore, the data necessary for this exercise is limited and since estimates are based on energy prices measured 'at the pump', they incorporate significant non-traded components which biases estimates. In this paper, I propose a completely novel, indirect, model-based method for estimating the size of fossil-fuel subsidies by examining country-specific patterns in carbon emission-to-GDP ratios, known as emission intensities.

The method is based on two observations about carbon emission intensity which this paper proposes to analyze. First, emission intensities tend to follow a hump-shaped pattern with income. Figure 1(a) plots emission intensity time paths for 26 OECD countries versus each country's GDP per capita, for 1751-2010. The graph suggests that middle-income countries produce dirtier output than rich or poor countries. Second, the emission intensity of later developers tends to follow a so-called 'envelope'-pattern over time: the intensities of later developers rise quickly until they roughly reach the intensity of the United Kingdom (UK) - the first country to start the modern development process - after which, their intensity tends to approximately follow the same path as that of the UK. An illustrative example of this envelope-pattern is shown in Figure 1(b).[6] In the graph, the obvious exceptions are China and the former USSR, which greatly overshoot this pattern. In this paper I argue that the extent to which countries like China deviate from the hump-shaped, envelope pattern is indicative of different types of distortions - or wedges - within those economies. I then demonstrate how a simple model can be used to disentangle and measure these distortions as well as their environmental and economic costs.

To do this, I construct a model of structural transformation calibrated to the experience of the UK. The model takes as given the UK's measured sectoral productivities as well as direct estimates

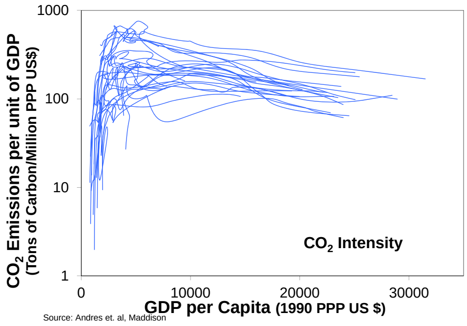
[2] Rough, lower-bound estimates by IMF (2013) show that global fossil-fuel subsidies in 2009 were on the order of magnitude of US$ 480 billion.

[3] See, for example, IEA (2012), OECD (2015), IMF (2013) or Koplow (2009).

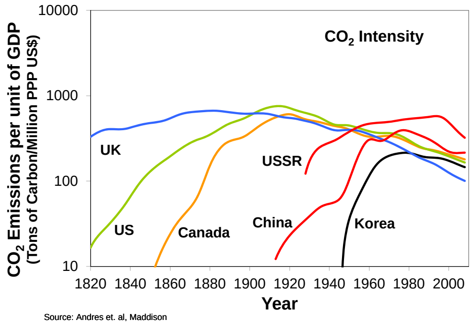
[4] Work by OECD (2015) is the only attempt to directly calculate carbon subsidies. These estimates, however, are only for a select number of countries and years and they are not comparable across countries.

[5] For example in the US, oil and gas producers receive support if they have older technology or access to more expensive reserves. As argued by Koplow (2009), "the subsidy is not likely to change the market price of heating oil or gasoline, simply because the subsidized producer is a very small player in the global oil market."

[6] Whilst both figures are illustrative, the hump-shape and envelope patterns are statistically robust as is shown in Appendix 11.2.



(a) OECD CO_2 Emission Intensity, 1751-2010. Each line represents the CO_2 emission intensity of one OECD country plotted against the country's GDP per capita.



(b) Timing and Emission Intensity. An illustrative example of the 'envelope-pattern' for CO_2 emission intensities with respect to time.

Figure 1: Carbon Dioxide Emission Intensity Patterns

of the UK's net fossil-fuel subsidies and subsequently reproduces the UK's hump-shaped emission intensity by generating an endogenously changing fuel mix and energy intensity. I then examine cross-country differences in emission intensity through the lens of this model. In my framework, any deviation in a country's emission intensity from the hump shape pattern of the UK is indicative of one of three distortions or wedges within that economy: 1) a wedge to agricultural productivity, 2) a wedge to non-agricultural productivity and a 3) subsidy (or tax)-like wedge to fossil-fuel prices. Following the language of Chari et al. (2007) and Duarte and Restuccia (2007), these 'wedges' are objects that appear like shocks to productivity or prices in a standard model but in fact reflect a wider set of distortions, country-specific characteristics, imperfections or government policies found in the data. Given the calibrated, structural model I can then use data on a country's CO_2 intensity, the size of its agricultural sector and its GDP levels to measure the size and importance of these three wedges for a panel of 170 countries over the 1980-2010 period.

It is instructive to highlight the precise purpose of the above wedge estimates and to relate them to the broader wedge-estimation literature. The first strand of this literature, represented by papers like Chari et al. (2007), use wedges as a guide to help researchers identify the categories of distortions which are quantitatively more important at driving real business cycles. The wedges in this paper offer similar guidance to researchers wishing to understand cross-country variation in emission intensity and hence in total carbon emissions. For example, one contribution of the paper is to show that the envelope pattern in CO_2 emission intensities is a consequence of agricultural productivity wedges in poorer countries. These wedges delay the start of industrialization and result in a lengthy catch-up process to the technological frontier of the leader. Any other deviations from the hump-shaped pattern of the leader are symptomatic of either non-agricultural productivity wedges or subsidy-like wedges on fossil-fuels. Another contribution of the paper is to show that these fossil-fuel price wedges play a quantitatively important role in driving carbon-emissions intensities in many countries. This suggests that future research on detailed frictions that translate into energy price wedges in those countries is likely to be quantitatively more important than research on frictions that translate into productivity wedges.[7]

The second strand of the literature, represented by papers like Restuccia and Rogerson (2008), Herrendorf and Schoellman (2015) or Hsieh and Klenow (2009), uses wedges to quantify aggregate policy costs. Hsieh and Klenow (2009), for example, measure the role played by capital misallocation in the manufacturing sector in China and India to explain low aggregate productivities in those countries. They first estimate the size of capital wedges and then calculate the benefits of removing those distortions. The current paper also assesses the costs of resource misallocation, but focuses on fossil-fuel price wedges and their economic and environmental cost. Importantly however, the current paper goes beyond the Hsieh and Klenow (2009) approach and advocates its energy-price wedge estimates as a complement and at times even a direct alternative to other methodologies used to estimate public support for fossil-fuels. Whilst this interpretation of fossil-fuel price wedges does have its limitations it can nonetheless be very helpful to policy makers and to researchers.

There are three key benefits to using the proposed methodology as an alternative to other methods of fossil-fuel subsidy estimation. First, my approach overcomes an important issue of data scarcity. Existing *direct*-measures of fossil-fuel subsidies are not comparable internationally and available for only limited countries and time periods. The *indirect*, price-gap method of inferring fossil-fuel subsidies depends on knowing the cost of fossil-fuels 'at-the-pump'. This data is often limited to a few countries and years and can be proprietary. My approach however can easily provide measures of fossil-fuel wedges for many decades and countries. Second, this measure of energy distortions is a residual and hence will be wider than a direct or price-gap measure of fossil-fuel subsidies. This is helpful since it provides a broader picture of the extent of support to fossil-fuels around the world and allows us to infer subsidies that are not reported or do not directly affect energy prices. Finally, and perhaps most importantly, the model-based approach allows me to perform counterfactuals in the spirit of Hsieh and Klenow (2009) and to examine how both output and emissions would have evolved without energy-price wedges in place. This provides a broader measure of the costs of fossil-fuel subsidies.

Of course this approach also has certain limitations. First, it entails a broad view of subsidies - the wedge is a residual which captures *everything* that distorts energy consumption relative to the baseline economy given productivity wedges. Whilst this can be seen as positive for the above reasons, it also means that wedges include policies that only indirectly support fossil-fuel consumption[8] as well as some potentially non-policy, energy-specific country characteristics not captured by other wedges.[9] Second, it cannot identify particular policies driving observed price wedges nor does it tell us whether these distortions can be easily removed. Third, it only gives us a measure of *net*-subsidies for each country and hence might miss subsidies in one part of the economy that

[7] For example, a logical next step in understanding carbon emission intensities could be the construction of a model that captures detailed frictions on different types of energy (such as coal, oil or renewable energy) so as to evaluate which are relatively more important at driving the aggregate fossil-fuel price wedge.

[8] For example, wage subsidies to coal miners or the portion of broad-based and non-energy targeted tax provisions that influence energy consumption (such as the US mortgage interest rate deduction). See Nordhaus et al., eds (2013) for more examples.

[9] For example, in as far as country-specific features such as differences in transportation costs, resource endowments, geography, weather or tariffs impact energy consumption above and beyond their effect on sectoral productivity, they may influence the energy price wedge.

are offset by taxes in another part. Crucially, the price-gap approach suffer from the same problems and - as I will argue - to an even greater extent.[10] In comparison, the suggested approach is more comprehensive, it yields more data which is also internationally comparable and it can be used to perform counterfactuals to fully gauge the opportunity costs of distortions. Furthermore, the results are robust to a wide range of extensions that control for various sources of cross-country heterogeneity such as resource endowments, trade or a finer industrial structure. Thus, despite its shortcomings, the proposed methodology is useful: at the very least the suggested approach can complement existing, directly and indirectly measured fossil-fuel subsidy estimates; at its most helpful it can provide information on fossil-fuel subsidies when no other alternative measures exist or when subsidies are indirect or hidden.

Examining the resulting fossil-fuel wedges, I find that the global size of subsidies is enormous - 983 billion (1990 PPP) US dollars in 2010 alone. Energy price wedges were roughly constant throughout the 1980s and most of the 1990s, however since the late 90s they more than quadrupled in size. Crucially, I find evidence of large, indirect subsidies in some countries such as China. The model suggests that support to fossil-fuel energy in those countries is not entirely reflected in prices of petrol at the pump, but is in fact indirect. This matches well with earlier studies - like Zhao (2001) - who find that the Chinese government supports energy intensive industries through a wide range of indirect subsidies. Finally, I perform a counterfactual were I turn off energy wedges in each country and find that up to 36% of global carbon emissions between 1980 and 2010 were driven by subsidies and that GDP was up to 1.7% lower per year because of the distortive implicit subsidies. The total (direct and indirect) economic costs of these distortions amounted to a staggering 3.8% of total world GDP in 2010.

In the following section, I perform an accounting exercise on a panel of international data to isolate the key drivers of the hump-shaped emission intensity. I show that the hump-shape is driven by two factors: a changing fuel-mix and a falling energy intensity. To capture these two mechanisms, in section 3, I build and solve a two-sector, general equilibrium growth model of structural transformation similar to Gollin et al. (2002), Rogerson (2007) or Duarte and Restuccia (2007) but with energy as an intermediate input. In section 4, I calibrate the model to match the structural features, the energy consumption patterns and the directly measured net-fossil-fuel subsidies of the UK between 1820 and 2010.[11] Section 5 then demonstrates the impact of different types of wedges on emission intensity and uses the calibrated model to quantify the role that each wedge plays in driving cross-country differences in emission intensity. Section 6 shows how fossil-fuel price wedges relate theoretically and empirically to subsidies calculated using alternative approaches. Section 7 examines the obtained energy price wedges and their impact on emissions and output. Section 8 considers a number of robustness exercises and extensions to the baseline model. Section 9 discusses the key strengths and weaknesses of the proposed methodology, whilst section 10 offers some concluding remarks on the importance of the suggested methodology.

[10] In particular: 1) all price deviations from a baseline price are attributed to subsidies; 2) the source of price deviations cannot be pinned down to specific policies; and 3) price-deviations are also measures of net-subsidies.

[11] As I explain later, I choose the UK since it has long-run data covering the entire industrialization process, relatively small subsidies and it was arguably the first country to begin the industrialization process.

2 Stylized Facts

In this section I pinpoint the mechanisms driving the hump-shaped CO_2 emission intensity documented above by performing a "pollution accounting" exercise on UK data.[12] These findings will be used to motivate the model constructed in the next section and in turn, the model will be used to analyze distortions across countries. Throughout I consider *only* carbon emissions stemming from the *consumption* of fossil-fuels as these account for approximately 80% of all anthropogenic carbon dioxide emissions (Schimel et al., 1996).[13] More importantly, this data is widely available due to the tight, physicochemical link between the type of fuel combusted and the quantity of carbon released (EPA, 2008).[14]

The total emissions in an economy stemming from fossil-fuel combustion can be expressed by the following identity, $P_t \equiv \eta_t E_t$, where P_t is carbon emissions, E_t is total energy use and η_t represents the emissions per unit of energy which I call 'energy impurity'. Dividing both sides of the identity by GDP, relates pollution intensity (emissions per unit of GDP) with energy intensity (energy per unit of GDP) and impurity:

$$\frac{P_t}{Y_t} = \eta_t \frac{E_t}{Y_t}. \tag{1}$$

Using data on carbon emissions, energy and PPP GDP, I calculate impurity as a residual and show the above decomposition for the UK in Figure 2(a).[15] Notice that over the 1820-2010 period the UK's CO_2 emission intensity followed an inverted-U shape, its energy impurity largely rose whilst energy intensity fell. The initial increase in emission intensity was thus driven by an increase in impurity, whereas the subsequent decline was driven by falling energy intensity. Next, I examine the likely sources driving the observed changes in impurity and energy intensity.

Energy Impurity Since carbon emissions are linked directly to the type of fuel consumed, a changing fuel mix must be the source of rising impurity.[16] Figure 2(b) shows how the fuel mix in the UK has shifted from "clean" renewable fuels like wood, towards "dirty" fossil-fuels like coal. According to most international protocols, the burning of biomass materials for energy does not add to the concentrations of carbon dioxide in the biosphere since it recycles carbon accumulated by the plant-matter during its lifecycle. The burning of fossil-fuels however contributes to higher levels of carbon concentration since it releases CO_2 that had previously been removed or 'fixed' from the biosphere over millions of years and locked under ground in the form of fossil-fuels.[17]

[12] In Appendix 11.2 I demonstrate that the experience of the UK is representative.

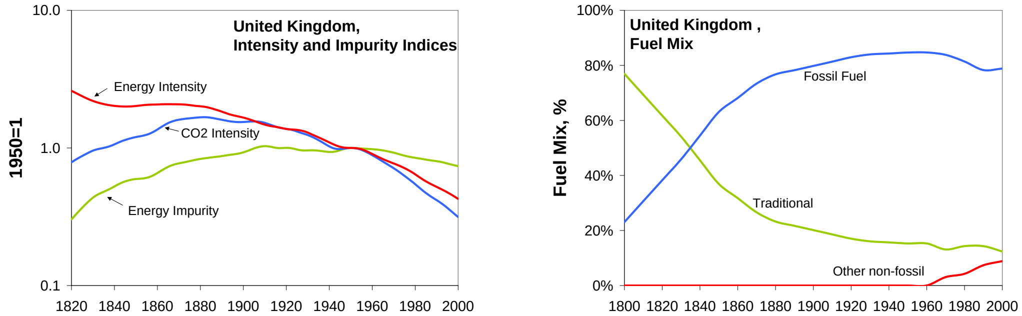
[13] The remaining 20% stems largely from changes in land use - such as deforestation or urbanization.

[14] Thus, given energy consumption data, we can accurately infer the quantity of emitted carbon.

[15] For details on data construction, see Appendix 11.1.

[16] Suppose there are a number of different energy sources, $E_{i,t}$, and each emits a fixed quantity of pollution, η_i. Total emissions are given by, $P_t \equiv \sum_i \eta_i E_{i,t}$. Dividing both sides by GDP I can write: $\frac{P_t}{Y_t} = \left(\sum_i \eta_i \frac{E_{i,t}}{E_t}\right) \frac{E_t}{Y_t}$, where $E_t = \sum_i E_{i,t}$ is total energy and the term in brackets is its impurity. As the proportion of energy coming from some dirty fuel, $E_{D,t}/E_t$, increases, so does the energy impurity.

[17] Both the Intergovernmental Panel on Climate Change (IPCC) and the US Energy Information Administration consider biomass emissions to be carbon neutral and recommend that "reporters may wish to use an emission factor of zero for wood, wood waste, and other biomass fuels". For details see, *Emissions of Greenhouse Gases in the United States 2000* (November 2001).



(a) Pollution intensity decomposition of the UK according to equation (1).

(b) Fuel mix in the UK. The graphs shows the change in the composition of total energy used in the UK.

Figure 2: Source of the hump-shaped emission intensity, UK.

I argue that the change in fuel mix is driven by the evolution of a country's economic structure from agriculture to industry and services. Traditional fuels are relatively abundant in an agricultural and rural setting and subsistence agriculture lends itself to bio-fuel use. On the other hand, industrial processes and services require modern types of energy which are more dependable, have greater flexibility, higher energy density and burn hotter than bio-fuels. Thus as an economy shifts from an agrarian to an industrialized state, a change in fuel mix will occur - from renewable biomass materials to (predominantly) fossil-fuels such as coal, oil or gas. This change in fuel mix will in turn contribute to higher energy impurity. The above idea is relatively well represented in the literature in papers such as Grossman and Krueger (1993) or Fischer-Kowalski and Haberl, eds (2007).

Energy Intensity A novel contribution of the paper are the two simultaneous channels that potentially drive falling energy intensity: differential productivity growth and complementarity. Energy is a special type of good since it is necessarily an input at *every* stage of production. Consequently, assuming there is technological progress at each stage of production, energy will likely benefit disproportionately from technological gains relative to other inputs. If, in addition, energy and non-energy inputs are gross complements in production, over time an economy will devote relatively more resources to the slower growing non-energy sector in order to maintain relatively fixed proportions of both types of inputs. This will contribute to falling energy intensity. The relative importance of these channels is pinned down in the calibration, once a structural model has been specified.

The Environmental Kuznets Curve Finally, notice that the stylized facts presented above tie into a long tradition of investigating the connection between emissions and economic development. This literature is extensive and begins at least in the 1970s with work by Forster (1973), Solow (1973), Stiglitz (1974) and Brock (1977). The examination became more empirically orientated with work by Grossman and Krueger (1994, 1995) who argued that there was a hump-shaped relationship between total emissions and economic development within and across countries, which they dubbed the Environmental Kuznets Curve (EKC). Theoretical explanations for this phenomenon have been made by Lopez (1994), Copeland and Taylor (1994), Stokey (1998), Aghion and Howitt (1998), Jones and Manuelli (2001), Andreoni and Levinson (2001), Brock and Taylor (2010), Stefanski (2013) and many others. The authors have argued that a number of factors could drive the EKC such as changes in scale of production, changes in output and input mix, the current state of technology, improvements in production efficiency, emissions specific changes in processes or the sectoral composition of the economy. For a more complete review of the EKC literature see Chapter 2 of Copeland and Taylor (2003).

The basis of the work in this paper however, is *not* the classical Kuznets Curve - which has been criticized by Stern (2004) and Carson (2010) among others - as lacking rigorous empirical support. Instead, I rely on the existence of a hump-shaped emission *intensity* curve (pollution *per unit of GDP*) over income and time. The hump-shaped pattern of carbon emission intensity is relatively well known and far more robust than the standard EKC curve. Tol et al. (2009) examine this relationship for the US for the 1850-2002 period. Lindmark (2002), Kander (2002) and Kander and Lindmark (2004) demonstrate that this relationship holds for Sweden. Bartoletto and Rubio (2008) find evidence of a similar pattern in Italy and Spain. Lindmark (2004) examines carbon emission intensity in forty six countries and finds that the hump shape is a feature in most of those economies. Finally, Stefanski (2013) demonstrates that a hump-shaped intensity plays a key role in driving emissions in 149 countries between 1960 and 2005. Thus, whilst the work connects to the traditional EKC literature, its approach is complementary and is based on an arguably more robust empirical finding.

3 The Baseline Model

Next, I specify and solve a structural model that can capture rising impurity as well as falling energy intensity and hence can generate the hump-shaped emission intensity documented above. A calibrated version of the model will be used to examine the sources of cross-country variation in emission intensity.

Preferences There is an infinitely lived representative agent endowed with a unit of time in each period. Utility is defined over per-capita consumption of agricultural goods, a_t, and non-agricultural goods, c_t. To generate structural transformation, I follow Gollin et al. (2002) by assuming a simple type of Stone-Geary period utility:

$$U(a_t, c_t) = \begin{cases} \bar{a} + u(c_t) & \text{if } a_t > \bar{a} \\ a_t & \text{if } a_t \leq \bar{a}, \end{cases} \tag{2}$$

with lifetime utility being given by $\sum_{t=0}^{\infty} \beta^t U(a_t, c_t)$, where $0 < \beta < 1$ is the discount factor and $u'(c_t) > 0$. Given this setup, once per capita output in the agricultural sector has reached the level $\bar{a}$, all remaining labor moves to the non-agricultural sector.

Technologies Non-agricultural output (Y_{Ct}) is produced using labor (L^y_{Ct}) and a modern energy inputs (E_{Ct}):

$$Y_{Ct} = \left(\alpha_C (B_{lCt} L^y_{Ct})^{\frac{\sigma-1}{\sigma}} + (1-\alpha_C)(B_{Et} E_{Ct})^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \tag{3}$$

where, α_C is the weight of labor in production, σ is the elasticity of substitution between labor and energy, whereas B_{lCt} and B_{Et} are exogenous labor and energy augmenting productivity terms at time t respectively. Modern energy is produced using labor (L^e_{Ct}):

$$E_{Ct} = B_{eCt} L^e_{Ct}, \tag{4}$$

where B_{eCt} is exogenous productivity at time t. Since the modern energy sector consists of non-agricultural sectors such as mining, drilling or electricity generation, total employment in non-agriculture in the model is given by the sum of employment in both energy and non-energy sub-sectors, $L_{Ct} \equiv L^y_{Ct} + L^e_{Ct}$.

Agricultural output (Y_{At}) is produced using labor (L^y_{At}) and a traditional energy input(E_{At}):

$$Y_{At} = B_{At} {L^y_{At}}^{\alpha_A} {E_{At}}^{1-\alpha_A}. \tag{5}$$

In the above equation, α_A is the weight of labor in production and B_{At} is exogenous productivity at time t in the agricultural output sector. In contrast to the non-agricultural sector, I assume that the production function is Cobb-Douglas so that the elasticity of substitution between energy and labor is one. This is in line with the argument put forward by Lucas (2004) that "traditional agricultural societies are very like one another". I take this to mean that the composition of hours and labor devoted to various activities in traditional agricultural societies remains the same, implying the above production function. Traditional energy, is produced using labor (L^e_{At}):

$$E_{At} = B_{eAt} L^e_{At}, \tag{6}$$

where B_{eAt} is exogenous productivity at time t in the traditional energy sector. The traditional energy sector can be taken to be the gathering of fuel wood or charcoal production etc. and as such total employment in the agricultural sector is given by the sum of employment in both sub-sectors, $L_{At} \equiv L^y_{At} + L^e_{At}$. Finally, I assume that the total (and exogenous) size of the labor force is given by $L_t = L_{At} + L_{Ct}$.

Notice that I assume traditional energy is only used in agriculture whilst modern energy is only used in non-agriculture. This assumption is made both for simplicity but also because long run data on sectoral use of different fuels does not exist.[18] Despite its seeming starkness, it turns out that this assumption fits the data well and it is unlikely to be quantitatively important.

To see this, notice that traditional fuels are probably not widely used in non-agriculture due to the nature of those sectors' production processes. Industry and services often require modern types of energy which are more dependable, have greater flexibility, higher energy density and burn hotter than bio-fuels.[19] Furthermore, agriculture in poor countries will largely use traditional

[18] Mulder and de Groot (2012) argue that constructing even recent sectoral energy use data is difficult due to concordance issues with the ISIC classification arising from residential energy use. Here I sidestep this issue by attributing *all* modern energy use to the non-agricultural sector. See Appendix 11.4.2 for details.

[19] Of course some industries - especially in poorer countries- will use bio-fuels like charcoal or wood but their use will tend to be relatively limited - especially due to the small size of the non-agricultural sector in poorer countries (Fischer-Kowalski and Haberl, eds, 2007).

energy since it is abundant in rural settings and since subsistence agriculture lends itself to bio-fuel use. Agriculture in rich countries, on the other hand, will certainly use modern fuels, but by that advanced stage of development the agricultural sector will tend to be relatively small and will thus demand relatively little energy. Consequently, agricultural energy demand will be important only when the agricultural sector is large and hence when it is dominated by traditional energy. This implies that the contribution of agricultural energy demand to carbon emissions should be small throughout the development process. In Appendix 11.2 I show evidence that the share of carbon emissions stemming from agricultural energy use is indeed very small - approximately 2.1% of total carbon emissions globally - and that this proportion does *not* change with development. Thus, abstracting from modern fuel use in agriculture is perhaps not as strong a simplification as it might initially seem.[20] Finally, if this were a quantitatively important assumption, the model would not do well in predicting cross-country differences in fuel-mix. However, in section 5, I show that the model gives exceptionally accurate predictions regarding cross-country consumption patterns of traditional and modern fuels.[21] Thus, not including modern fuel use in agriculture and traditional fuel use in non-agriculture is unlikely to quantitatively impact the results.

Pollution Burning a unit of modern energy, E_{Ct}, releases P_{Ct} units of pollution:

$$P_{Ct} = \eta_{Ct} E_{Ct} \tag{7}$$

where η_{Ct} is a coefficient of proportionality. Due to the assumption that agriculture only uses traditional energy, only non-agricultural energy will generate emissions. Furthermore, any changes in modern energy impurity, η_{Ct}, will reflect changes in the mix of modern fuels used to generate energy. In this paper I take changes in η_{Ct} as exogenous and attribute them entirely to exogenous technological progress which will result in an (un-modeled) change in the composition of modern fuel mix and hence modern energy impurity.[22] This turns out *not* to be an important assumption for the results of the paper: very similar results will hold even if η_{Ct} is assumed to be constant. This is because - in the data - η_{Ct} has remained relatively flat over time. Finally, notice I assume that emissions influence neither utility nor productivity - and are thus simply a by-product of energy consumption and production. This is a good assumption for CO_2 - at least historically - since carbon dioxide is a colorless, odorless and tasteless gas and the concern with climate change is a very recent phenomenon.

Government I allow government to potentially subsidize/tax modern energy consumption by the non-agricultural output producers at a rate τ_t. This policy is supported by lump sum taxes/transfers on the household, T_t.[23]

[20] Other important agricultural pollutants are chemical fertilizers, however these contribute to methane and nitrate emissions and not to carbon emissions (FAOSTAT, 2012). Traditional agriculture also emits significant amounts of carbon though changes in land use - such as clearing of rainforests. Whilst potentially important, due to lack of data, this paper only focuses on carbon emissions from the consumption of fossil-fuels.

[21] See also Figure 17(a) in Appendix 11.2, that shows a remarkably strong correlation between traditional energy share and agricultural employment share.

[22] Notice that changes in the modern energy fuel mix can encompass both different types of fossil-fuels like oil, gas or coal (which generate fixed amounts of carbon emissions per fuel type) but also renewable non-traditional fuels like wind, solar or nuclear (which, according to the EIA, generate zero carbon emissions).

[23] Section 6, shows that the results remain almost unchanged if the subsidy is placed on modern energy producers

Competitive Equilibrium I focus on the (tax-distorted) competitive equilibrium of the above economy which for every t is defined as the: (i) Price of agricultural and non-agricultural goods, wage rates, as well as traditional and modern energy prices, $\{p_{At}, p_{Ct}, w_t, p_{eAt}, p_{eCt}\}$; (ii) household allocations: $\{a_t, c_t\}$; (iii) firm allocations and emissions $\{L^y_{At}, L^e_{At}, L^y_{Ct}, L^e_{Ct}, P_{Ct}\}$; and (iv) energy policy $\{\tau_t, T_t\}$ such that:

(a) Given prices and policy, households' allocations maximize utility in equation (2) subject to the budget constraint of the household: $p_{At}a_t + p_{Ct}c_t = w_t - T_t$.

(b) Given prices and policy, firms' allocations solve the firms' problems in output and energy subsectors for $s = A, C$: $\max_{L^y_{st}, E_{st}} p^s_t Y_{st} - w_t L^y_{st} - \bar{p}_{est} E_{st}$ and $\max_{L^e_{st}} p_{est} E_{st} - w_t L^e_{st}$ where $\bar{p}^e_{At} = p_{eAt}$ and $\bar{p}_{eCt} = p^e_{Ct}(1 - \tau_t)$ and firms emit carbon according to equation (7).

(c) The government period budget constraint is given by $L_t T_t = \tau_t p^e_{Ct} E_{Ct}$.

(d) Goods and labor markets clear: $Y_{At} = L_t a_t$, $Y_{Ct} = L_t c_t$. $L^y_{At} + L^e_{At} + L^y_{Ct} + L^e_{Ct} = L_t$.

Quantities The model is solved in two parts. The first step takes employment across agriculture and non-agriculture as given and allocates labor within each sector between energy and output subsectors. Equating the wage-to-energy price ratios derived from the first-order conditions of output and energy firms in each sector gives the following distribution of labor across subsectors within agriculture:

$$L^e_{At} = (1 - \alpha_A) L_{At} \text{ and } L^y_{At} = \alpha_A L_{At}. \tag{8}$$

Due to the Cobb-Douglas structure of agriculture, a constant proportion of agricultural workers are devoted to the production of energy and non-energy inputs. In non-agriculture however, since the elasticity of substitution is potentially different from 1, the proportion of workers devoted to the energy and non-energy sectors is potentially non-constant:

$$L^e_{Ct} = \left(\frac{1}{1 + x_{Ct}}\right) L_{Ct} \text{ and } L^y_{Ct} = \left(\frac{x_{Ct}}{1 + x_{Ct}}\right) L_{Ct}, \tag{9}$$

where, $x_{Ct} \equiv \left(\frac{\alpha_C}{1-\alpha_C}\right)^{\sigma} \left(\frac{B_{Et} B_{eCt}}{B_{lCt}}\right)^{1-\sigma} (1 - \tau_t)^{\sigma}$. Notice that energy benefits from technological progress twice - both when it is produced (B_{eCt}) and when it is consumed (B_{Et}) - whereas labor only benefits once (B_{lCt}). Thus, we may reasonably expect the ratio $\frac{B_{Et} B_{eCt}}{B_{lCt}}$ to increase over time. If, in addition, the elasticity of substitution between energy and non-energy inputs is less than one, $\sigma < 1$, these differences in sectoral productivity growth will result in an increase in x_{Ct} over time. Since $L^y_{Ct}/L^e_{Ct} = x_{Ct}$, this will generate a reallocation of inputs from energy to non-energy production in the non-agricultural sector. Finally, higher subsidies on modern energy will result in a lower x_{Ct} and hence more workers devoted to modern energy production.

The second step determines the division of labor across agriculture and non-agriculture. Assuming that a country is satisfying its subsistence requirements, preferences imply that $Y_{At} = \bar{a} L_t$.

rather than energy consumers. It also shows how the existence of other subsidy/tax wedges influences this measure of energy subsidies and what happens when non-lump sum taxes are used to pay for fossil-duel subsidies.

Combining this with equations (5), (6) and (8), employment in agriculture and non-agriculture is respectively given by:

$$L_{At} = \frac{\bar{a}}{\alpha_A{}^{\alpha_A}(1-\alpha_A)^{1-\alpha_A} B_{At} B_{eAt}^{1-\alpha_A}} L_t \text{ and } L_{Ct} = L_t - L_{At}. \tag{10}$$

Higher productivity in agricultural sectors (B_{At}, B_{eAt}) results in a smaller proportion of workers being needed to produce the subsistence level of food and their subsequent reallocation to non-agriculture. Given the above, equations (4), (6) and (7) determine sectoral energy use and emissions.

Prices Normalizing the wage rate to one, $w_t = 1$, final good firms' first-order conditions imply that the price of sector $s = A, C$ goods is $p_{st} = 1/\frac{\partial Y_{st}}{\partial L^y_{st}}$. Using the above results:

$$p_{At} = \frac{1}{\alpha_A^{\alpha_A}(1-\alpha_A)^{1-\alpha_A} B_{At} B_{eAt}^{(1-\alpha_A)}} \text{ and } p_{Ct} = \frac{1}{\alpha_C^{\frac{\sigma}{\sigma-1}} B_{lCt}\left(1+(1-\tau_t)/x_{Ct}\right)^{\frac{1}{\sigma-1}}}. \tag{11}$$

Improvements in productivity in agricultural sectors (B_{At}, B_{eAt}) will lead to falling prices of agriculture. If both labor specific productivity in non-agriculture (B_{lCt}) and x_{Ct} increase over time and $\sigma < 1$, so that the non-agricultural sector substitutes away from modern energy, then prices of non-agriculture will also fall over time. Taking the first-order conditions of the energy firms, the price of traditional and modern energy is given by:

$$p_{eAt} = 1/B_{eAt} \text{ and } p_{eCt} = 1/B_{eCt}. \tag{12}$$

Improvements in productivity in the energy sectors (B_{eAt}, B_{eCt}) will result in falling energy prices.

Intensity Next, I examine the evolution of emission intensity over time in the framework of the model. Constant price GDP evaluated at time t^* prices is given by $Y_t \equiv p_{At^*}Y_{At} + p_{Ct^*}Y_{Ct}$. Aggregate emission intensity, N_t, can then be written as the product of the constant price share of non-agriculture in GDP, $d_t \equiv \frac{p_{Ct^*}Y_{Ct}}{p_{At^*}Y_{At}+p_{Ct^*}Y_{Ct}}$, and non-agricultural emission intensity, $N_{Ct} \equiv \frac{P_{Ct}}{p_{Ct^*}Y_{Ct}}$:

$$N_t \equiv \frac{P_t}{Y_t} = \frac{P_{Ct}}{p_{At^*}Y_{At} + p_{Ct^*}Y_{Ct}} = \frac{p_{Ct^*}Y_{Ct}}{p_{At^*}Y_{At} + p_{Ct^*}Y_{Ct}} \frac{P_{Ct}}{p_{Ct^*}Y_{Ct}} = d_t N_{Ct}. \tag{13}$$

The first equality follows from the fact that only non-agriculture emits carbon and from the definition of constant price GDP. For illustrative purposes, in the remainder of this section only, I impose the following:

Assumption 1. *$\frac{B_{jt+1}}{B_{jt}} = g_j > 1$ for $j = A, eA, lC, E, eC$; $\frac{g_E g_{eC}}{g_{lC}} > 1$; $\tau_t = 0$ and $\eta_{Ct} = 1$.*

I then establish the following two theorems describing the evolution of d_t and N_{Ct} to gain insight into the evolution of N_t. For proofs, see Appendix 11.3.

Proposition 1. *Suppose Assumption 1 holds. Then when $L_{At} = L_t$, $d_t = 0$; when $L_{At} < L_t$, $d_{t+1}/d_t > 1$ and $\lim_{t\to\infty} d_t = 1$.*

Intuitively, as agricultural productivity rises, less workers are needed to satisfy subsistence which results in a reallocation of workers to non-agriculture and an accompanying increase in the constant prices share of non-agriculture over time.

Proposition 2. *Suppose that Assumption 1 holds and* $\sigma < \min\left\{\frac{\log(g_E)}{\log(g_E)+\log(g_{eC})-log(g_{lC})}, 1\right\}$ *then, when* $L_{At} < L_t$*,* $N_{Ct+1}/N_{Ct} < 1$ *and* $\lim_{t\to\infty} N_{Ct} = 0$*.*

Intuitively, if there is enough complementarity between energy and non-energy inputs, higher technological progress associated with energy will result in a reallocation of resources away from energy towards non-energy in the non-agricultural sector at a fast enough pace to engender a monotonic decline in non-agricultural emission intensity towards zero.[24]

Putting these facts together lends some insight into the evolution of aggregate emission intensity. A country on the brink of industrialization has zero aggregate emission intensity since it is completely dominated by non-polluting agriculture. As the economy shifts towards dirty non-agriculture, aggregate emission intensity rises. However, emission intensity in non-agriculture falls with time, and thus - as an ever greater proportion of GDP is produced in non-agriculture - aggregate emission intensity of the economy will also fall.[25] Nonetheless, the exact shape of emission intensity will depend on underlying parameters. Testing the model thus requires choosing reasonable parameters to see if these can reproduce observed patterns of energy and emission intensity in the data.

4 Calibration and UK Results

In this section I calibrate the baseline model to the experience of the UK between 1820-2010. The UK is chosen for three reasons. First, it was the earliest country to start the industrialization process and thus it captures the evolution of emission intensity over all stages of development. Second, the UK has excellent long-run data which do not exist for many other countries and which allow for more accurate parameter estimates. Finally, and perhaps most importantly, the UK has 'some of the smallest (carbon subsidies) in the OECD' and is one of the few countries for which *direct* estimates of gross subsidies exist (OECD, 2015). This last factor is especially important, as the calibration procedure requires as an input a directly estimated measure of net-subsidies for the baseline country. The calibrated model will serve as a reference that will allow me to derive the quantitative role that a variety of wedges play in driving cross-country differences in emission-intensities. All data sources and their construction are described in Appendix 11.1.

Calibration The exercise I perform is similar to Solow (1956) who measures technological residuals with production functions. The productivity in agricultural sectors is measured as:

$$B_{eAt} = \frac{E_{At}}{L^e_{At}} \text{ and } B_{At} = \frac{Y_{At}}{{L^y_{At}}^{\alpha_A} {E_{At}}^{1-\alpha_A}}. \tag{14}$$

In non-agriculture, the productivity in the energy sector and the impurity of emissions is measured as:

$$B_{eCt} = \frac{E_{Ct}}{L^e_{Ct}} \text{ and } \eta_{Ct} = \frac{P_{Ct}}{E_{Ct}}. \tag{15}$$

[24] Notice, the condition on elasticity will be tighter than $\sigma < 1$ if and only if $g_{eC} > g_{lC}$. If labor productivity in the modern energy sector does not grow 'too quickly' (i.e. $g_{eC} \leq g_{lC}$), then $\sigma < 1$ and $\frac{g_E g_{eC}}{g_{lC}} > 1$ are sufficient conditions for a declining non-agricultural intensity.

[25] In fact, if d_t and N_{Ct} are replaced by their first-order linear approximations, the resulting product will be a hump-shaped, quadratic parabola so that aggregate emission intensity is hump shaped to a first approximation.

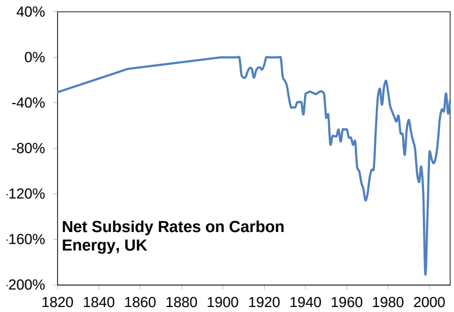


Figure 3: Directly measured net-subsidy rates for carbon in the UK, 1820-2010. For construction details see Appendix 11.1.

The setting for non-agricultural output production is more complex than in Solow (1956) and as such I follow the methodology suggested by Hassler et al. (2012). I assume perfect competition in the input markets so that marginal products equal factor prices. Then, labor's and energy's (after-subsidy) shares of income are respectively given by:

$$s_{Ct}^{l} \equiv \frac{\partial Y_{Ct}}{\partial L_{Ct}^{y}} \frac{L_{Ct}^{y}}{Y_{Ct}} = \alpha_C \left(\frac{B_{lCt} L_{Ct}^{y}}{Y_{Ct}} \right)^{\frac{\sigma-1}{\sigma}} \text{ and } s_{Ct}^{e} \equiv \frac{\partial Y_{Ct}}{\partial E_{Ct}} \frac{E_{Ct}}{Y_{Ct}} = (1-\alpha_C) \left(\frac{B_{Et} E_{Ct}}{Y_{Ct}} \right)^{\frac{\sigma-1}{\sigma}}. \quad (16)$$

Notice that in the above $s_{Ct}^{l} + s_{Ct}^{e} = 1$. These equations can then be re-arranged to obtain:

$$B_{lCt} = \frac{Y_{Ct}}{L_{Ct}^{y}} \left(\frac{s_{Ct}^{l}}{\alpha_C} \right)^{\frac{\sigma}{\sigma-1}} \text{ and } B_{Et} = \frac{Y_{Ct}}{E_{Ct}} \left(\frac{s_{Ct}^{e}}{1-\alpha_C} \right)^{\frac{\sigma}{\sigma-1}}. \quad (17)$$

Thus, given values for Y_{At}, E_{At}, L_{At}^{e}, L_{At}^{y}, Y_{Ct}, E_{Ct}, P_{Ct}, L_{Ct}^{e}, L_{Ct}^{y}, E_{Ct}, s_{Ct}^{e} as well as parameter values for σ, α_C and α_A, I can measure the evolution of all productivity terms using equations (14), (15) and (17) - like Solow (1956) or Hassler et al. (2012). However, unlike these papers, my focus on more disaggregated as well as historical data gives rise to two additional challenges. First, in general, I do not have data on employment in the energy and non-energy sub-sector, i.e. $L_{At}^{e}, L_{At}^{y}, L_{Ct}^{e}, L_{Ct}^{y}$. Second, the existing (constant-price) sectoral value-added data potentially suffers from a number of measurement issues.

To address the first problem, I continue to rely on the assumption of perfect competition in input markets. Since wage-to-energy price ratios are equalized across sub-sectors, equations (8) and (9) hold. Using these relationships and the non-agricultural energy production function, I can write:

$$s_{Ct}^{e} \equiv \frac{\partial Y_{Ct}}{\partial E_{Ct}} \frac{E_{Ct}}{Y_{Ct}} = \frac{1}{1 + \frac{x_{Ct}}{(1-\tau_t)}}. \quad (18)$$

Re-arranging I obtain:

$$x_{Ct} = \frac{s_{Ct}^{l}}{s_{Ct}^{e}} (1-\tau_t). \quad (19)$$

The above in conjunction with equations (8) and (9), implies the following relationships between sectoral and sub-sectoral employment:

$$L_{At}^{e} = (1-\alpha_A) L_{At} \text{ and } L_{At}^{y} = \alpha_A L_{At}. \quad (20)$$

Parameter	Values	Ave. Gr. Rate	Target
B_{lC1990},B_{E1990}, L_{1990},E_{C1990}, P_{C1990}	1	-	Normalization
$\bar{a}$	1	-	Normalization
$1-\alpha_A$	0.08	-	Share of time spent gathering fuel wood
$1-\alpha_C$	0.06	-	Modern Energy Share in Non-Agr VA, 1990
σ	0.76	-	Berndt and Wood (1975) and Griffin and Gregory (1976)
$\{B_{At}\}_{t=1820}^{2010}$	$\{\cdot\}$	1.70%	Agriculture Empl. Share, t
$\{B_{lCt}\}_{t=1820}^{2010}$	$\{\cdot\}$	0.84%	GDP per capita, t
$\{B_{eAt}\}_{t=1820}^{2010}$	$\{\cdot\}$	1.40%	Trad. Energy Consumption, t
$\{B_{eCt}\}_{t=1820}^{2010}$	$\{\cdot\}$	1.28%	Fossil Energy Consumption, t
$\{B_{Et}\}_{t=1820}^{2010}$	$\{\cdot\}$	2.44%	Modern Energy Share in Non-Agr, t
$\{L_t\}_{t=1820}^{2010}$	$\{\cdot\}$	0.66%	Labor Force, t
$\{\eta_{Ct}\}_{t=1820}^{2010}$	$\{\cdot\}$	-0.12%	Emissions/Modern Energy, t
$\{\tau_t\}_{t=1820}^{2010}$	$\{\cdot\}$	-	IFS (2013), IEA, (BP, 2008), Mitchell (2011)

Table 1: Calibrated parameters

$$L_{Ct}^e = \left(\frac{s_{Ct}^e}{s_{Ct}^e + s_{Ct}^l(1-\tau_t)}\right) L_{Ct} \text{ and } L_{Ct}^y = \left(\frac{s_{Ct}^l(1-\tau_t)}{s_{Ct}^e + s_{Ct}^l(1-\tau_t)}\right) L_{Ct}. \tag{21}$$

Thus taking τ_t and L_{Ct} as given, I can infer employment in individual sub-sectors. Notice that estimates of net fossil-fuel subsidies for the UK, τ_t, are calculated *directly* in Appendix 11.1 by combining tax data from the IFS (2013), Bolton (2014) and Hausman (1987) with subsidy data from OECD (2015). Figure 3 shows the resulting estimates of net-subsidy rates in the UK. These are negative, as historically the UK has imposed large taxes on carbon energy (Parry and Small, 2005).

To address the second problem, I follow the approach of Duarte and Restuccia (2010). In particular, rather than using data on (potentially mismeasured) sectoral value-added, I take *aggregate* GDP data (where mismeasurement might be less of an issue) and use the model to infer implied sectoral value added, Y_{At} and Y_{Ct}. In particular given the simple preference structure specified in the model, agricultural value added is:

$$Y_{At} = \bar{a} L_t. \tag{22}$$

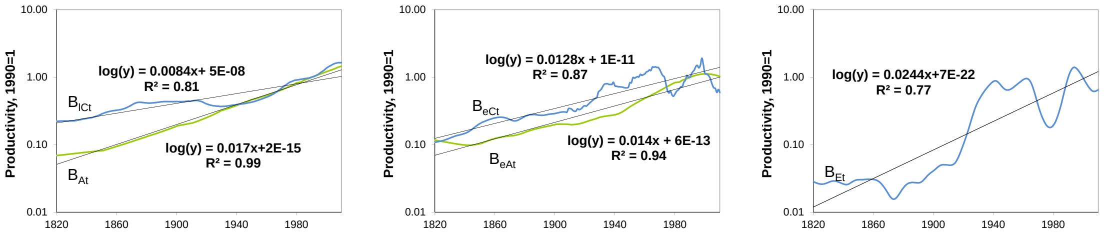
Since constant price GDP is defined as: $GDP_t \equiv p_{A1990} Y_{At} + p_{C1990} Y_{Ct}$, non-agricultural value-added is given by:[26]

$$Y_{Ct} = \frac{GDP_t - p_{A1990} Y_{At}}{p_{C1990}}. \tag{23}$$

All that then remains to be done is to choose parameters σ, α_C, α_A and $\bar{a}$.[27]

[26] Since the wage rate in the model is normalized to one in each period, I ensure that the implied level of GDP in the model and the data in 1990 match, by normalizing constant price GDP in the data in 1990 by the level of GDP in the model, $GDP_{1990}^{model} \equiv w_{1990}\left(L_{A1990} + \frac{(1+x_{C1990}-\tau_{1990})}{1+x_{C1990}} L_{C1990}\right)$.

[27] In the robustness section, I construct estimates of L_{Ct}^e and L_{Ct}^y using data on employment in the mining and utilities sector. I also construct historical estimates of Y_{At} and Y_{Ct}. I then proceed to calibrate the model directly using this data. I find that the estimated productivity growth rates are quantitatively and qualitatively similar to the ones I present below as are the subsequent results regarding subsidies. However, as I discuss in sections 8 and 9, this long run data has several drawbacks which influences its quality and hence I choose to remain with the baseline calibration.



(a) TFP in agriculture and labor productivity in non-agriculture

(b) Labor productivity in energy sectors

(c) Energy productivity in non-agriculture

Figure 4: Productivity implied by the model in the UK, 1820-2010.

I set $\alpha_A = 0.92$ to match the proportion of time that traditional agricultural households devote to gathering fuel wood. Since I lack historical time-use data for the UK, I match this parameter to data from a traditional agricultural economy that I do have data on - Nepal. The results are robust to changes in this parameter.

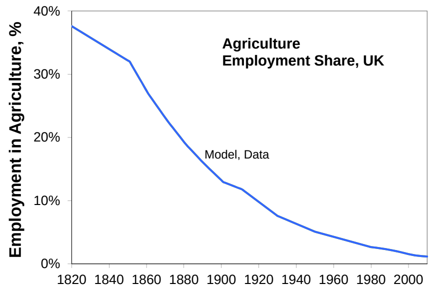
I set the elasticity of substitution between labor and energy in non-agriculture to be $\sigma = 0.76$. This is chosen to lie in the mid-range of values usually estimated for Allen partial elasticities between energy and labor in industry. Berndt and Wood (1975) estimate this elasticity in US manufacturing to be 0.65. Griffin and Gregory (1976) estimate this elasticity for numerous advanced European countries and the US to be between 0.72 and 0.87. Stefanski (2014b) estimates the elasticity of substitution between oil and non-oil inputs in the non-agricultural sector to be between 0.72 and 0.75. Kemfert (1998) as well as Kemfert and Welsch (2000) estimate this elasticity for Germany to be 0.871. I show robustness to changes in σ in section 8.

Next, I normalize $B_{lC1990} = B_{E1990} = 1$, and take the ratio of the equations in (17) for the year $t = 1990$. Solving this for α_C I obtain:

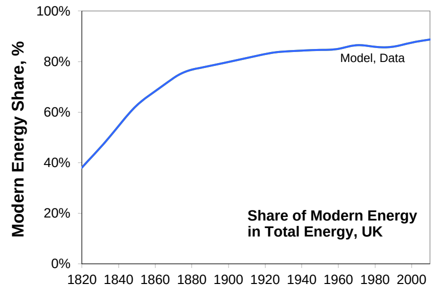
$$\alpha_C = 1 - \left(1 + \left(\frac{L^y_{C1990}}{E_{C1990}}\right)^{\frac{1-\sigma}{\sigma}} \frac{slc_{1990}}{sec_{1990}}\right)^{-1}. \tag{24}$$

Given the above parameter values, 1990 sectoral prices come from equation (11) and the fact that $B_{lC1990} = B_{E1990} = 1$. Finally, I normalize $\bar{a} = 1$ as well as $L_{1990} = E_{C1990} = P_{C1990} = 1$.

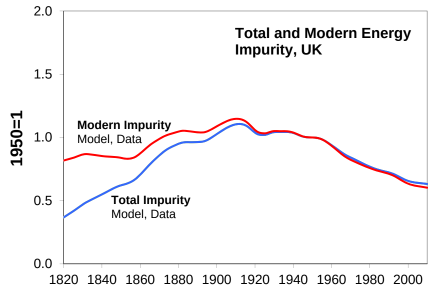
Table 1 summarizes the calibrated parameters and Figure 4 shows the evolution of implied productivity terms. Agricultural TFP grew at an average 1.7% per year over the the entire period. Labor-specific productivity in non-agriculture grew by 0.84% a year: approximately at 0.5% pre-WWII and at 2.3% post-WWII. Labor productivity growth rates implied in the energy sectors were approximately 1.4% in the traditional energy sector and 1.3% in the modern energy sector over the entire period. Modern energy-specific productivity grew on average by 2.4% a year. It was relatively flat until the last decade of the 19$^{\text{th}}$ century, after which it started growing slowly and then picked up significantly in the inter-war period (1919-1939). This then followed a time of stagnation and collapse in modern energy specific productivity until 1978, after which we saw productivity rising once more.



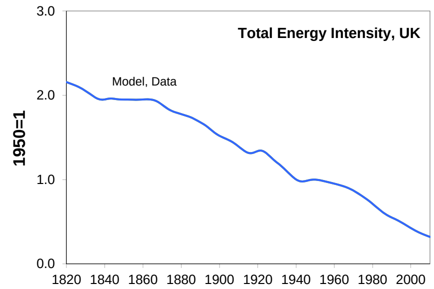
(a) UK Agricultural Employment Share.



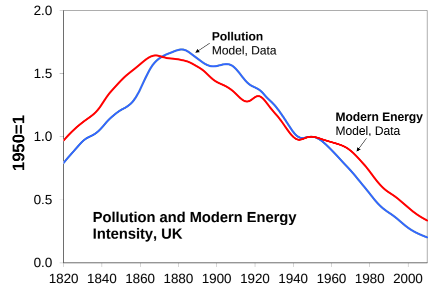
(b) UK Modern Energy Share.



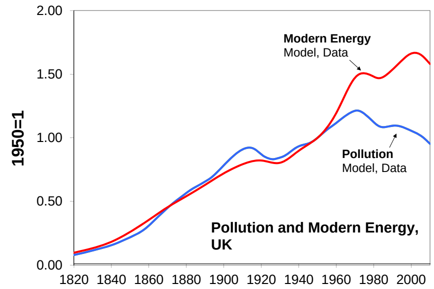
(c) Modern and Total Energy Impurity.



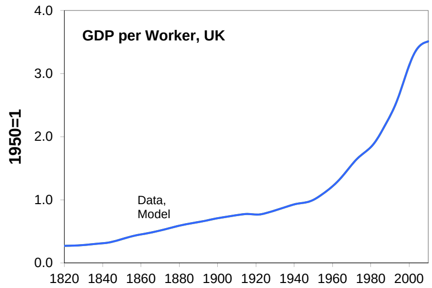
(d) UK Total Energy Intensity.



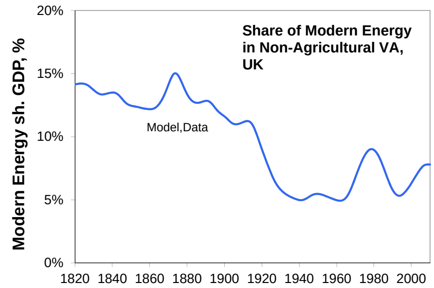
(e) UK CO_2 Emission Intensity.



(f) Total Emissions.

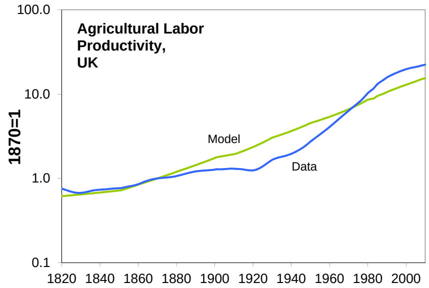


(g) GDP per Capita.

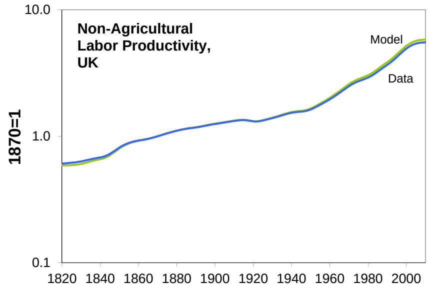


(h) Share of Modern Energy in Non-Agr VA.

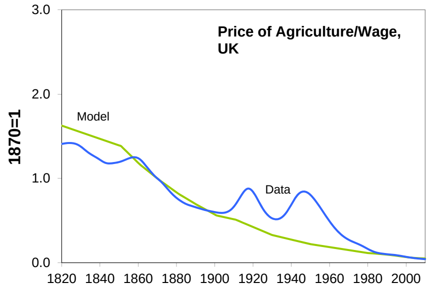
Figure 5: Simulations and data for UK, 1820-2010.



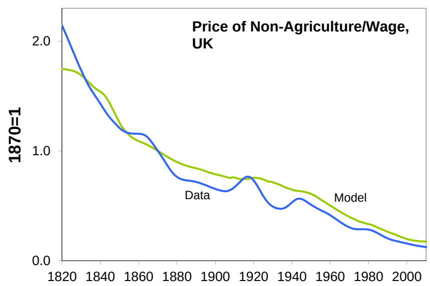
(a) Agricultural labor productivity.



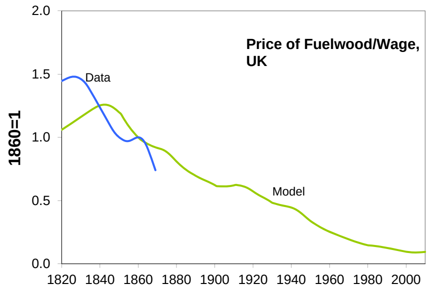
(b) Non-Agricultural labor productivity.



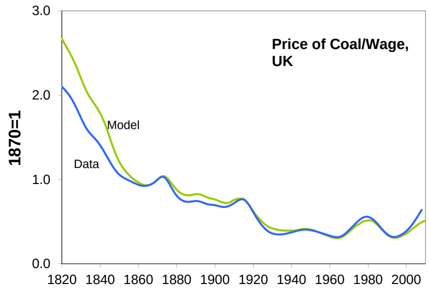
(c) Price of agriculture relative to the wage.



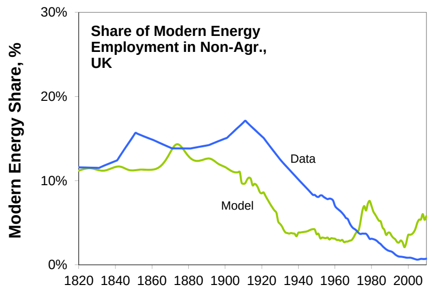
(d) Price of non-agriculture relative to the wage.



(e) Price of fuelwood relative to the wage.



(f) Price of coal relative to the wage rate.



(g) Modern energy employment share in non-agriculture.

Figure 6: Simulations and data for UK - not directly calibrated moments, 1820-2010.

UK Results Taking as given the above parameters, net-subsidies and sequences of productivities, the model (by construction) replicates a number of features of the UK economy shown in Figure 5. Increasing productivity in agriculture results in fewer workers being needed to produce the subsistence level of food and the subsequent reallocation of workers to non-agriculture (Figure 5(a)). As workers move to the sector that uses modern-fuels, the share of modern energy consumption rises (Figure 5(b)) and consequently so does total energy impurity (Figure 5(c)). At the same time, the low elasticity of substitution between energy and non-energy inputs in the non-agricultural sector, $\sigma < 1$, coupled with higher energy productivity causes a falling proportion of non-agricultural value added to be spent on modern energy (Figure 5(h)) and a declining energy intensity (Figure 5(d)). Finally, Figure 5(e) shows the resulting hump-shaped emission intensity curve. Notice that the difference between the modern energy intensity curve and the pollution intensity curve in the figure comes entirely from the exogenously changing impurity of modern energy (Figure 5(c)). The two curves follow a similar path, which indicates that the key driver of the hump shaped emission intensity is the change in the composition of total energy from traditional to fossil-fuels, rather than the change in the composition of modern energy itself. The remaining graphs in Figure 5 shows the result for emissions, modern energy use and GDP per worker.

The model also does relatively well in replicating features of the data to which it has *not* been directly calibrated as shown in Figure 6. In particular, Figure 6(a) and 6(b) show the constant price sectoral value added per worker in each sector (evaluated in 1990 prices). Recall that productivities were inferred using the structure of the model and aggregate GDP. The fact that implied labor productivities do not differ too much from observed labor productivities reinforces the assumption that the model is well specified. Figures 6(c)-6(f) show the evolution of prices of agriculture, non-agriculture, traditional energy and fossil-fuel energy relative to wages in the UK both the model economy and the data. The model does very well in matching the decline in prices. In section 3, I showed that model prices are determined by sectoral productivity terms. Since I use the model to extract productivity from the data, the fact that model-implied and observed prices match up well, provides further evidence of the validity of the mechanism presented in the model. Finally, Figure 6(g) shows the employment share of modern energy in non-agriculture in the model and the data.[28] Despite the data being less volatile, both series predict that pre-1900 employment share was largely flat or slightly increasing, followed by a decline in employment in modern energy. This highlights the validity of the substitution mechanism driving falling emission intensity.

5 The Role of Wedges

Next, I show how the model can be used as a lens with which to examine cross-country differences in intensities. I assume that each country is a version of the above, calibrated model but differs by a series of country- and year-specific *wedges*. A wedge is a distortion that in the model looks like a productivity shock or a subsidy/tax. However, as in Chari et al. (2007), Duarte and Restuccia

[28] The comparison is a difficult one, as the closest appropriate data is employment in mining and utilities. This however, includes workers in non-energy mining and non-energy utilities, and excludes various other parts of the economy involved in energy production - such as transportation, sales and storage - for which no long-run data exist. Furthermore, much of the early data has to be interpolated.

(2010) or Gollin et al. (2002), wedges are *catchalls* for all differences between countries in terms of development, taxation, regulation, property rights, institutions, climate, geography, mineral endowments and so on. In the framework of the model, *any* deviation in a country's emission intensity from that of the baseline arises from one of three wedges: 1) a wedge to agricultural productivity, 2) a wedge to non-agricultural productivity and a 3) subsidy-like wedge to fossil-fuel prices. Importantly, the existence of these wedges means that countries will *not* necessarily follow identical paths of emission-intensities.[29] After a suitable calibration, the model can be used to identify *which* wedges drive a country's deviation from the baseline emission intensity and - in particular - to quantify the role that subsidy-like energy-price wedges play in this deviation.

Defining Wedges I introduce country-i-specific wedges to agricultural productivity (D^i_{At}), to non-agricultural productivity (D^i_{Ct}) and to modern energy prices ($\bar{\tau}^i_t$). The overall productivity of each sector j, in each country, i, B^i_{jt}, is the product of baseline (UK) productivity, B_{jt}, and the country-i-specific sectoral wedge. Thus I can write $B^i_{jt} = D^i_{At}B_{jt}$ for sectors $j = A, eA$ and $B^i_{jt} = D^i_{Ct}B_{jt}$ for sectors $j = lC, E, eC$.[30] The energy price wedge in country i is the sum of the baseline (UK) energy price wedge, τ_t, and the country-i-specific price-wedge $\bar{\tau}^i_t$: $\tau^i_t = \bar{\tau}^i_t + \tau_t$. Next, I examine how these wedges impact emission intensity. Whilst, in general, the effects of wedges on emission intensity are non-monotonic, Proposition 3 shows that the impact of wedges on the two *components* of emission intensity discussed in the previous section is monotonic.

Proposition 3. *Suppose $L_{At} < L_t$ and $\sigma < 1$ then for given time t: 1) $\frac{\partial d_t}{\partial D^i_{At}} > 0$ and $\frac{\partial N_{Ct}}{\partial D^i_{At}} = 0$; 2) $\frac{\partial d_t}{\partial D^i_{Ct}} > 0$ and $\frac{\partial N_{Ct}}{\partial D^i_{Ct}} < 0$; and 3) $\frac{\partial d_t}{\partial \bar{\tau}^i_t} < 0$ and $\frac{\partial N_{Ct}}{\partial \bar{\tau}^i_t} > 0$.*

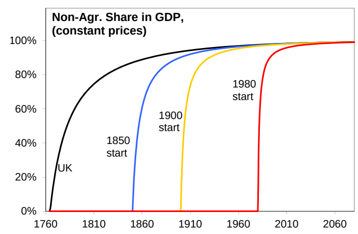
I discuss the implications of this theorem using an illustrative numerical example below for each of its three parts. To aid exposition in the next three paragraphs, I impose Assumption 1, set parameters to those of Table 1, and assume that sectoral productivities grow at their average rates.

Agricultural Wedges (Counterfactual 1) First, I examine the impact of agricultural productivity wedges on emission intensity. I set $D^i_{At} = 0.26; 0.12; 0.034$ to generate industrializations that start in 1850, 1900 and 1980. This last wedge is chosen to roughly match agricultural employment share in China in 2010. In Figures 7(a)-(c), I show the effect of these different wedges on the constant price share of non-agriculture in GDP, non-agricultural emission intensity and total emission intensity.[31] From part 1 of Proposition 3, lower agricultural productivity translates into a lower proportion of non-agriculture in GDP but an unchanged intensity of non-agriculture. Thus, lower agricultural productivity delays the start of industrialization as more workers are needed to satisfy the subsistence requirements. However, since non-agricultural emission intensity is declining over

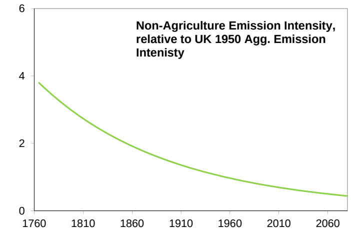
[29] For example, poor quality agricultural land in a country will be captured by a permanent wedge to agricultural productivity giving rise to permanently lower agricultural productivity and a different path of emission intensity relative to a country with high quality land.

[30] I thus assume that sectoral wedges are common across sub-sectors. This is largely done for simplicity, as there does not seem to be a clear and comprehensive way of disentangling sub-sector specific wedges. However, this assumption may potentially introduce some bias in the estimates of the subsidies. In the robustness section, I allow the possibility of different distortions across sub-sectors and show that this does not quantitatively change the results.

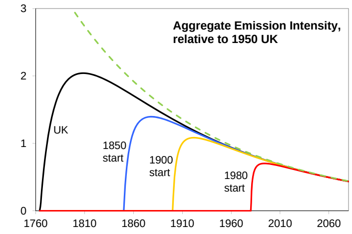
[31] All of these are computed using 1990 UK prices.



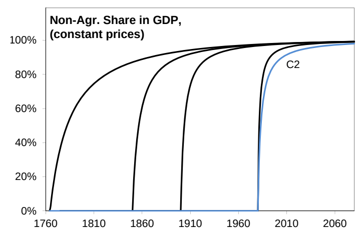
(a) **Counterfactual 1 (C1):** Each line shows the share of non-agriculture in GDP (measured in 1990 UK prices) for the UK and countries starting industrialization in 1850, 1900 and 1980.



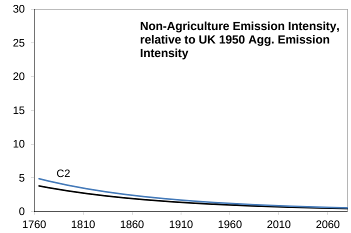
(b) **Counterfactual 1 (C1):** The non-agriculture emission intensity (relative to 1950 UK aggregate emission intensity) for the UK and countries starting industrialization in 1850, 1900 and 1980. Changing the start date of industrialization has no impact on this measure.



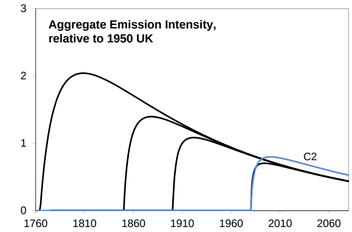
(c) **Counterfactual 1 (C1):** The aggregate emission intensities (relative to 1950 UK) for the UK and countries starting industrialization in 1850, 1900 and 1980. The dashed line is the non-agriculture emission intensity from Figure 7(b). Aggregate intensity tends to approach the (common) non-agriculture intensity, generating an 'envelope-pattern'.



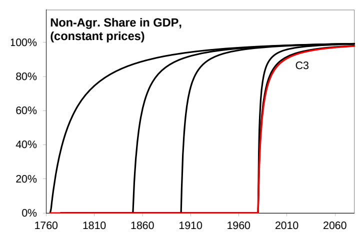
(d) **Counterfactual 2 (C2):** Share of non-agriculture in GDP (measured in 1990 UK prices). The blue line shows a country starting industrialization in 1980 with a wedge in non-agriculture. The black lines reproduce counterfactual 1 (C1) from Figure 7(a) for comparison.



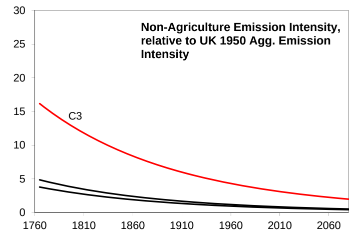
(e) **Counterfactual 2 (C2):** Non-agriculture emission intensity (relative to 1950 UK aggregate emission intensity). The blue line shows a country starting industrialization in 1980 with a wedge in non-agriculture. The black lines reproduce counterfactual 1 (C1) from Figure 7(b) for comparison.



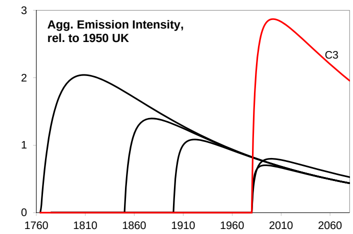
(f) **Counterfactual 2 (C2):** Aggregate emission intensity (relative to 1950 UK). The blue line shows a country starting industrialization in 1980 with a wedge in non-agriculture. The black lines reproduce counterfactual 1 (C1) from Figure 7(c) for comparison.



(g) **Counterfactual 3 (C3):** Share of non-agriculture in GDP (measured in 1990 UK prices). The red line shows a country starting industrialization in 1980 with a wedge in non-agriculture and a positive energy price wedge. The black lines reproduce counterfactuals 1 and 2 (C1, C2) from Figures 7(a) and 7(d) for comparison.



(h) **Counterfactual 3 (C3):** Non-agriculture emission intensity (relative to 1950 UK aggregate emission intensity). The red line shows a country starting industrialization in 1980 with a wedge in non-agriculture and a positive energy price wedge. The black lines reproduce counterfactuals 1 and 2 (C1, C2) from Figures 7(b) and 7(e) for comparison.



(i) **Counterfactual 3 (C3):** Aggregate emission intensity (relative to 1950 UK). The red line shows a country starting industrialization in 1980 with a wedge in non-agriculture and a positive energy price wedge. The black lines reproduce counterfactuals 1 and 2 (C1, C2) from Figures 7(c) and 7(f) for comparison.

Figure 7: Counterfactuals examining the impact of wedges on emission intensity.

time - countries industrializing later move to a less energy and emission intensive non-agricultural sector. This effect can be interpreted as 'catching-up' to the technological frontier and means that countries industrializing later, will tend to form an *envelope pattern* in emission intensities relative to earlier industrializers, as demonstrated in Figure 7(c).

Non-agricultural Wedges (Counterfactual 2) Second, I examine the effect of non-agricultural wedges on emission intensity. I keep $D^i_{At} = 0.034$ and additionally I set $D^i_{Ct} = 0.49$ to roughly match the GDP per worker of China in 2010. The results of this are shown in Figures 7(d)-(f). From part 2 of the theorem, a wedge to non-agricultural productivity results in a lower share of non-agriculture in GDP and a higher non-agricultural pollution intensity. Intuitively, lower productivity in non-agriculture translates to less non-agricultural output being produced and hence a lower share of it in total output. The wedge also results in a composition of the non-agricultural sector that resembles one of the past - when more workers were employed in non-agricultural energy production and the non-agricultural sector used more energy. This translates to a higher emission intensity. Since the two effects go in opposite directions, the final impact on total emission intensity is ambiguous and depends on parameters. In this case, aggregate emission intensity is initially lower and then higher (relative to the case without the wedge) as first the size and then the intensity effects dominate.

Energy Price Wedges (Counterfactual 3) Third, I demonstrate the impact of modern energy price wedges on emission intensity. I continue to examine the economy with $D^i_{At} = 0.034$ and $D^i_{Ct} = 0.49$ but I additionally assume that non-agricultural final good producers also benefit from an energy price wedge of $\bar{\tau}^i_t = 0.84$. This last wedge is chosen to roughly reproduce the emission intensity of China in 2010. The results are shown in Figures 7(g)-(i). As part 3 of the theorem implies, the subsidy is distortive and lowers non-agricultural output and hence the share of non-agriculture in GDP. However a higher $\bar{\tau}^i_t$ also makes the energy sector more attractive to workers, resulting in higher production of modern energy and higher emissions. The impact of the wedge on emission intensity is again ambiguous. However, due to the relatively small weight of modern energy in output, the distortion to GDP is small whilst the impact on emission intensity is large. Hence, as seen in Figure 7(i), aggregate emission intensity tends to rise with energy subsidies.

Pollution Accounting In the above I showed examples of how individual wedges drive emission intensity. Next, I use the calibrated model to extract a series of country- and year-specific wedges that together account for all cross-country variation in emission intensity for a 170 countries for 1980-2010. This accounting exercise allows me to disentangle the sources of variation in emission intensity across countries and to quantify the importance of each wedge in driving this variation.

I take each country, i, in each period, t, to be a closed economy. I assume that countries differ from the calibrated baseline only with respect to their labor force and the three previously defined wedges. I choose each wedge to match an observable feature of a particular economy in each period. Since agricultural productivity influences the size of agricultural employment in a country, I set the *agricultural productivity* wedge, D^i_{At}, to match country i's agricultural employment share at time t. I choose the *non-agricultural productivity* wedge, D^i_{Ct}, to match the ratio of GDP-per-worker between

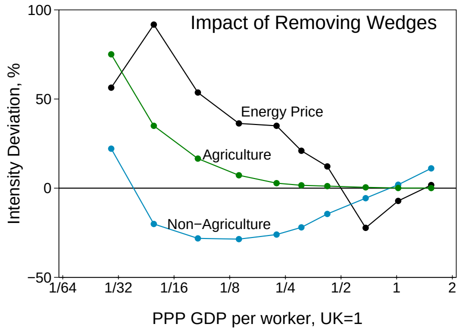


Figure 8: The impact of removing wedges on emission intensity at different income levels. Each line describes the percent by which emission intensity changes after removing a particular wedge at each income level.

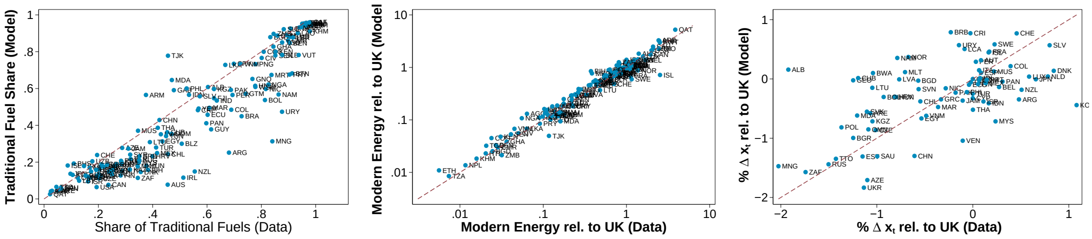
country i and the UK. In this way, I control for any remaining aggregate productivity differences across countries not accounted for by differences in agricultural productivity. Finally, I choose a *fossil-fuel subsidy* wedge, $\bar{\tau}_t^i$, to match the ratio between emission intensity of country i and the UK. Since this wedge influences the total modern energy produced in a country, it allows me to capture any remaining cross-country differences in emission intensity not captured by the other two wedges. The model thus reproduces cross-country differences in GDP-per-worker, agricultural employment shares and carbon emission-intensities and hence also total carbon emissions.[32]

Finally, I quantify the importance that individual wedges play in driving emission intensity differences across countries. I 'turn-off' wedges one at a time, first setting $\bar{\tau}_t^i = 0$, then $D_{At}^i = 1$ and finally $D_{Ct}^i = 1$ and examine how the removal of each wedge individually impacts emission intensities across countries. Since wedges have different effects at different stages of development, I present the results for different income levels in Figure 8. To do this, I sort the pooled data by GDP-per-worker (normalized by the UK's GDP-per-worker in each year) and sub-divide the data into ten income groups. Finally, for each income group I plot the average impact that the removal of a particular wedge will have on emission intensity relative to observed intensity.

Agricultural wedges have the largest impact on emission intensity in the lowest income countries. Removing agricultural wedges in these countries increases emission intensity - on average - by 75%. Without agricultural wedges, the structure of poor countries shifts from being dominated by clean agriculture to dirty non-agriculture and hence emission intensities rise. The impact of this wedge declines with income, as the size of the agricultural sector shrinks. Thus, when incomes reach approximately 20% and 50% of UK income respectively, the removal of the wedge only increases intensity by 5% and (less than) 1% respectively. This is consistent with the story of industrialization-driven changes in fuel mix and subsequently rising energy impurity.

The effects of non-agricultural wedges are non-monotonic as observed in section 5. In countries with the lowest incomes, removing non-agricultural wedges results in an emission intensity that rises by 22%. This is because the increase in the size of non-agriculture after wedges are removed outweighs the decline in non-agricultural emission intensity associated with higher non-agricultural productivity. For the second to eighth deciles of income, removing non-agricultural wedges results

[32] See Appendix 11.1 for all data sources.



(a) Traditional fuel share, model versus data (2000).

(b) Modern Energy consumption, model versus data (2000).

(c) Modern energy employment share, model versus data (2000).

Figure 9: Model Fit. See Appendix 11.1 for data sources.

in a decline of emission intensity of - on average - 21%. In this case, lower non-agricultural emission intensity will outweigh the increasing size of non-agriculture. For the highest decile removing non-agricultural wedges results in emission intensity that increases by approximately 10%. The story is the same as for deciles 2-8 - but in reverse. Removing wedges lowers productivity since the richest countries have higher non-agricultural productivity than the UK. This results in an increase in non-agricultural emission intensity that is larger than the decline in the size of non-agriculture - economies revert back to a 'less-developed' state and intensity rises.

Finally, the figure also depicts the impact of removing energy price wedges. Notice that in general the effects are positive. This implies that - on average - countries at most income groups tend to implicitly *tax* fossil-fuel energy. At the lowest income decile, removing subsidy wedges would result in emissions that increase by 56%. In the highest income countries, removing energy price wedges increases intensity by approximately 1.7%.[33]

Quantitatively, agricultural and energy price wedges dominate the variation in emission intensities in low income countries - accounting for 39% and 49% of deviations respectively. In high income countries it is the non-agricultural wedges and energy price wedges that dominate - accounting for 23% and 77% of deviations respectively. Notice also that the importance of all wedges declines with income. This is consistent with the envelope-pattern in emission intensity. Finally, whilst agricultural and non-agricultural wedges play a large role, energy wedges are very important in accounting for a large amount of cross-country variation in emission intensities. Thus to understand the observed patterns of carbon emissions across countries, it is crucial to take into account differences in carbon energy price wedges across countries.

International Results Finally, having extracted wedges and determined their role in driving emission intensity, I now demonstrate how well the model does in matching cross-country data to which it has not been specifically calibrated given the above wedges. First, Figure 9(a) plots the share of traditional fuels in total energy consumption whilst Figure 9(b) plots the quantity of modern energy consumed by each country (relative to the UK) in the data and the model for the year 2000.[34] Both Figures include a 45 degree line for easier comparison. The model does

[33] Of course, whilst most countries tax fossil-fuels, I focus on the subsidizing countries.

[34] The year 2000 is chosen, since it is the only year for which data exists on traditional fuel consumption that is comparable to the data used to calibrate the UK model. See appendix 11.1 for details.

	Model			
	log(pa/w)	log(pc/w)	log(pa/w)	log(pc/w)
Data	0.66***	0.87***	0.40***	1.11***
	(0.02)	(0.01)	(0.01)	(0.02)
Obs.	682	682	4,131	4,131
R^2	0.72	0.87	0.34	0.72
Country FE	yes	yes	yes	yes
Sample	OECD	OECD	All	All

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

Table 2: Relative prices in model and data. Regressions compare the log of agricultural and non-agricultural price-to-wage ratios in the model and the data. Since the data is in the form of indices, a country-fixed effect is included to only capture changes over time. Results are shown for OECD countries (columns 1 and 2) and the entire sample (columns 3 and 4).

extremely well in predicting both energy shares and quantities consumed across countries. This provides further evidence that structural transformation is an important mechanism for generating cross-country variation in observed fuel-mix and that the model captures the important features generating differences in cross-country energy demand. Figure 9(c) then plots the percent deviation of ratio of output to modern-energy employment in a country (i.e. $L^y_{Ct}/L^e_{Ct} \equiv x_{Ct}$) from that of the UK in 2000.[35] Whilst there is now less available data, the model does well in predicting employment in the modern energy sector. This indicates that the model captures the key mechanism generating the reallocation of labor from energy to non-energy sectors across countries.

Next, I compare the predictions of the model with respect to prices. In Appendix 11.1, I construct a panel of agriculture and non-agriculture price-to-wage indices for each country for 1980-2010. Table 2 presents regressions comparing the log of agricultural and non-agricultural price-to-wage ratios in the model and the data. Since the data is in the form of indices, I include a country-fixed effect to only capture changes over time. Results are shown for OECD countries and the entire sample. The model does very well in capturing the evolution of prices, especially in the OECD, which provides further external validity for the mechanism of the model.

6 Comparisons with other Measures

In this section I examine how the above energy-price wedge estimates relate to subsidies calculated using the price-gap approach and the direct approach. In particular, I construct a detailed model - similar to the baseline - but with a number of additional policy distortions. I then show how these distortions map into the energy price wedge in the baseline model. Next, I use the price-gap and direct approaches to construct measures of subsidies in the detailed model and compare these with the subsidies obtained using my methodology. I find that the price-gap approach misses indirect subsidies that are not reflected in the price of energy. The direct approach can potentially captures the same policies as the baseline wedge but not the way it is most often constructed in the literature.

[35] Here I take modern energy employment to consist of employment in mining and utilities. As was emphasized before, this is not an ideal measure - but it is the best that can be done.

Finally, I compare subsidy predictions from my model with price-gap subsidy estimates from the data. This provides a further test of the model and points to countries where indirect policies not captured by the price-gap approach may be more prevalent.

Detailed Model Consider a model similar to the baseline but with additional government policies. Denote all prices, allocations and productivities of this 'detailed economy' with a hat-symbol over the corresponding variable. Suppose also that the consumer problem is identical to the baseline problem but that utility is now given by: $V(\hat{a}_t, \hat{c}_t, \hat{P}_{Ct}) \equiv U(\hat{a}_t, \hat{c}_t) - v(\hat{P}_{Ct})$ where U is as before and $v(\cdot)$ captures all potential negative effects associated with emissions so that $v'(\hat{P}_{Ct}) > 0$. Suppose the agricultural sector remains the same, but that firms in non-agriculture now face subsidy wedges to labor, $\hat{\tau}^L_{Ct}$, and to energy, $\hat{\tau}^E_{Ct}$ such that the non-agricultural firm's problem is:

$$\max_{\hat{L}^y_{Ct}, \hat{E}_{Ct}} \hat{p}^C_t \hat{Y}_{Ct} - \hat{w}_t(1-\hat{\tau}^L_{Ct})\hat{L}^y_{Ct} - \hat{p}^e_{Ct}(1-\hat{\tau}^E_{Ct})\hat{E}_{Ct}, \tag{25}$$

where, $\hat{Y}_{Ct} = (\alpha_C(\hat{B}_{lCt}\hat{L}^y_{Ct})^{\frac{\sigma-1}{\sigma}} + (1-\alpha_C)(\hat{B}_{Et}\hat{E}_{Ct})^{\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}}$. In the modern energy sector, suppose there are subsidy wedges to labor, $\hat{\tau}^L_{Et}$, and to the price of energy, $\hat{\tau}_{Et}$ such that the modern energy firm's problem is:

$$\max_{\hat{L}^e_{Ct}} \hat{p}_{eCt}(1+\hat{\tau}_{Et})\hat{E}_{Ct} - \hat{w}_t(1-\hat{\tau}^L_{Et})\hat{L}^e_{Et}, \tag{26}$$

where, $\hat{E}_{Ct} = \hat{B}_{eCt}\hat{L}^e_{Ct}$. As before, assume the government budget constraint balances period by period:

$$\hat{w}_t\hat{\tau}^L_{Ct}\hat{L}^y_{Ct} + \hat{p}^e_{Ct}\hat{\tau}^E_{Ct}\hat{E}_{Ct} + \hat{w}_t\hat{\tau}^L_{Et}\hat{L}^e_{Et} + \hat{p}_{eCt}\hat{\tau}_{Et}\hat{E}_{Ct} = \hat{T}_t. \tag{27}$$

A tax-distorted competitive equilibrium can be defined as before and the following proposition holds.

Proposition 4. *Given a vector of productivities, $\{\hat{B}_{At}, \hat{B}_{eAt}, \hat{B}_{lCt}, \hat{B}_{Et}, \hat{B}_{eCt}\}$ and government policies, $\{\hat{\tau}^L_{Ct}, \hat{\tau}^E_{Ct}, \hat{\tau}^L_{Et}, \hat{\tau}_{Et}\}$ at time t, the equilibrium allocations from the detailed economy are identical to those in the baseline economy if productivities in both economies are identical (i.e. $B_{At} = \hat{B}_{At}$ etc.) and the energy-price wedge in the baseline economy, τ_t, satisfies the following relationship:*

$$\tau_t = 1 - \frac{(1-\hat{\tau}^L_{Et})(1-\hat{\tau}^E_{Ct})}{(1+\hat{\tau}_{Et})(1-\hat{\tau}^L_{Ct})}. \tag{28}$$

This proposition, proven in Appendix 11.3, demonstrates that the energy-price wedge in the baseline economy captures a range of government policies in the detailed economy that act to increase employment in the modern energy sector (via equation (9)) and hence to increase modern energy use and carbon emissions. Notice that this mapping is *entirely* independent of whether policies are chosen optimally[36] and that the baseline wedge captures a variety of policies that are not necessarily targeted at fossil-fuel energy directly but nonetheless contribute to higher emissions. This emphasizes that a fossil-fuel subsidy in this paper is defined as *any* policy action by the government that results in an increase in fossil-fuel energy use and hence in carbon emissions. Next, I demonstrate how my measure of subsidies relates to price-gap and directly measured subsidies.

[36] Thus my measure of subsidies is tighter than the so-called 'post-tax subsidy' estimate used by the IMF (2013) since it does *not* consider the cost of potential externalities associated with fossil-fuel consumption.

The price-gap approach The price-gap approach compares the final price of energy paid by consumers or received by producers to a reference energy price, p^*_{eCt}. In this framework, subsidy rates for consumers and producers are respectively given by $\frac{p^*_{eCt}-\hat{p}^e_{Ct}(1-\hat{\tau}^E_{Ct})}{p^*_{eCt}}$ and $\frac{\hat{p}_{eCt}(1+\hat{\tau}_{Et})-p^*_{eCt}}{p^*_{eCt}}$. The reference price is usually taken to be the weighted average of international spot prices. Since there is only one country in the detailed model, the corresponding measure would be $p^*_{eCt} = \hat{p}_{eCt}$. As such, price-gap consumer and producer subsidies in the detailed model are $\hat{\tau}^E_{Ct}$ and $\hat{\tau}_{Et}$ respectively.[37]

Thus, for small enough subsidies, we can write total price-gap estimated subsidy rates using a Taylor approximation as $\hat{\tau}^E_{Ct} + \hat{\tau}_{Et} \approx 1 - \frac{(1-\hat{\tau}^E_{Ct})}{(1+\hat{\tau}_{Et})}$. Price-gap estimated rates thus differ from wedges found in the baseline model in equation (28). My methodology picks up additional policy distortions to non-energy inputs in non-agricultural sectors that influence fossil-fuel use and carbon emissions but are not directly reflected in the energy price. For example, I capture the impact of differing wage subsidy rates across sectors, subsidies to inputs in the modern energy sector or differences in the types of distortive taxation used to pay for energy subsidies.[38]

The direct approach Next, I turn to the direct-approach of calculating the the value of energy subsidies. This involves specifying which policies should be counted, choosing a pro-rate factor for individual policies and then tallying up the costs.[39] Whilst conceptually simple this turns out to be more complicated in practice. As shown in the above proposition, there are four policy instruments that map into the baseline energy wedge. Even assuming these policies are not pro-rated and that all information is available, this nonetheless gives rise to potentially $16(= 2^4)$ different fossil-fuel subsidies estimates depending on which policies I choose to count. A lack of consensus with respect to which policies constitute a fossil-fuel subsidy is a pertinent issue in the literature on directly measured fossil-fuel subsidies. Koplow and Dernbach (2001) examine values of (directly-measured) US fossil-fuel subsidies from 10 studies between 1933 and 1998. They find that subsidy estimates for the same years but from different sources varied by up to four orders of magnitude - between 200 million and 1.5 trillion (1990 PPP) USD a year - largely because of different choices regarding which policies to include. In Appendix 11.2, I perform a similar exercise for the US for more recent data and find that subsidy estimates varied by nearly three orders of magnitude in a given year. A disaggregation of these subsidies by target sector highlights that the main source of this deviation were differences across studies with respect to which policies were counted as fossil-fuel subsidies.

This paper defines subsidies as policies that increase fossil-fuel use and carbon emissions. In the context of the above detailed model, this includes the cost of providing subsidies to producers $(\hat{p}_{eCt}\hat{\tau}_{Et}\hat{E}_{Ct})$, to consumers $(\hat{p}^e_{Ct}\hat{\tau}^E_{Ct}\hat{E}_{Ct})$ and to workers in the modern-energy sector $(\hat{w}_t\hat{\tau}^L_{Et}\hat{L}^e_{Et})$.

[37] The equilibrium price of energy in the detailed economy, normalizing $w_t = 1$, is $\hat{p}_{eCt} = (1-\hat{\tau}^L_{Et})/((1+\hat{\tau}_{Et})\hat{B}_{eCt})$. It could thus be argued that the 'correct' reference price should be the undistorted price, $p^*_{eCt} = 1/\hat{B}_{eCt}$, which would imply consumer subsidy rates of $1-(1-\hat{\tau}^L_{Et})(1-\hat{\tau}^E_{Ct})/(1+\hat{\tau}_{Et})$ and producer subsidy rates of $-\hat{\tau}^L_{Et}$. Using a Taylor approximation we can show that $1-(1-\hat{\tau}^L_{Et})(1-\hat{\tau}^E_{Ct})/(1+\hat{\tau}_{Et}) - \hat{\tau}^L_{Et} \approx \hat{\tau}^E_{Ct} + \hat{\tau}_{Et}$ for small enough distortions. Thus, both reference prices yield similar energy subsidy rates.

[38] For example, consider two countries with identical consumer and producer energy subsidy rates. The first country finances energy subsidies with a distortive tax on wages in non-agriculture whilst the second uses a lump sum tax on consumers. The price-gap approach would identify both countries as having identical energy subsidies, whereas my methodology would capture the additional role played by distortive taxation.

[39] Pro-rating refers to calculating the proportion of the cost of a policy that can be counted as a fossil-fuel subsidy. For example, one might not wish to attribute the entire cost of a subsidy to car manufacturers as a fossil-fuel subsidy, but only count the part of the policy that encourages additional fuel use.

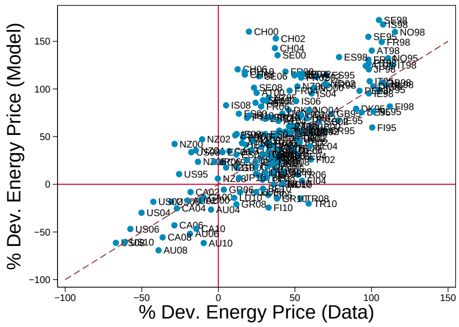


Figure 10: Subsidies implied by the model versus those inferred from the data using the price-gap approach. Each point shows the percent deviation of the after-subsidy fossil-fuel price from the undistorted price in an OECD country at a point in time in the model and data. Observations for 1995 and 1998-2010 (biennial).

Furthermore, distortions to wages of non-energy, non-agricultural workers $(\hat{w}_t \hat{\tau}^L_{Ct} \hat{L}^y_{Ct})$ also impact energy consumption and emissions. However, the entire value of this last policy should probably not be counted as it does not target energy directly. As such, I pro-rate this policy by a factor of $\frac{\hat{L}^e_{Ct}}{\hat{L}^y_{Ct}}$ - the relative size of energy to non-energy employment. The directly measured cost of fossil-fuel subsidies in the detailed model, $\hat{V}^E_t$, is thus given by: $\hat{V}^E_t \equiv \hat{p}^e_{Ct} \hat{\tau}^E_{Ct} \hat{E}_{Ct} + \hat{p}_{eCt} \hat{\tau}_{Et} \hat{E}_{Ct} + \hat{w}_t \hat{\tau}^L_{Et} \hat{L}^e_{Et} - \hat{w}_t \hat{\tau}^L_{Ct} \hat{L}^y_{Ct} \left(\frac{\hat{L}^e_{Ct}}{\hat{L}^y_{Ct}} \right)$. In Appendix 11.3 I show that - to a first-order approximation - this equals the value of energy-price wedges in the baseline model. Thus, the direct approach can *potentially* capture the same set of policies as the baseline wedge. However, differences in the definition of subsidies, missing data or an alternative choice of pro-rate factors, may mean that - in practice - directly measured subsidies will differ from the baseline wedge.

Price-gap and baseline subsidies in the data Having established a theoretical relationship between the energy-price wedges and price-gap estimates of subsidies, it is informative to see how these two measures compare in the data.[40] Using the price-gap technique, I construct a simple measure of carbon subsidy rates from data on at-the-pump gasoline prices, following the methodology used by IMF (2013) and IEA (2012).[41] Taking data from the WDI (2013) on the price of gasoline at-the-pump for available countries and years between 1991 and 2010, I calculate the percent deviation of the gasoline price in a particular country, i, in a given year, t, relative to an undistorted reference energy price. A negative deviation is indicative of low energy prices and hence net-subsidies in a country, whilst a positive deviation is indicative of net-taxes.[42] Importantly, subsidy rates inferred in this manner will necessarily be different from the observed wedges. First, prices at the pump include the cost of auxiliary service (e.g. delivery, refining etc.) that potentially vary across

[40] Notice, I cannot compare my wedges with *directly* measured subsidies from the OECD, as 'national tax expenditure estimates can only be considered in the broader context of the particular tax system of the country in question' (OECD, 2015) and are hence internationally not comparable.

[41] Whilst I closely follow the general methodology of the IMF and the IEA there are a number of crucial reasons for being very cautious when comparing my subsidy estimates with those of the IMF/IEA directly. For a discussion of these issues and for a direct, albeit imperfect comparison, see Appendix 11.2.

[42] To see this notice that $p^i_t / p^{Ref}_t - 1 = (1 - \tau^i_t) p^{Ref}_t / p^{Ref}_t - 1 = -\tau^i_t$. Since I do not have data for undistorted reference price in each country, I take as a reference price the UK gasoline price, adjusted for the UK's net-subsidies so that $p^{Ref}_t = p^{UK}_t / (1 - \tau^{UK}_t)$.

	$\log(1-\tau^i_{Model,t})$					
$\log(1-\tau^i_{Data,t})$	1.01***	0.84***	1.03***	0.72***	0.63***	0.73***
	(0.08)	(0.09)	(0.06)	(0.04)	(0.04)	(0.05)
Obs.	185	185	185	883	883	883
R^2	0.49	0.56	0.88	0.24	0.29	0.87
Time FE	no	yes	no	no	yes	no
Country FE	no	no	yes	no	no	yes
Sample	OECD	OECD	OECD	All	All	All

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

Table 3: Regressions comparing subsidies in the model and the data. Variables capture the percent deviation of the after-subsidy energy price relative to to the corresponding undistorted reference energy price in the model and the data. Observations for 1995 and for 1998-2010 (biennial). Columns 1-3 focus on the OECD with and without country/time-fixed effects, whilst columns 4-6 focus on all the countries with and without country/time-fixed effects.

countries - here, for lack of data, the reference price is taken to be the same in all countries. Second, countries may have policies that subsidize more than one type of fuel so that not all energy subsidies might be reflected in gasoline prices. And third, as was argued above, subsidies inferred using the price-gap approach - unlike those imputed by the model - will not capture indirect policies that support or hinder fossil-fuel use but are not reflected in the price. To limit the extent to which the above problems can hamper the comparison, in this exercise I focus primarily on OECD countries which are likely to suffer less from unobserved cross-country heterogeneity - i.e. they are likely to have similar auxiliary service prices and presumably limited indirect subsidy policies. Figure 10 plots the price deviations found in the data and those arising from the model as well as a 45 degree line to aid in the comparison. There is a remarkably strong correlation between energy price wedges and subsidy rates calculated using the price-gap approach.

A formal analysis of this is shown in Table 3 which depicts regressions between the (the log of) the ratio of the after-subsidy energy price relative to to the corresponding undistorted reference energy price in the model and data for all years.[43] The model does well in accounting for both the across and within country variation in subsidies - capturing up to 88% of the variation in OECD countries. Notice that the correlation in non-OECD countries is also high, but that there is more variation in the data. This is perhaps unsurprising since indirect energy policies and price differences are more likely to play a larger role in non-OECD countries.

Interestingly, the deviations between the data and the model can also have an informative interpretation. Since the model-based wedges provide a broader measure of support than subsidy rates extracted using the price-gap method - the deviation between the two can shed light on the extent of indirect distortions not reflected in at-the-pump gasoline prices. Thus, for example, we can interpret countries below the 45-degree line and in the bottom left quadrant of Figure 10 (such as Australia or Canada), as providing more support to fossil-fuels than is captured by the deviation of the gasoline price. Examples of such policies could include state guarantees of bank loans to

[43] Thus, the quantities under consideration are $\log(p^i_t/p^{Ref}_t) = \log(1-\tau^i_t) \approx -\tau^i_t$.

energy intensive industries, disproportionately generous benefits to coal miners or additional protection for energy intensive industries from outside competition. Countries above the 45 degree line and in the top right quadrant - like France or Switzerland - are those that in addition to high taxes also have other policies to discourage fossil-fuel consumption. For example, in France, there are strong restrictions on generating energy from fossil-fuels and an emphasis on nuclear energy. Whilst these types of policies are not a direct tax, they nonetheless discourage the use of fossil-fuels and hence show up in the energy wedge. This broad interpretation of the differences between the baseline wedges and the price-gap subsidy has to be used with caution. The price-gap estimates here are only based on the consumer price of petroleum and may not capture polices affecting other fossil-fuels or firms. Furthermore, since wedges are catchalls, they include all policy *and* non-policy distortions that encourage or discourage countries to use disproportionately more or less fossil-fuels. Thus, undoubtedly, some of the deviation between model and data stems from non-policy factors such as endowments or geography. Nonetheless, a large deviation between the price-gap subsidy and the estimated fossil-fuel price wedge should serve as an interesting starting point for researchers investigating indirect or 'hidden' fossil-fuel subsidies.

7 Energy Price Wedges and their Effects

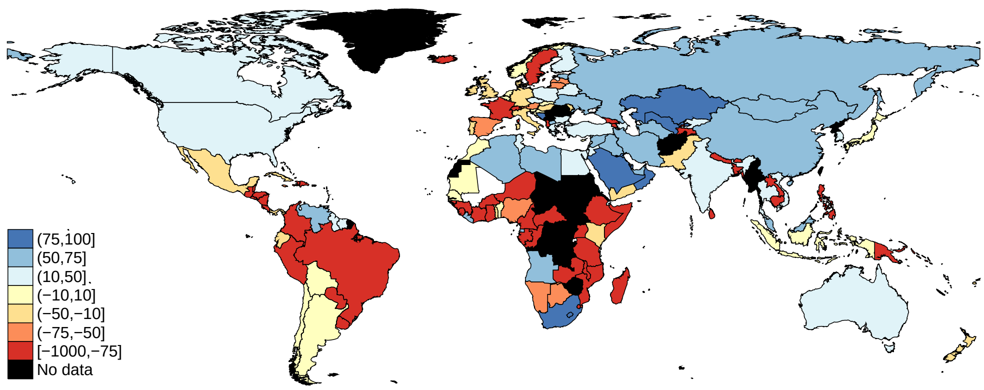
I now examine the above energy-price wedges and their impact on emissions and output. Table 11(a) presents the subsidy rates, the (current price) share of subsidies in GDP as well as total and per worker subsidies (in 1990 international dollars) for the largest 20 subsidizers in 2010. Figure 11(b) shows a map of subsidy rates around the world. Oil rich countries as well as current/ex-communist countries have the highest subsidy rates. These countries tend to have a history of direct subsidies on dirty energy and supporting heavy industries that use large quantities of energy. In the framework of the model, these policies are captured as subsidies on carbon energy. In absolute terms, China, the US, Russia and India are the largest subsidizers. The carbon wedges in these four countries cost approximately 717 billion dollars (in international 1990 dollars) in 2010. Countries in Europe tend to have implicit net-taxes on carbon energy. This captures either high levels of direct energy taxation or - for instance - the fact that many European countries subsidize 'green' energy or discourage carbon energy through high direct taxation or indirect policies. Finally, countries in sub-saharan Africa as well as South America have the highest implicit taxes. This may be due to high taxes on energy, tariffs on imported fossil-fuels, the closed nature of those economies or their distance from energy producers, which is captured as implicit net-taxes on carbon energy.

Next, I examine the rate and level of fossil-fuel subsidy wedges over time. Figure 12(a) shows the global (emission-weighted) mean of implied subsidy rates over time. Globally, subsidy rates are roughly constant (and negative) until the late 90s after which there is a large increase.[44] Figure 12(b) confirms the trend by showing the global total of all (positive) net-subsidies over the period.

[44] Notice the spike in 1998. This decline may be due to the structure of energy taxes. Countries tend to levy most of their (gross) energy taxes as dollar quantities 'per unit of energy'. This implies that falling energy prices generate rising (gross) energy tax *rates* and vice-versa. In 1998, world energy prices fell to their lowest levels in nearly 25 years. In Stefanski (2014a), I calculate energy tax rates for Canada directly using government sources and show that this decline in price explained practically the entire spike in the energy price wedge in that year.

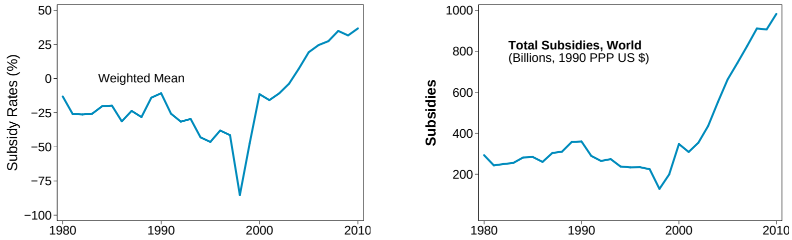
Rank	(1) Subs Rate (%)		(2) Subs/GDP curr. prices, (%)		(3) Subs. Total bill. 1990 PPP $		(4) Subs. per cap. 1990 PPP $	
1	KWT	88.56%	KWT	34.41%	CHN	419.8	QAT	6509
2	TTO	87.08%	TTO	27.13%	USA	169.7	TTO	4731
3	SAU	84.40%	SAU	25.40%	USSR	122.5	KWT	4525
4	QAT	84.25%	ZAF	25.19%	RUS	83.6	SAU	3012
5	OMN	84.15%	KAZ	24.43%	IND	43.9	OMN	2555
6	KAZ	83.74%	UZB	22.28%	IRN	29	BRN	2251
7	ZAF	81.68%	QAT	21.83%	SAU	27	ARE	2175
8	UZB	79.71%	BIH	21.34%	ZAF	25.9	BHR	1939
9	BHR	77.40%	BHR	19.63%	UKR	14.5	KAZ	1723
10	BIH	75.76%	OMN	18.05%	KAZ	14.3	ZAF	1450
11	EST	74.49%	EST	16.08%	KOR	13.7	EST	1416
12	IRN	73.68%	VEN	15.57%	CAN	12.8	TKM	1166
13	CHN	73.58%	UKR	14.75%	AUS	11.8	LBY	1151
14	GNQ	70.21%	MNG	14.09%	VEN	9.7	RUS	1126
15	RUS	69.76%	LBY	13.71%	POL	9.4	IRN	1104
16	VEN	69.51%	RUS	13.56%	MYS	9.1	USA	1089
17	BRN	68.99%	IRQ	13.30%	THA	8.2	AUS	1029
18	UKR	68.96%	USSR	12.59%	ARE	7.1	BIH	893
19	LBY	68.51%	IRN	12.27%	UZB	5.7	USSR	857
20	MNG	68.40%	BRN	12.05%	KWT	5.7	VEN	763

(a) Top 20 countries subsidizing fossil fuels in 2010 according to the following measures: (1) Subsidy rates (2) current price share of subsidies in GDP (3) total subsidies (billions 1990 PPP dollars) (4) subsidies per capita (billions 1990 PPP dollars). Country Codes: Australia (AUS), Bahrain (BHR), Bosnia and Herzegovina (BIH), Brunei (BRN), Canada (CAN), China (CHN), Equatorial Guinea (GNQ), Estonia (EST), India (IND), Iran (IRN), Iraq (IRQ), Kazakhstan (KAZ), Kuwait (KWT), Libya (LBY), Malaysia (MYS), Mongolia (MNG), Oman (OMN), Poland (POL), Qatar (QAT), Russia (RUS), Saudi Arabia (SAU), South Africa (ZAF), South Korea (KOR), Thailand (THA), Trinidad and Tobago (TTO), Turkmenistan (TKM), Ukraine (UKR), United Arab Emirates (ARE), United States (USA), Former Soviet Union (USSR), Uzbekistan (UZB), Venezuela (VEN)



(b) Map of subsidy rates predicted by model in 2010, %.

Figure 11: Implied subsidies around the world, 2010.



(a) Emission-weighted average of global fossil-fuel subsidy rates, %.

(b) Total global fossil-fuel subsidies (billions, 1990 PPP US $).

Figure 12: Evolution of Global Subsidies in the Model.

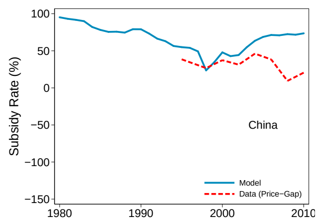
Until the end of the 90s total subsidies are approximately 200 billion dollars a year. After that there is a massive increase and by the end of 2010, total subsidies have reached a staggering 983 billion US dollars a year. Other studies on fossil-fuel subsidies like those by Coady et al. (2010), IMF (2013) or IEA (2010), whilst focusing on much shorter periods than this study, also find evidence of rising fossil-fuel subsidies in the post-2000 period. Coady et al. (2010) and IEA (2010) argue that the increase is closely linked to rising energy prices after 2000 driven by a significantly low pass through of international prices to local consumers.[45] Figure 13 then presents the corresponding graphs for some interesting countries. China, the USA, the ex-USSR and India are the largest subsidizers in the world. Observe that each one of the countries has seen a large increase in implicit fossil-fuel wedges, but none more so than China, where implicit total subsidies increased from roughly 100 billion dollars in the late 90s to over 400 billion dollars by 2010. As can be seen from Figure 13(a), this was largely driven by an increase in indirect subsidies, not captured by the price-gap method but detected by the implicit wedges of the model. Also, included in the figure are graphs for Saudi Arabia - a country with one of the highest rates of subsidization in the world - and for Germany a country with very high implicit taxes on fossil-fuel energy. In both countries there is an increase in net-subsidies after the late 90s. Notice that most of the distortions are direct since there is agreement between the implicit wedges and the subsidies extracted using the price-gap approach.[46]

Counterfactuals Finally, I use the model to measure the effect of energy price-wedges on global emissions and GDP. I assume that the evolution of productivity in each country stays the same, but I set all positive energy-price wedges to zero in all countries and calculate the resulting counterfactual estimate of global emissions and GDP. Importantly, I am thus assuming that all energy-price wedges arise from governmental policies and *can* be removed - thus the subsequent estimates are upper-bounds. I discuss this issue in more detail in sections 8 and 9.

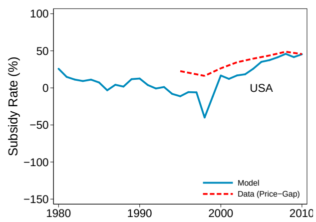
Figure 14(a) shows the effect of this counterfactual on emissions. In 2010 alone, annual emissions would have been 36% lower were it not for massive fossil-fuel wedges, whilst over the 1980-2010 period, cumulative emissions would have been 21% percent lower. Removing these wedges can thus

[45] Indeed, using the world average net-subsidy rates between 1980-2010 arising from my methodology, I find that a percentage increase in the oil price is associated with a 0.43 percentage point increase in fossil-fuel subsidies.

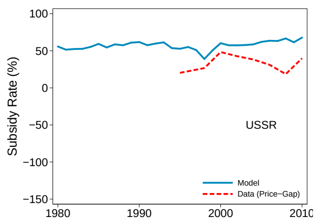
[46] I present a more detailed regional- and country-level analysis of the resulting energy price wedges in an accompanying paper in Stefanski (2014a). The implicit wedges are also available online to download.



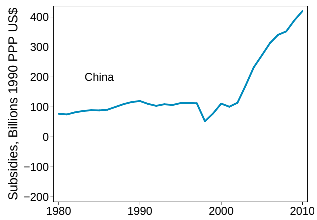
(a) Sub. Rate: China



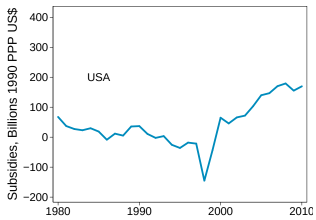
(b) Sub. Rate: USA



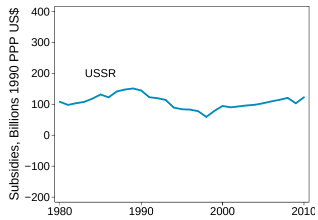
(c) Sub. Rate: USSR



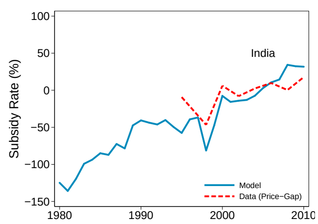
(d) Sub. Quantity: China



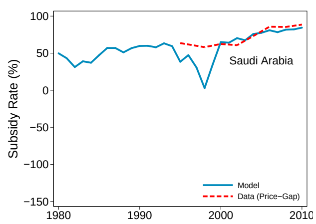
(e) Sub. Quantity: USA



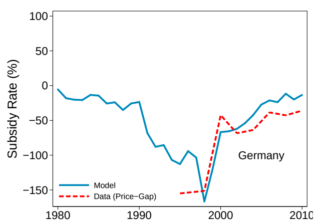
(f) Sub. Quantity: USSR



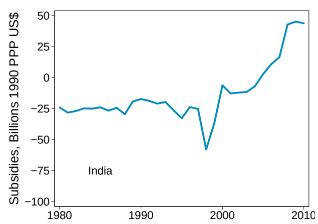
(g) Sub. Rate: India



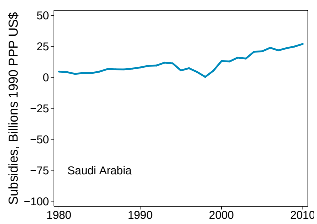
(h) Sub. Rate: S. Arabia



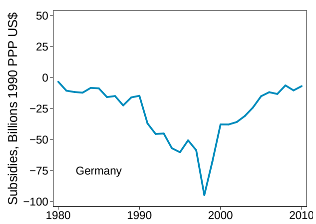
(i) Sub. Rate: Germany



(j) Sub. Quantity: India

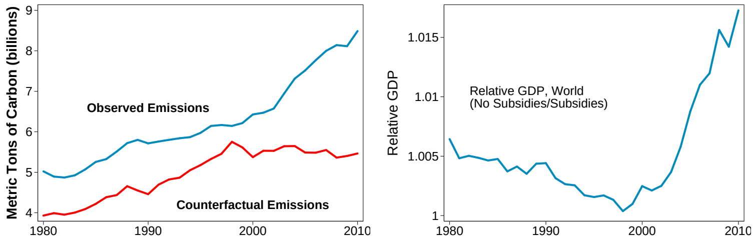


(k) Sub. Quantity: S. Arabia



(l) Sub. Quantity: Germany

Figure 13: Subsidy rates and total subsidies (billions of 1990 PPP USD) in the model and (for subsidy rates only) in the data for selected countries. The subsidy rates from the data are obtained using the price-gap method described in section 6.



(a) Global carbon emissions with and without subsidies.

(b) Ratio of global GDP with and without subsidies.

Figure 14: The effects of subsidies on global carbon emissions and GDP.

potentially massively lower emissions. Second, the elimination of subsidy distortions would have resulted in higher output over the period. Figure 14(b) shows the ratio of GDP in this counterfactual world relative to observed GDP. Prior to the late 90s annual GDP would have been higher by approximately 0.3% on a global scale. The increase in output associated with eliminating wedges rises to approximately 1.7% of global GDP or approximately 838 billion US dollars by 2010. Importantly, this is *in addition* to the direct cost of the wedges. Notice that the effects are even larger for particular countries. For example, China's GDP would have been higher by 6.1% or approximately 431 billion US dollars in 2010 alone. These are massive effects.

8 Robustness

The implied wedges that emerge from this model are - by definition - residuals that depend on the model itself. Constructing a more detailed model could potentially change these residuals. It is thus imperative to understand to what extent the extracted price wedges can be interpreted as implicit or explicit fossil-fuel subsidies. Since energy-price wedges could reflect differences in country-specific characteristics not captured by agricultural and/or non-agricultural wedges, it is crucial to examine how important such changes could be.

One answer to the above problem is provided in Table 3 which shows a strong correlation between implicit wedges and price-gap subsidies across countries - especially in the OECD, where unobserved cross-country heterogeneity is likely small. Furthermore, the same table shows a very strong correlation between the data and the model even after accounting for country-fixed effects which should control for much of the unobserved cross-country heterogeneity. To provide more support to the claim that price wedges are good estimates of direct and indirect subsidies, I now consider a number of extensions and robustness exercises. In particular, 1) I examine the impact of different elasticity of substitution parameters, σ; 2) I re-calibrate the model using constant price sectoral value-added data to infer sectoral productivities and 3) I demonstrate how the addition of capital to the model would impact energy-price wedge estimates. I also consider extensions to the baseline model that allow for 4) cross-country differences in fossil-fuel endowments, 5) differences in sub-sectoral composition, 6) trade in natural resources as well as differences in 7) population density, 8) climate and 9) urbanization rates. I show that, quantitatively, the baseline subsidies are not too sensitive to

σ	(1) g_E	(2) Model to Data Elast., $p_{c,t}$	(3) OECD Subs.	(4) Subs. Total 2010	(5) Subs.2010 /Subs. 1980	(6) Subs.2010 /Ave. Subs 1980-1999	(7) CO_2^τ /CO_2 2010	(8) GDP^τ /GDP 2010
0.10	0.7%	1.03	5.18	1614	2.2	2.3	0.67	1.035
0.30	0.9%	0.90	1.97	1380	2.3	2.4	0.67	1.026
0.60	1.5%	0.87	1.18	1088	2.9	3.2	0.66	1.019
0.76	**2.4%**	**0.87**	**1.01**	**983**	**3.4**	**3.7**	**0.64**	**1.017**
0.90	5.7%	0.86	0.91	911	3.7	3.8	0.64	1.016
1.10	-5.6%	0.86	0.82	832	4.3	3.7	0.62	1.015
1.50	-1.0%	0.86	0.70	721	4.0	3.3	0.60	1.015
5.00	-0.1%	0.86	0.48	591	3.8	2.8	0.44	1.022
10.00	0.0%	0.86	0.44	526	3.6	2.8	0.40	1.023

Table 4: Effects of varying σ on the results. For details, see text.

changes in parameters, to different calibrations or to richer variants of the model. Furthermore, the qualitative finding that subsidies were flat and then began rising rapidly since the turn of the century (as well as the extent to which they have been rising) remains almost entirely unchanged. This robustness supports the claim that energy-price wedges are good estimates of direct and indirect fossil-fuel subsidies.[47]

Finally, notice that there is a tradeoff between potentially tighter estimates of subsidies arising from more complicated models and their quality and quantity. The more detail I include in a model, the more data is needed to back out wedges. Furthermore, some of this detailed data - such as that on endowments or sectoral energy consumption - may be of extremely poor quality. Thus, richer theoretical environments necessarily result in fewer and (perhaps) less-certain observations. The goal of the baseline model is to obtain estimates of subsidies for as many countries and as long a period of time as possible. In this section I show that the simple, baseline estimates are robust to changes and extensions of the model.

Elasticity I start by examining the role played by the energy-labor elasticity of substitution, σ. I vary σ between 0.1 (near-Leontief) and 10 (near-perfect substitution), re-calibrating the model each time. Table 4 shows the results. Column (1) presents the implied average growth rate of energy-specific technological progress between 1820-2010 for each choice of σ.[48] Choosing $\sigma > 1$ results in growth rates less than or equal to zero. Over such a long period of time, a negative or even zero technological growth rate seems highly implausible. Realistically, the σ parameter should thus be smaller than one.[49] Choosing too small a σ, however, also contributes to unrealistic results. Column (2) shows the slope parameters from the regression of the log of non-agricultural price to wage ratio in the model to that of the data in the OECD (controlling for country fixed effects), whilst column (3) shows the slope of the regression of $\log(1-\tau_t^i)$ in the model to that of the data in the OECD.[50] Choosing $\sigma < 0.6$, results in either prices or subsidies in the model that change

[47] This reasoning follows the insights of Cole and Ohanian (2004) and Chari et al. (2007). If modifying a model changes some wedges, those wedges (pre-modification) were capturing the effects of the subsequent modification. Conversely, if changing a model leaves a wedge largely unchanged, then that wedge is arising from other sources.

[48] These are derived as the slope of the regression of the log of the implied values of B_{Et} on time.

[49] Recall that when $\sigma = 1$, the production function is Cobb-Douglas and B_{Et} cannot be identified.

[50] For $\sigma = 0.76$, these are simply the coefficients found in column 2 and column 1 of Tables 2 and 3 respectively.

more than those in the data. A realistic estimate of σ would thus lie between approximately 0.6 and 0.9. This squares remarkably well with the empirical evidence discussed in section 4, which points towards σ being between 0.65 and 0.871.

Column (4) of the table shows implied global subsidies in 2010. In the "realistic" range of σ, subsidies lie between 911 billion and 1.1 trillion dollars. The predicted subsidies are also large for other values of σ. Furthermore, column (5) - which shows the ratio of global subsidies in 2010 and 1980 - demonstrates that subsidies are growing over time for all values of σ. Next, column (6) shows the ratio of implicit global subsidies in 2010 with respect to average, annual global subsidies between 1980 and 1999. For values of $\sigma < 1.5$, columns (5) and (6) are very similar, suggesting that the finding that most of the increase in subsidies occurred post-1999, is robust to other values of σ. Finally, columns (7) and (8) show the ratio of counterfactual emissions and GDP to observed emissions and GDP respectively in 2010, where the counterfactual sets positive subsidies to zero. A higher σ implies a greater positive impact of removing subsidies on GDP and emissions. For reasonable values of σ emissions would be 1/3 lower without subsidies whilst GDP would be 1.6-1.9% higher. The key results of the paper are thus qualitatively and quantitatively robust to different choices of σ.

Measured Productivity In the baseline calibration I used the model and aggregate GDP-per-worker data to infer sectoral value-added and I used the assumption that wages are equalized across sectors to infer the size of employment in the modern energy sector. Now, I re-calibrate the model taking estimates of constant price sectoral value-added and employment in modern energy production directly from the data. The new calibration is identical to the baseline, with the exception of equations (21)-(23) which are no longer needed. In addition, I am now no longer free to normalize $\bar{a}$ to 1. In particular, given sectoral value added, $\bar{a}$ influences the size of the agricultural sector and is chosen to match UK's agricultural employment share in the year 1990. Table 5 shows the evolution of predicted total global subsidies in this case (as well as for subsequent robustness checks).[51] The results are almost identical and indicate roughly constant subsidies pre-1999 and a sharp increase post-1999. Notice however, that this approach suffers from several drawbacks. Constructing the long run data involves concatenating numerous data sources of varying quality and provenance as well as a large degree of interpolation for missing values. For employment data we also need to accept certain inconsistencies in sectoral definitions.[52] Finally, to obtain historical sectoral value-added, estimates of sectoral price deflators must be used which can be problematic due to the scarcity and inconsistency of service-sector prices over longer periods. Thus, given the similar results, the baseline calibration may be more appropriate. See Appendix 11.4 for estimated parameter values and a more detailed examination of subsidy rates implied by this and all subsequent extensions.

[51] To maintain comparability across scenarios, total subsidies are evaluated using prices found in the baseline model. Also, to maintain comparability, in the table I show results only for observations that are available for each extension. For each extension I also indicate the maximum number of observations available.

[52] The mining and utilities sector, which I take to be employment in energy production, includes workers in non-energy mining and non-energy utilities, and excludes various other parts of the economy involved in energy production - such as transportation, sales and storage - for which no long-run data exist.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
				Relative to Baseline				
	Ave. Tot Sub. 1980-99	Tot Sub. 2010	Sub.2010 /Ave. Sub 1980-99	Ave. Tot Sub. 1980-99	Tot Sub. 2010	Sub.2010 /Ave. Sub 1980-99	Obs	Max. Obs.
Baseline	**247**	**848**	**3.43**	**1.00**	**1.00**	**1.00**	**1663**	**4440**
Measured Prod.	245	836	3.41	0.99	0.99	1.00	1663	4377
Sectors	312	1064	3.41	1.26	1.25	0.99	1663	2399
Endowment	187	635	3.40	0.75	0.75	0.99	1663	2524
End. & Trade	242	834	3.45	0.98	0.98	1.01	1663	2495
Ar., Temp., Urb.	217	832	3.84	0.88	0.98	1.12	1663	4006
All Features	**294**	**925**	**3.14**	**1.19**	**1.09**	**0.92**	**1663**	**1663**

Table 5: Robustness: Global fossil-fuel subsidies from different models. (1) Average total annual global subsidies, 1980-1999; (2) Total global subsidies, 2010; (3) Ratio of column 2 to column 3; (4)-(6) Ratio of columns (1)-(3) relative to baseline; (7) Number of observations used in comparison; (8) Maximum number of observations available.

Capital Notice that in the baseline model I abstracted from physical capital. In Appendix 11.4.1 I show theoretically that under a set of reasonable conditions regarding the share of capital across sectors, this does not influence my measure of fossil-fuel subsidies. In particular, the addition of capital affects only sectoral productivity estimates whilst the fossil-fuel price wedge in a model with capital continues to capture the same set of distortions as the fossil-fuel price wedge in the baseline model without capital.

Sub-Sectors Next, I further divide the non-agricultural sector into industry and services and model the transition from industry to services using complementarity and asymmetric sectoral productivity growth rates in a similar fashion to Duarte and Restuccia (2010). The reason why a sub-sectoral division may be important is that the use of energy might well vary systematically between industry and services. In particular, it might be the case that the most intensive use of energy is in industry. Given that both industrial employment and value-added shares exhibits a hump-shape in the data over time and income,[53] a sectoral reallocation could potentially help explain the hump-shape emission intensity curve and hence systematically influence the fossil-fuel subsidy wedges. The results are shown in Table 5. Whilst this idea is intuitively appealing, both qualitatively and quantitatively its impact is quite limited. If anything, the sub-division of non-agriculture *increases* the estimates of the size of fossil-fuel subsidies. The results however, have to be approached with caution as the exercise is hampered by serious data limitations with respect to sectoral employment as well as sectoral energy consumption. In particular there are well known difficulties in constructing disaggregated modern energy consumption data that is compatible with the ISIC classification used in the rest of the paper (Mulder and de Groot, 2012). Also, since the model will now require both industry and service sector employment to infer energy wedges in a country, these can only be estimated for 2399 country-dates, instead of 4440 country-dates in the baseline. For additional details see Appendix 11.4.2.

[53] See, for example, Maddison (1982), Echevarria (1997), Buera and Kaboski (2008) etc.

Endowments Next, I allow countries to differ in their energy endowments. I assume countries have an exogenous fixed factor, D_t, which is owned by the household and captures the size of fossil-fuel energy reserves at time t. These reserves combine with labor to produce modern energy in a standard Cobb-Douglas fashion, replacing equation (4) in the baseline model with:

$$E_{Ct} = B_{eCt}(D_t)^{1-\gamma}(L^e_{Ct})^{\gamma}, \tag{29}$$

where $1-\gamma$ is the share of endowments in energy production. Notice, I assume that reserves are non-reproducible and non-exhaustible and that they act much like land in the model of Gollin et al. (2007).[54] Modern energy firms then hire both labor and reserves from households to produce final modern energy. All other aspects of the model remain as in the baseline. Given the closed nature of the economy countries with more reserves will use more fossil-fuels and will hence seem dirtier than otherwise identical countries with lower reserves. As can be seen in Table 5 this means that price wedges will be necessary lower in order to match the variance of emission intensities across countries. Nonetheless, the main quantitative and qualitative facts of the model still go through. However, as with sub-sectoral extension, there are also well-known difficulties in constructing an accurate measure of fossil-fuel endowments which further limits the scope (these can only be estimated for 2524 instead of 4440 country-dates) and potential quality of the estimates. For more details see Appendix 11.4.3.

Trade Notice that the above extension leaves out a role for trade which can be key when endowments are heterogenous, since resource-rich countries can simply export modern fuel rather than consuming it. I now keep the above setup of an economy with natural resource endowments, but additionally allow countries to trade in non-agricultural goods and in modern energy. Whilst higher endowments translate to higher modern energy consumption and hence higher emissions in a closed economy, in an open economy this is not necessarily the case. Economies can simply export energy in exchange for consumption goods which in turn can result in lower (local) emissions.[55] As such, including trade significantly tempers the role that heterogenous endowments play in influencing a country's emission intensity. Furthermore, a setup with trade allows me to control for international implicit trade costs (including tariffs), by incorporating an additional wedge on the price of traded goods. From the table, notice that once I allow for trade, a model that includes heterogenous endowments implies modern-energy subsidy wedges that are almost identical to those of the baseline. For more details on this model see Appendix 11.4.4.

Other Factors: Population Density, Climate and Urbanization Differences in land area (and hence population density), climate or urbanization rates across countries can also impact energy consumption and hence influence emission intensity. This in turn could potentially bias baseline energy subsidy estimates. However, the strength of the "wedge-accounting" approach is that these

[54] I am thus abstracting from exhaustion - this, of course, is a simplification but - since endowments of coal are included in the figures and reserves of coal are for all intents and purposes in-exhaustible - see Krautkraemer (1998) or Dvir and Rogoff (2009) - this is not necessarily an unrealistic assumption.

[55] Importantly, since I consider almost all countries in the world and I match each countries levels of energy consumption *and* production, the fact that emissions within one country decline due to energy exports will be entirely captured by another countries higher imports of energy and hence will not affect total global emissions in any way.

types of distortions (and others like them) tend to be picked up by the existing sectoral productivity wedges rather than energy price wedges. Only when energy is *disproportionately* affected by a distortion relative to the other sub-sectors, do the productivity wedges not pick up the residual source of heterogeneity and a bias emerges. To test the largest possible extent of this bias on the subsidy estimates, I assume that the above distortions *only* impact energy demand. Recall that the overall productivity of sector j, in country i, B^i_{jt}, is the product of UK productivity, B_{jt}, and the country-i-specific sectoral wedge. As in the baseline, I will have $B^i_{jt} = D^i_{At}B_{jt}$ for sectors $j = A, eA$ and $B^i_{jt} = D^i_{Ct}B_{jt}$ for sectors $j = lC, eC$. However, I now allow for an additional wedge, Z^i_{Et}, that impacts modern-energy consumption so that $B^i_{Et} = D^i_{Ct}Z^i_t B_{Et}$. Using data on population density, temperatures and urbanization rates, in Appendix 11.4.5 I construct estimates of Z^i_{Et} and examine its role on implied energy-price wedges. From Table 5 notice that even making the extreme assumption that these distortions only impact energy demand, the additional wedges generate only a small effect on the resulting subsidies.

All Factors Finally, I consider how endowments, trade, sub-sectors as well as population density, climate and urbanization - taken together - impact the estimated price wedges. I examine a three sector economy composed of agriculture, industry and services with fossil-fuel energy endowments as well as trade in modern energy and industrial goods. I also allow countries to vary in the extent of their population density, their climate and their urbanization rates. The model thus simply combines the individual features presented in the above paragraphs. I find that implied evolution of total subsidies is qualitatively very similar to that of the baseline, whilst quantitatively total subsidies are - if anything - slightly higher. The baseline subsidy-wedge estimates are robust to a wide range of changes and extensions to the model. This suggests that estimated energy-price wedges may indeed be good estimates of fossil-fuel subsidies. For details see Appendix 11.4.6.

9 Strengths and weaknesses

The proposed methodology has a number of crucial strengths and some potential weaknesses. Importantly many of the weaknesses are shared by other indirect methods of subsidy measurement - especially the commonly used price-gap approach. However, the proposed methodology improves over the price-gap approach along a number of key dimensions. I start by considering four potential weaknesses of the methodology and then move on to its strengths.

Weaknesses First, whilst the model identifies price wedges in the data, it cannot pinpoint the specific policy or non-policy factors driving these distortions. Furthermore, the method does not address the political-economy question of *how* to remove energy price wedges nor does it explore the distributional aspects of policy change. These are important features of the debate discussed in more detail by IMF (2013), Koplow (2009) and IEA (2010). Instead, like the price-gap approach, the methodology should be thought of as primarily a tool for measurement and complementary to direct measures of subsidies, when these are available.

Second, the implicit price wedges are residuals and do not necessarily exclusively represent distortions arising from government policies. In particular, as I argued in the previous section, they could also reflect other factors that influence energy consumption but have been left out of the model. Despite the numerous extensions performed above, price wedges should be viewed as aspects of individual economies that result in fossil-fuels being used more intensively than they otherwise 'should-be'. Importantly however, the price-gap approach suffers from the same potential weakness but to an even greater extent: it interprets *all* energy price differences across countries (irrespective of whether they came from policy, non-policy or other structural aspects of the economy) as net-subsidies. The methodology of this paper is more nuanced and, because of cross-country differences in sectoral productivity, it is capable of capturing cross-country differences in energy prices even if no energy price wedges exist.[56] For example, in as far as aspects like differences in transportation costs or geography impact sectoral productivity, they will not bias the energy price wedges but will rather be picked up by the sectoral productivity wedges. The current methodology will only generate biased subsidy estimates if missing features result in systematic distortions to the energy sector - above and beyond distortions to sectoral productivity wedges. Furthermore, unlike the price-gap approach, my methodology can easily be extended to control for additional sources of cross-country heterogeneity such as the extensions performed in the previous section.

Third, the above points have an implication for the counterfactual exercises performed using the model. These exercises assume that energy price wedges emerge entirely from government policies and hence that those wedges can be completely and costlessly eliminated. If this is not the case, then the counterfactuals may result in an overestimate of the role played by government policies in driving carbon emissions. This should be kept in mind when considering the results. On the other hand, neither the price-gap nor the direct method of measuring subsidies can be used to think about counterfactual outcomes, thus my methodology still provides useful insights.

Finally, many countries simultaneously have some policies that subsidize and other policies that tax fossil-fuels. For example, Turkey has some of the highest taxes on gasoline at the pump in the world, but at the same time it provides massive subsidies to employees of coal mining industry which it sees as strategically important (IEA, 2010). The baseline version of the model however, only calculates net-subsidies within a country.[57] This can be seen as either a positive or a negative aspect of the model. On the positive side, it gives a clear, one-figure summary of all policies carried out by the government. On the negative side, reporting a single number might miss large subsidies in an economy that are 'netted-out' by corresponding taxes. This however again is a flaw that also exists in the price-gap approach since consumer energy prices in a country capture the net effects of potentially conflicting government policies.

Thus, whilst the suggested methodology does have drawbacks these are mostly shared by the price-gap approach. Furthermore the proposed setup has a number of crucial strengths.

[56] In more complicated price-gap subsidy calculations attempts have been made to correct for very specific differences in energy prices resulting from differences in distribution, marketing or transportation costs of energy. These attempts however, tend to be ad-hoc and are usually applied indiscriminately to large groups of countries. In its calculations of energy subsidies, the IMF (2013) assumes the same distribution and transportation margins for *all* importers of fossil-fuels and no distribution and transportation margins for countries that are net exporters.

[57] Although, as argued in Appendix 11.4, the extension of the model with trade can be used to disentangle between consumer and producer subsidies.

Strengths First, since the baseline methodology is not very data intensive it can be applied to a wide range of countries and result in subsidy estimates which would otherwise not be available. Thus, I provide new information for a far wider set of countries than is standard - 170 in total. For comparison, subsidy estimates are provided by the IEA (2010) only for 37 countries.

Second, price-gap subsidy estimates are available only for a limited number of years. The earliest data estimated using the price-gap methodology is usually available only for 1991 or 1995, whilst later data is available only biennially from 1998.[58] The methodology in this paper is used to determine annual subsidies going back to 1980 for almost all countries, and could be extended further back for a substantial portion of the world's economies.

Third, estimating comparable subsidies across countries and time is challenging as there is significant measurement error and substantial costs of gathering information since subsidy mechanisms are often opaque, complicated or purposefully hidden (Koplow, 2009). Since the suggested approach uses a uniform methodology which does not rely on country-reported data nor on the examination of individual tax codes or subsidy laws, it provides a database of *comparable* fossil-fuel subsidies across countries and time.

Fourth, since the methodology examines total emissions rather than prices, unlike the price-gap approach it can capture subsidies that support carbon energy without changing its final price. This can include a range of diverse subsidy mechanisms such as guaranteed loans to small oil-drillers, subsidized loans to companies buying oil-bearing land, the distribution of vouchers that entitle consumers to a certain amount of fuel at a discounted price or income-tax codes that encourage employers to offer free fuel in place of higher salaries to their executives using company cars (IEA, 2010). Thus the proposed methodology offers a more comprehensive overview of support than standard price-gap measures.

Fifth, in as far as the model accurately captures cross-country variation in price levels, it allows for energy price variation across countries that stems from non-energy-subsidy sources making the estimates more accurate. For example, poorer countries tend to have lower price levels of services than richer countries due to sectoral productivity differences (the so-called Balassa-Samuelson effect). In as far as this translates to lower energy prices at the pump, the price-gap approach would interpret these low prices as subsidies. The suggested methodology however is robust enough to account for cross-country price differences arising from variation in productivity and not misattribute these differences to energy subsidies or taxes.

Finally, since the proposed methodology is model-based, it allows me to perform counterfactuals to gauge the impact that subsidies have on the environment (by promoting too much fossil-fuel consumption) or on GDP (by promoting a misallocation of resources). This allows for better estimates of total opportunity costs of fossil-fuel subsidies.

In short, whilst the proposed methodology admittedly possesses some of the same potential weaknesses of other indirect methods of subsidy estimation - like the price-gap approach - it is more comprehensive both in scope (since it considers more countries over a longer period of time) and in completeness (since it captures a broader measure of subsidies) and importantly it is comparable

[58] This is due to the fact that the price-gap approach uses data on gasoline and/or diesel prices at-the-pump provided by the Deutsche Gesellschaft fuer Internationale Zusammenarbeit (GIZ) on a biennial basis.

across countries and time whilst offering the possibility of calculating total opportunity costs of fossil-fuel subsidies. Of course, both the direct and the price-gap approach remain highly relevant. A consistent, comparable and directly measured database of fossil-fuel subsidies is very desirable as it would help identify specific policies driving subsidies. Price-gap estimates also remain useful as both a check on baseline wedge estimates and as a way to identify direct and indirect energy subsidies. The fossil-fuel price wedges developed here should thus be thought of as an additional - complementary rather than supplementary - measurement tool, providing novel information to academics and policy makers interested in understanding the role of fossil-fuel subsidies in driving carbon emissions.

10 Conclusion

Countries exhibit carbon emission intensities that are hump-shaped with income. This paper argues that industrialization drives this pattern whilst deviations from it are symptomatic of wedges to sectoral productivity or to the price of fossil-fuels. I use a calibrated model of structural transformation to disentangle and measure these distortions and to extract energy price-wedges on fossil-fuels for 170 countries between 1980 and 2010. I argue that these energy-price wedges can be used as estimates of fossil-fuel energy price subsidies. Additionally, these estimated energy price wedges benefit from a number of attractive properties. In particular, the wedges are available for many countries and years, they are comparable across countries and time and - unlike measures based on the price-gap approach - they also capture indirect support to fossil-fuels and allow the researcher to control for price differences across countries. Since the proposed methodology gives rise to the most comprehensive database of its kind, it should prove to be a crucial tool for both policy makers and researchers.

Finally, since my method of estimating wedges is model-based, it allows me to perform counterfactuals and hence to measure the impact of those wedges on emissions and growth. I find that subsidy-like wedges are a massive contributor to global carbon emissions, accounting for more than a quarter of emissions over the last thirty years. The direct cost of these distortions was 983 billion dollars in 2010 alone. Furthermore, by distorting energy prices, subsidy-like wedges also resulted in global GDP that was 838 billion dollars lower in 2010 than what it would have been without those wedges. Together, the cost of these distortions amounted to 3.8% of total world GDP in 2010. To put this into the starkest possible perspective, the 2014 IPCC report estimates that climate change will lower global GDP by at most 2% in 50 years. By this measure, subsidy-like wedges on fossil-fuels are potentially more damaging than climate change. Worryingly, using the long time-series data arising from my method, I also find that wedges have been rising drastically since the end of the 1990s. Whilst not all of the estimated distortions can be eliminated, removing even some of these subsidy-like wedges can potentially help strained government budgets, contribute to higher levels of global GDP and make a significant (and importantly cheap) contribution to the fight against climate change.

11 FOR ONLINE PUBLICATION: Appendix

The appendix consists of four parts. Part 11.1 describes the sources of all data used in the paper and their construction. Part 11.2 performs all the extended empirical analysis described in the main body of the paper. Part 11.3 provides proofs to the four propositions in the paper. Finally, part 11.4 provides a detailed description of the extensions performed in section 8 as well as their solution and their calibration. The final section of part 11.4 also compares the results of the different extensions to each other, to the baseline and to the data.

11.1 Data Sources

GDP (PPP) and Labor Force Data I use data from Penn World Tables version 7.1. (see Heston et al. (2012)) to construct annual time series of PPP-adjusted GDP in constant 1990 prices, PPP-adjusted GDP per worker in 1990 constant prices, and total employment between 1950-2010. For each country, I construct total employment L using the variables Population (POP), PPP Converted GDP Chain per worker at 2005 constant prices (RGDPWOK), and PPP Converted GDP Per Capita (Chain Series) at 2005 constant prices (RGDPCH) as $L = (RGDPCH \times POP)/RGDPWOK$. I then construct PPP-adjusted GDP in constant 2005 prices using the variables "PPP Converted GDP Per Capita (Laspeyres), derived from growth rates of c, g, i, at 2005 constant prices (RGDPL)" and "Population (POP)" as $GDPK = RGDPL \times POP$. I then re-base the 2005 data to 1990 prices.

I extend the labor force and GDP data calculated above back in time for the period 1750-1950 using growth rates from Maddison (2007). In particular, I calculate the pre-1950 growth rates for Maddison's GDP measure (in 1990 Geary-Khamis dollars) and use it to extend the GDP measure calculate above. I also calculate the population growth rates from Maddison's data and assume that the growth rate of the labor force pre-1950 is the same as the growth rate of the population (which is true if the labor force to population ratio stays constant over time). I then use these population growth rates to extend the labor force data calculated above back in time. The series for PPP-adjusted GDP per worker in constant prices is then computed as $y = GDP/L$. Finally, I smooth the GDP and labor force data using an HP filter, with smoothing parameter $\lambda = 100$. In the main body of the text, GDP and labor force data are referred to as GDP_t and L_t respectively.

Agricultural and Non-Agricultural Employment I construct contemporary (1980-2010) agricultural employment share using data from the FAOSTAT (2012) by taking the ratio of economically active population (labor force) in agriculture to total economically active population (labor force). For the UK, I then combine this with the agricultural employment share from Maddison (1995) for 1820-1980. I then obtain total employment in agriculture by multiplying the agricultural employment shares calculated above by the labor force data found in the previous paragraph. Non-agricultural employment is then the difference between total employment and agricultural employment. In the main body of the text, agricultural and non-agricultural employment data are referred to as L_{At} and L_{Ct} respectively. For the extensions of the baseline model I obtain data for industrial and services sector employment from the (Timmer and de Vries, 2007) and WDI (2013). In particular, I first calculate the fraction of non-agriculture workers employed in industry and then multiply this by L_{Ct}

to obtain employment in industry. Taking the difference between L_{Ct} and the number of workers employed in industry gives the number of workers employed in the service sector. When calculating the ratio of $L^{y}_{Ct}/L^{e}_{Ct} = x_{Ct}$ in section 5, I take L^{e}_{Ct} to be employment in mining and utilities and L^{y}_{Ct} to be employment in non-agriculture except mining and utilities. This data comes from the ILOSTAT Online Database and combines the ISIC 3 and ISIC 2 measures.

Contemporary and Historical Emissions Data This paper focuses on CO_2 emissions derived from energy use. Since historical energy production and trade is well documented, this allows for the estimation of long run carbon emissions 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).[59] 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 1950-2010 CO_2 emission estimates reported by Andres et al. (1999) are derived primarily from energy consumption statistics published by the United Nations Nations (2006) using the methods of Marland and Rotty (1984). The data is now maintained and updated by the Carbon Dioxide Information Analysis Center (Boden et al., 2013).[60]

In the main body of the text, carbon emission data are referred to as P_t.

Figure 1(a) plots total CO_2 emissions per dollars of GDP for 26 OECD countries versus each country's GDP per capita, for the years 1820-2010. The countries and the years under consideration are: Canada (1870-2010), Mexico (1900-2010), United States (1870-2010), Japan (1875-2010), Korea, Rep. (1945-2010), Australia (1875-2010), New Zealand (1878-2010), Austria (1870-2010), Belgium (1846-2010), Denmark (1843-2010), Finland (1860-2010), France (1820-2010), Germany (1850-2010), Greece (1921-2010), Hungary (1924-1942; 1946-2010), Ireland (1924-2010), Italy (1861-2010), Netherlands (1846-2010), Norway (1835-2010), Poland (1929-1938; 1950-2010), Portugal (1870-2010), Spain (1850-2010), Sweden (1839-2010), Switzerland (1858-2010), Turkey (1923-2010) and the United Kingdom (1830-2010). The Czech and Slovak Republics, Iceland and Luxembourg were not considered due to the lack of data. Emissions of CO_2 are measured in thousands of metric tons of carbon and the data comes from Andres et al. (1999).

Energy Consumption Data Whilst historical data on modern, non-biomass energy consumption is well documented, the consumption of traditional or biomass fuels is not as well documented. For the United Kingdom I obtain modern (non-biomass) energy consumption data from Fouquet and Pearson (1998) for 1800-1960 and from DUKES (2012) for 1970-2010. This energy consists of coal, petroleum, natural gas, nuclear and other non-fossil-fuels (wind, hydro and solar). I obtain the share of biomass energy used by the UK from Krausmann et al. (2008a) for the years 1820-2000. I then extrapolate this last measure between 2001-2010 by assuming that the share of biomass energy declined at the average 1820-2000 rate. Next, I combine the modern energy data with the biomass

[59] Mitchell's work tabulates solid and liquid fuel imports and exports by nation and year.
[60] The data is available for download at http://cdiac.ornl.gov/trends/emis/overview.html.

share to construct total energy consumed by the UK. In the main body of the text, the above measure of modern (non-biomass) energy consumption data is referred to as E_{Ct}, whilst the above measure of biomass energy consumption is referred to as E_{At}.

I obtain the cross-section of biomass (or traditional) energy share in the year 2000 from Krausmann et al. (2008b), who performs a very careful global energy accounting exercise for 175 countries in the year 2000. Importantly, this measure is comparable to the biomass energy share used to calibrate the UK model in Krausmann et al. (2008a). Finally, modern energy data for 1980-2010 comes from the WDI (2013) and is defined as the use of (non-biomass) primary energy before transformation to other end-use fuels.

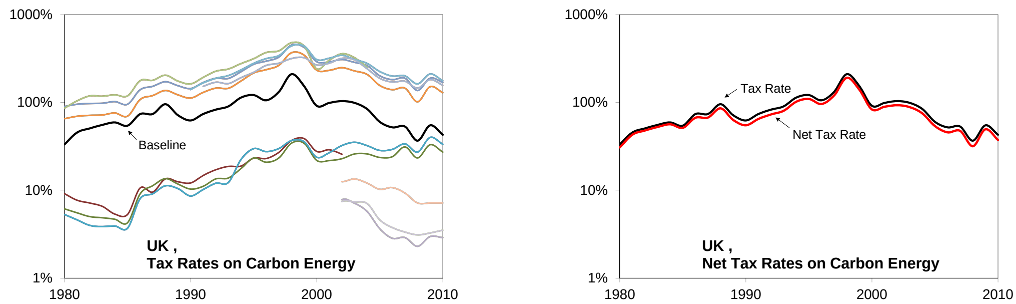
Net fossil-fuel Subsidies in the UK To construct net fossil-fuel subsidies, I build separate measures of tax rates and of subsidy rates and subtract these from each other to obtain net subsidy rates. Importantly, this series is constructed very carefully for the 1980-2010 period. Pre-1980, however, the same data is not readily available and the resulting series is a best guess. Notice, however, that in the key cross-country exercise of the paper, I only make use of the post-1980 data and thus the diminished accuracy of the pre-1980 estimates does not effect the implied cross-country wedges calculated in the main exercise of the paper.

First, I calculate the value of government tax revenues stemming from fossil-fuels using IFS (2013) for the period 1980-2010. In this measure, I include revenues from the petroleum revenue tax, the supplementary petroleum duty, fuel duties, the climate change levy and oil royalties. I then take the consumption of fossil-fuel energy (expressed in barrels of oil equivalent) from DUKES (2012) and multiply it by the price of a barrel of Brent crude oil from BP (2008) to calculate an estimate of the tax/subsidy-free value of energy consumption in the UK.[61] Dividing my measure of tax revenues stemming from fossil-fuels by the above tax-free value of oil consumption gives me a measure of the average tax rate on fossil-fuels in the UK. This baseline tax rate is shown in Figure 15(a). Also included in the figure are the tax rates for different classes of energy products in the UK over the period as set directly by Her Majesty's Revenues and Customs and obtained from OECD.Stat (2013).[62] The baseline tax rate I calculate lies in the middle of the directly observed tax rates on individual energy products. This is unsurprising since the baseline tax rate is fundamentally a weighted average of product-specific tax rates. Notice that I use the above method of estimating the baseline tax-rate (instead of taking a weighted-average) since I do not have access to consumption levels of each type of energy product.

Next, I calculate estimates of fossil-fuel energy subsidy rates over the 1980-2010 period. This is a harder and less accurate exercise. Whilst, in general, there is no comprehensive and comparable database on directly measured fossil-fuel subsidies, the OECD (2015) has constructed a very limited directly measured database for several OECD members measuring fossil-fuel subsidies for the years

[61] I am thus assuming that the price of a barrel of Brent crude oil is equal to the tax/subsidy free price of a barrel of oil equivalent of any other fossil-fuel energy in the UK. I do this as this is the best estimate of an undistorted energy price.

[62] In particular the figure shows household and industry tax rates on: High and Low sulphur fuel oil, Light fuel oil, Automotive diesel, Premium leaded gasoline, Premium unleaded 95 and 98 RON, Regular unleaded gasoline, Natural gas, Steam coal, Coking coal and Electricity.



(a) Individual tax rates of different carbon fuels (such as 'Premium Leaded Gasoline', 'High Sulphur Fuel Oil', 'Coking Coal' etc.) and the resulting average carbon tax rate ('Baseline') used in the Paper. See text for more details.

(b) The Baseline average carbon tax rate (reproduced from Part (a) of this Figure) and the resulting net-tax rate.

Figure 15: Tax rates of carbon fossil-fuels in UK, 1980-2010.

2005-2010.[63] Subsidies over this period were 'some of the smallest in the OECD' and averaged a stable 0.23% of GDP between 2005 and 2010. Since data before 2005 is unavailable, I assume that subsidies between 1980 and 2004 were also 0.23% of GDP per year. Given this assumption and the subsidy data for the post 2005 period, I can calculate an estimate of the size of UK government expenditures on fossil-fuel subsidies over the 1980-2010 period. Dividing this measure by the (undistorted) value of fossil-fuel energy consumed by the UK, calculated above, results in an estimate of the subsidy rates imposed on fossil-fuel energy. Subtracting the tax rate from the subsidy rate gives me the net subsidy rate in the UK. I plot (the negative of) this in Figure 15(b). From the Figure we see that the UK had large energy taxes over the period (i.e. the negative energy subsidies) and that this tax was increasing until 1998 after which it has been steadily declining.

Calculating net-subsidy rate data on fossil-fuels before 1980 is difficult as the necessary revenue data is unavailable. I proceed as follows. I extend the tax rate on fossil-fuels calculated above to 1900 by using the growth rates of gasoline taxes obtained from Bolton (2014). I then extend the resulting series back to 1820 by using data on coal duties obtained from Hausman (1987). As for subsidies, I assume that pre-1980, energy subsidies were zero. Whilst this is certainly an oversimplification, this is the best we can do given the lack of data. Notice, again that since in the cross country estimates I only use post-1980 data, this does not affect the key results of the paper. Missing values are linearly interpolated. The resulting net subsidies are presented in Figure 3 in the main body of the paper and are referred to as τ_t.

Notice that whilst my tax-estimates above are reasonably accurate (as they are comprehensive and measured directly from government databases), subsidy estimates are harder to calculate and probably less accurate. The OECD subsidy estimates are constructed by tallying up the value of observed subsidy programs. As such estimated subsidies in the UK are likely underestimates - since they probably miss more opaque subsidies that were unmeasured or unmeasurable. The impact of this on my cross-country estimates is to also underestimate subsidies in the rest of the world. Given

[63] Notice, that the data is not comparable across countries, but will be sufficient to judge the size of direct energy subsidies in the UK only.

the differences in each country's emission intensity, if gross subsidy rates are higher in the UK than what is calculated here, then other countries must have even higher subsidy rates to generate the observed differences in emission intensity across countries. As such, the subsidy figures that emerge from this study are on the conservative side.

Constant and Current Price Sectoral and Aggregate Value Added Data on constant and current price agricultural, non-agricultural and total value added for 1970-2010 comes from the UN. This database provides sectoral value-added data at the one digit ISIC v.3 level in both current local currency prices and constant 1990 local currency prices. Non-agriculture is taken to all sectors except agriculture.

For the UK, I then proceed to extend this data backwards. First, I take the constant price (1990) sectoral value-added data in local currency prices and extend this back to 1855, using sectoral value added growth rates from the Groningen Growth and Development Center (GGDC). In particular I use the 10-Sector Productivity Database by (Timmer and de Vries, 2007) and the Historical National Accounts by Smits et al. (2009). Second, I extend the resulting sequence of data back to 1820 using growth rates from Broadberry and van Leeuwen (2010). In the robustness section, in the paragraph on measured productivity I use this data to calibrate sectoral productivities. Next, to construct current price sectoral GDP, I first obtain nominal total value-added data for 1820-2010. I begin with data from the UN for 1970-2010 which I extend backwards to 1830 using nominal GDP growth rates from Hills et al. (2010). Finally, I extend the resultant sequence back to 1820 using nominal GDP growth rates from Mitchell (2011). Having done this, I calculate current price sectoral value added shares for agriculture from UN for 1970-2010 and combine this with current price agricultural share for 1820-1970 from Buera and Kaboski (2008). I then multiply the agricultural value added shares (as well as one minus the agricultural value added share) by the current price value added series (calculated above) to obtain current price sectoral value added.

Historical Prices in the UK Wage data for craftsmen and farmers (1820-1914) comes from Greg Clark, on the Global Price and Income History Group web site.[64] The wage data for craftsmen is extended to 2010 using average nominal earnings data from Officer (2011). The data for fuel wood prices also comes from Greg Clark in the same data file for the year 1820-1869. For the price of fossil-fuels, I take the consumer price of coal in constant 2000 GBP from Fouquet (2011). The assumption here is that the price of a unit of energy is equalized across modern-energy types. Using historical tax data from above, I extract the net-of-tax nominal price of coal, and then multiply by the net-subsidy data derived above, i.e. by $(1-\tau_t)$, to find the nominal, after-subsidy price of coal. I convert this price back into nominal GBP using the CPI from Officer (2011). To construct the price indices for agriculture and non-agriculture, I take the ratio of current price sectoral value added to the corresponding constant price sectoral value added calculated in the previous paragraph.

Contemporary Agricultural and Non-agricultural Prices Sectoral price indices for the 1980-2010 period come from the UN. In particular, I obtain one digit ISIC v.3 sectoral value-added data

[64] Available at http://gpih.ucdavis.edu/Datafilelist.htm, in the file 'England prices and wages since 13th Century (Clark)'

Activity	hrs/person/day Men	Women	Children	hrs/HH/day Household†	HH Shares
Field Work	3.10	2.75	0.05	6.00	27.33%
Grazing	0.00	0.00	1.80	5.40	24.60%
Cooking	0.38	2.10	···	2.48	11.28%
Grass Collection	0.35	0.98	0.28	2.15	9.79%
Water	0.10	1.15	0.23	1.93	8.77%
Fuel Wood Collection	0.13	1.15	0.13	1.65	7.52%
Employment	0.80	0.13	···	0.93	4.21%
Food processing	0.20	0.70	···	0.90	4.10%
Leaf Fodder	0.10	0.35	0.03	0.53	2.39%
TOTAL	5.15	9.30	2.50	21.95	100.00%

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

Table 6: Patterns of time allocation in Nepal for Men, Women, Children and Households.

in constant 1990 USD prices ($VA^{1990}_{s,t}$) and current prices ($VA_{s,t}$) which can be used to calculate an index of sectoral prices relative to a base year: $P_{s,t}/P^{1990}_{s} = VA_{s,t}/VA^{1990}_{s,t}$.

Energy Share in Agriculture Table 6 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 International Food Policy Research Institute.[65] In particular, the first three columns of the table show the number of hours per person per day that were devoted to a particular activity. Kumar and Hotchkiss (1988) present the data disaggregated by season - the data in the above table, 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,[66] the average size of an agricultural household in Nepal is approximately 5 people - a man, a woman and three children. 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 Nepalese agricultural household/producer in each one of the above activities. From this, the fraction of time spent on fuel wood collection is approximately eight percent, which implies that, $1 - \alpha_A = 0.08$.

Energy Share in Non-Agriculture I construct s^e_{Ct}, the current price share of modern energy consumption in non-agricultural value added, by multiplying the nominal (after-subsidy) coal price by total modern (non-biomass) energy consumption (E_{Ct}) and dividing by current-price non-agricultural value added. The construction of all values is given above. Once s^e_{Ct} is determined, labor's share of income in non-agriculture is simply $s^l_{Ct} = 1 - s^e_{Ct}$.

[65] "Nepal Energy and Nutrition Survey, 1982/83," Western Region, Nepal.
[66] http://www.cbs.gov.np/nlfs_%20report_demographic_characteristics.php.

Employment in Modern Energy Production in the UK I construct an estimate of the employment in modern energy production in the UK, L^e_{Ct}, for 1980-2010 using data from the GGDC (Timmer and de Vries, 2007). This data is used in the robustness exercise that looks at measured productivity. Using the data I calculate the share of workers employed in the mining, manufacturing and utilities sectors in the UK. I then multiply the resulting share by the total labor force estimated above.

Directly measured fossil-fuel subsidies in the US Here I describe the sources, and definitions of the directly measured fossil fuel subsidies in the US shown in Table 11. The items below refer to the Table's columns.

(1) 'The value shifted from the federal government to (fossil-fuel) energy producers and consumers'. Values for 65 federal subsidy programs (8 pre-production, 32 production, 3 consumption, 5 post-production, 8 security, 2 environment, 2 road infrastructure, 5 housing/building infrastructure). Source: Koplow (2004);

(2-4) 'Direct budgetary transfers and tax expenditures that relate to fossil fuels, regardless of their impact or of the purpose for which the measures were first put in place'. Values for 15 federal subsidy programs (1 pre-production, 11 production, 1 consumption, 2 security) and 131 state level programs (4 pre-production, 62 production, 65 consumption). Source: OECD (2015);

(5) 'Tax preferences for fossil-fuel production activities and consumption subsidies funded by the Federal government'. Values for 12 federal subsidy programs (11 production, 1 consumption). Source: OMB (2015);

(6-7) 'Support for the (fossil-fuel) energy sector from targeted tax incentives, or tax incentives only available for the (fossil-fuel) energy industry'. Estimated revenue cost of 9 federal energy tax provisions (all producer). Source: Joint Committee on Taxation and the Department of the Treasury in Sherlock and Stupak (2015);

(8) 'Direct federal financial interventions and subsidies that are provided by the federal government, provide a financial benefit with an identifiable federal budget impact, and are specifically targeted at energy markets'. At least 18 federal programs (17 production and 1 pre-production). Subsidies are defined as policies specifically targeted at energy that provide a financial benefit with an identifiable federal budget impact. Source: EIA (2011).

11.2 Empirical Appendix

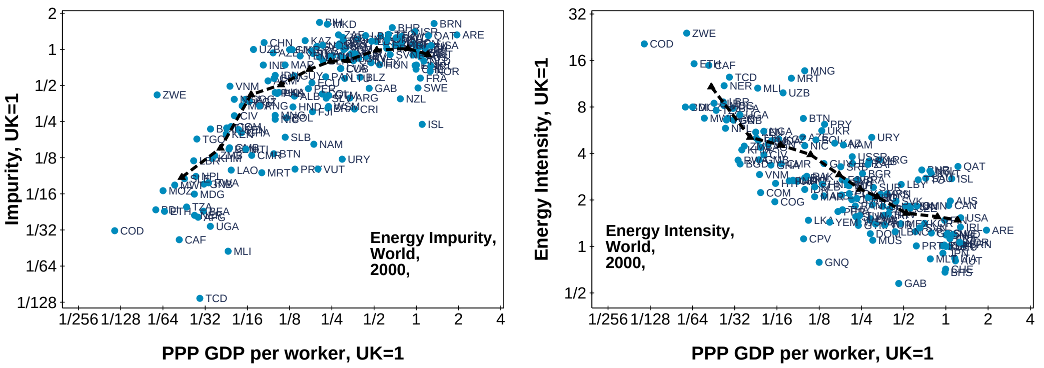
Pollution Decomposition in World, EU and US I perform the pollution accounting exercise described in section 2 (equation (1)) for a cross-section of global data, a long-run panel of EU countries as well as a long run time series of US data. The data for this exercise comes form three sources. The cross-section of global energy data comes from the Krausmann et al. (2008b). European energy data comes from Gales et al. (2007) who "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: Sweden (1820-2000), Holland (1846-2000), Italy (1861-2000) and Spain (1850-1935; 1940-2000). Data for the United States (1800-2001) comes from Wright (2006) and Grubler (2003). In their case, energy consumption consists of wood, coal, petroleum, natural gas, hydroelectric power, nuclear electric power and geothermal energy. Notice that since the above energy data (as well as the energy data for the UK used in the pollution accounting exercise in the main body of the paper) come from different sources and consists of slightly different energy types, they are not directly comparable to each other and are presented separately. For the cross-sectional exercise, GDP and labor force data come from Heston et al. (2012). For the panel data, GDP and population data come from Maddison (2007). Finally, carbon emissions data comes from Boden et al. (2013).

Figure 16 presents the results of the exercise. Energy impurity in the world, the EU and the US increases with GDP per worker (or per capita), whilst energy intensity falls. The increase in impurity predominantly takes place at low levels of income, whereas falling energy intensity seems to be a more continuous process. The implication of this is that the increases in emission intensity observed in low income countries is driven predominantly by rising impurity, whereas falling emission intensities in richer countries are driven predominantly by falling energy intensity.

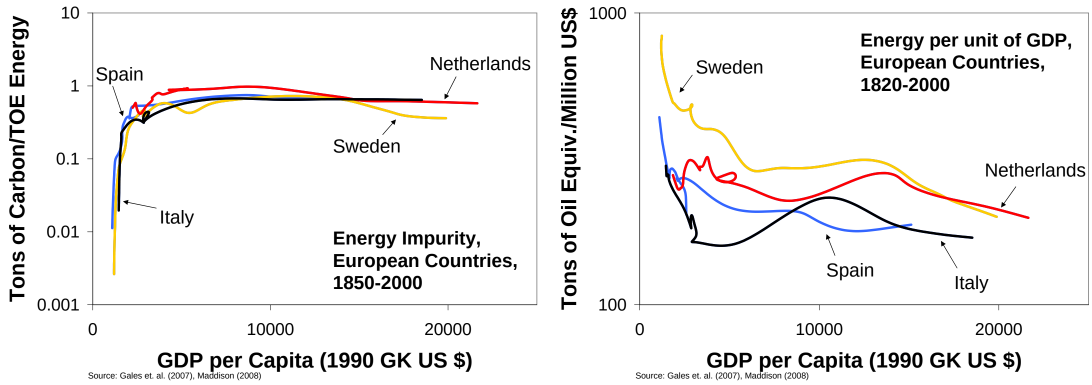
Fuel Mix and Structural Transformation I show evidence that structural transformation - the shift of an economy from agriculture to non-agriculture - is associated with changing fuel mix. I take the share of labor force employed in agriculture as a measure of the progress of structural transformation - countries with a lower shares of agriculture are further along in their structural transformation. Sources for energy consumption data are described in the previous paragraph. For the cross-sectional exercise, agricultural employment data comes form the FAOSTAT (2012). For European countries the sources for agriculture employment data are: Smits and van Zanden (2000) for the Netherlands (1849-1950), de la Escosura (2006) for Spain (1850-1950), Kuznets (1971) for Italy (1866-1891) and Edvinsson (2005) for Sweden (1850-1955), whilst 1956-2000 data for all countries comes from the OECD (2013). Employment data for the US comes from Wright (2006) (1800-1890), Kendrick (1961) (1890-1960) and OECD (2013) (1960-2000).

Figure 17 shows the extent to which the progress of structural transformation in a country is related to its fuel mix. From the graphs it is clear that countries at earlier stages of structural transformation derive a larger share of their energy from renewable combustibles. Countries at later stages derive a greater share of their energy needs from fossil-fuels.

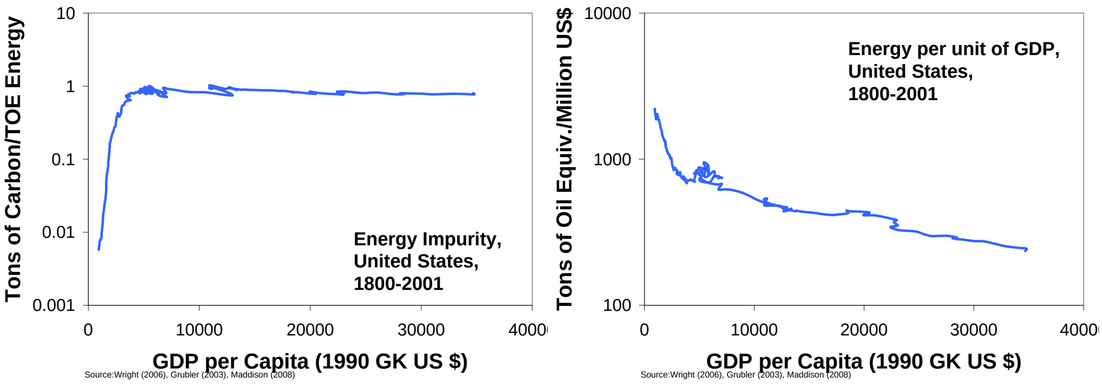
Hump Shape As I argue in the main body of the text, the hump-shaped pattern of emission intensity for carbon dioxide is relatively well known. Here I produce some additional evidence of this fact. Using carbon data from the Boden et al. (2013) as well as GDP and GDP per capita data from Maddison (2007) for 152 countries for the period 1750-2008, Table 7 shows the results of regressing the log of emission intensities on the log of GDP per capita and its square. The negative coefficient on the squared term indicates the existence of a hump-shaped emission intensity with income. The result is robust to including time- and country-fixed effects and to considering different sub-samples of the data; for example excluding OPEC countries and former/current communist



(a) Energy Impurity and Intensity in the World (2000)

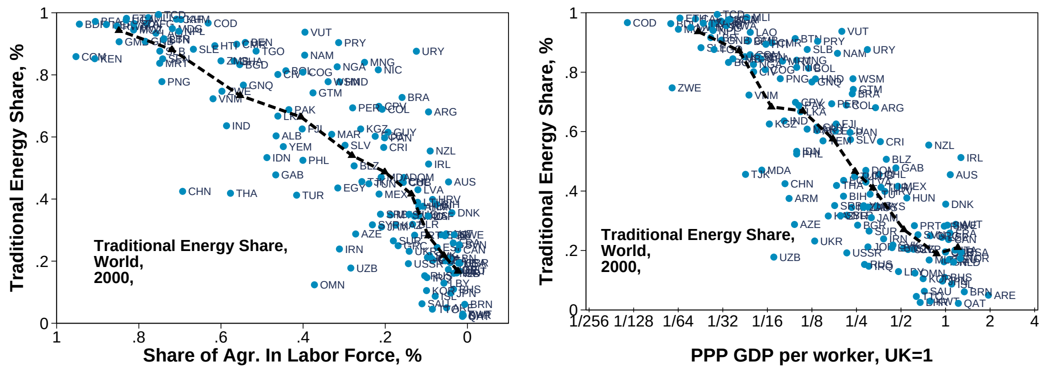


(b) Energy Impurity and Intensity of Selected European Countries, 1820-2000

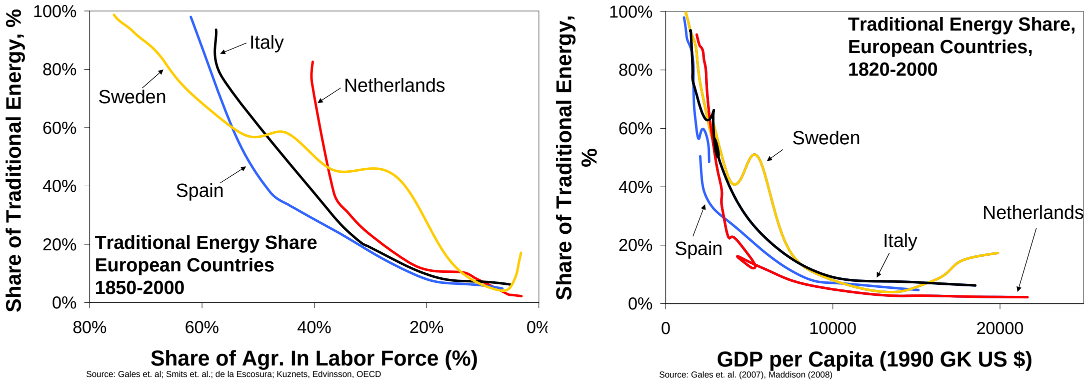


(c) Energy Impurity and Intensity of the US, 1800-2001

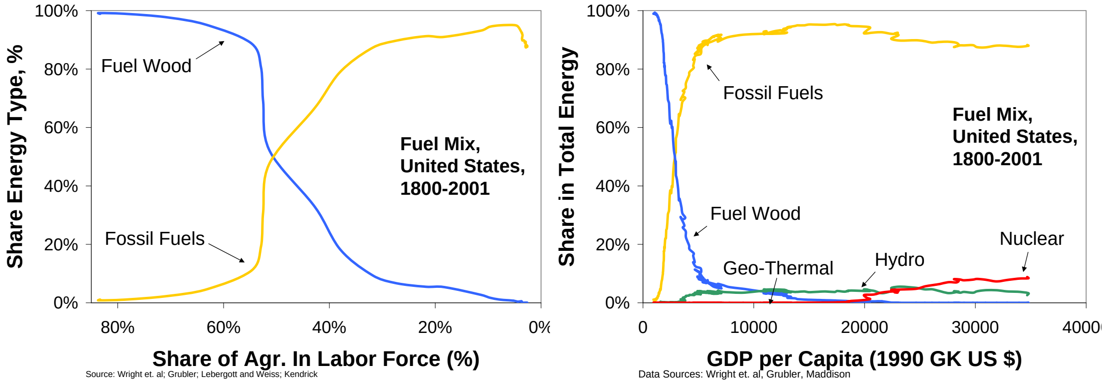
Figure 16: Decomposition of emission intensity into energy impurity and energy intensity terms for the World (1980-2005), selected EU countries (1820-2000) and the US (1800-2001).



(a) World Cross-Section (2000)



(b) EU (1820-2000)



(c) US (1800-2001)

Figure 17: Changes in fuel mix versus GDP per capita and agricultural employment share.

	(1) log(int)	(2) log(int)	(3) log(int)	(4) log(int)	(5) log(int)	(6) log(int)
loggdppc	4.46***	4.78***	5.80***	5.77***	6.07***	10.07***
	(0.14)	(0.14)	(0.13)	(0.13)	(0.14)	(0.29)
loggdppcsq	-0.24***	-0.26***	-0.37***	-0.37***	-0.38***	-0.57***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
Time FE	no	yes	yes	yes	yes	yes
Country FE	no	no	yes	yes	yes	yes
Sample	All	All	All	No OPEC	No OPEC No Comm	OECD
Obs.	10,451	10,451	10,451	9,635	8,140	3,247
R^2	0.29	0.32	0.76	0.78	0.75	0.77

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

Table 7: Regression of the log of emission intensities on the log of GDP per capita (loggdppc) and its square (loggdppcsq). Carbon data from the Boden et al. (2013), GDP and GDP per capita data from Maddison (2007) for 152 countries for the period 1750-2008. Columns (1)-(3) consider all the data (with and without country and time fixed-effects). Columns (4)-(5) examine non-OPEC and non-communist countries. Column (6) examines only OECD countries.

states or only considering the OECD.[67]

Envelope Pattern In this section I establish the existence of an envelope pattern in the data for carbon emission-intensities. In particular, I show that emission intensities of individual countries peak roughly at the level of intensity of the United Kingdom in the corresponding year and then they proceed to to decline at a rate similar to that of the UK emission intensity. In the baseline experiment I focus on 24 (pre-1994) OECD member countries over the 1751-2008 period. Figure 18 presents the emission intensities of these countries versus time. Whilst there is substantial variance in the data, an envelope pattern is discernable. Table 8 among other data shows - for each country - the year its intensity peaks, the average growth rate of emission intensity after a country's intensity peaks as well as each country's intensity relative to that of the UK at the time when the country's intensity peaked. From this we see that - on average - countries in the OECD peak at 83% of the UK's intensity in the corresponding year after which they decline at an average rate of 1.27% versus the UK's 1.46%. The bottom of Table 9, shows the summary statistics of this data including the standard errors and 95% confidence intervals. This demonstrates that I cannot reject the null hypothesis that the mean rate of decline of intensity in the OECD is statistically the same as the rate of decline of intensity in the UK.

In the above I focus on OECD countries as these have the longest time series and - more importantly - since these countries are a-priori most likely to have undistorted energy policies.[68]

[67] Throughout the paper I take the following as present or ex-communist states: Afghanistan, Angola, Albania, Armenia, Azerbaijan, Benin, Bulgaria, Belarus, China, Congo, Czechoslovakia, Cuba, Czech Republic, Estonia, Georgia, Croatia, Hungary, Kazakhstan, Kyrgyz Republic, Lithuania, Latvia, Moldova, Macedonia, Mongolia, Mozambique, Poland, North Korea, Romania, Russia, Somalia, Yugoslavia, Slovak Republic, Slovenia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan, Vietnam.

[68] Since the point of this paper is that energy policies drive emission intensities, it is logical to consider countries

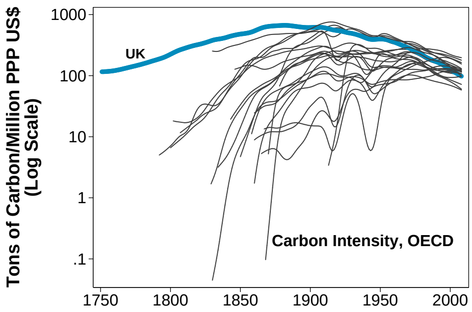


Figure 18: Envelope Pattern in OECD Carbon Emission Intensities, (tons of carbon/million 1990 international USD). Each line represents the carbon emission intensity of one country from the OECD over time. The thick blue line shows the carbon emission intensity of the UK.

Nonetheless largely similar results hold in a much broader sample of countries. In Table 9, I present estimates of the mean and median maximum emission intensities (relative to the corresponding UK intensity) as well as the mean and median rate of decline of emission intensities after a peak is reached for a variety of data samples. In the entire sample, emissions tend to peak much higher than the UK's intensity - on average 1.56 times that of the UK and the rate of decline tends to be much higher than that of the UK as well - 2.39%. Notice, however, the large difference between the medians and the means. This is indicative that outliers are driving the results. Two obvious groups of countries spring to mind as potential culprits - OPEC countries and current or former communist regimes. Both groups of countries are notorious for subsidizing carbon energy and heavy industry, which - as I argue in the paper - drives up emission intensities. Also, after the collapse of communism, many of these heavy industries were shut as subsidies were revoked which would contribute to rapidly declining intensity. Excluding OPEC and Communist countries from the sample brings down the mean to 0.83 - the same as in the OECD and the growth rate to -1.64% - faster than the OECD but not statistically different from that of the UK. Notice that since excluding OPEC countries does not significantly affect the rate of decline of intensity but does impact the average level at which countries peaked, this implies that emission intensities peaked at high levels in both OPEC and communist countries, but that intensities in OPEC countries have remained high, whereas those in communist countries have tended to fall rapidly. This is consistent with the rapid decline of intensity after the collapse of communism in former-eastern bloc countries.

Agricultural Carbon Emissions In the baseline model, I abstract from carbon energy use (and hence carbon emissions from energy) in the agricultural sector. I argue that in poor countries, the agricultural sector tends to be largely traditional and hence its primary source of energy will be bio-fuels which are carbon neutral.[69] Whereas in rich countries, although a high proportion of carbon fuels is used in agriculture, the size of the agricultural sector tends to be small and so the share of carbon energy used in agriculture in total carbon energy will also be small. In this section, I justify these assumptions.

where energy policy is presumably muted.

[69] Recall, I am not focusing on carbon emissions arising from changes in land-use changes.

	(1) Agr. Emp. Share 1980	(2) Agr. Emp. Share 1956	(3) Gr. Intensity before Peak	(4) Year of Peak	(5) Gr. Intensity after Peak	(6) Intensity Rel. to UK at Peak	(7) Max. Intensity
GBR	2.7%	5.1%	1.51%	1882	-1.46%	1.00	667
BEL	3.2%	8.7%	0.72%	1929	-2.04%	1.18	583
USA	3.5%	9.8%	4.43%	1915	-1.57%	1.33	757
NLD	5.0%	11.3%	0.88%	1932	-0.87%	0.54	259
CHE	5.5%	17.1%	3.91%	1910	-0.41%	0.23	140
SWE	6.1%	17.3%	5.95%	1908	-0.83%	0.38	237
AUS	6.5%	12.0%	1.97%	1982	-1.51%	1.35	277
CAN	6.7%	16.4%	6.66%	1920	-1.31%	1.12	609
DNK	6.9%	21.2%	1.59%	1969	-2.48%	0.84	247
DEU	6.9%	16.9%	4.24%	1917	-1.68%	1.20	671
NOR	8.2%	24.2%	5.66%	1910	-1.08%	0.50	303
FRA	8.5%	25.4%	2.63%	1928	-2.02%	0.68	342
NZL	9.8%	16.4%	3.41%	1909	-0.36%	0.37	229
AUT	9.8%	26.4%	3.81%	1908	-0.89%	0.87	538
JPN	11.0%	36.0%	9.58%	1928	-0.67%	0.41	205
FIN	12.1%	47.9%	2.94%	1974	-1.73%	0.98	252
ITA	12.7%	37.3%	1.95%	1973	-1.07%	0.59	158
ESP	18.4%	44.0%	3.39%	1977	-0.94%	0.70	165
IRL	18.6%	38.5%	26.00%	1934	-1.05%	0.70	324
PRT	26.4%	45.2%	0.59%	1999	-1.43%	0.92	120
GRC	32.2%	59.3%	2.44%	1995	-2.14%	1.34	199
TUR	53.0%	79.5%	2.94%	1997	-0.53%	0.94	131
Average	12.4%	28.0%	4.42%	1941	-1.28%	0.83	337
Median	8.4%	22.7%	3.17%	1929	-1.20%	0.86	256

Table 8: Evidence of the 'envelope-pattern' in carbon emission intensities in the OECD. (1) Agricultural employment share in 1980 (2) Agricultural employment share in 1956 (3) Growth rate of emission intensity before a country's intensity peaks (4) The year of a country's emission intensity peak (5) Growth rate of emission intensity after a country's intensity peaks (6) The emission intensity of a country relative to that of the UK in the year a given country's intensity peaks (7) Emission intensity of a country at its peak.

I obtain data on the carbon emissions of agriculture from energy consumption from the FAOSTAT (2012). This includes energy use from: gasoline, gas-diesel oils, natural gas (including LNG), residual fuel oil, liquefied petroleum gas (LPG), hard coal and electricity.[70] The data is for the years 1970-2010. For the 1970s there are on average 70 countries per year. For the 1980s and 1990s there are on average 93 countries and for the 2000s there are on average 110 countries in the data. In total there are 3743 data points. The median share of agricultural carbon emissions from energy use in total carbon emissions is 2.1%, whilst the mean is 3.6%. Thus, energy use in agriculture contributes little to total carbon emissions. Furthermore, the importance of agricultural carbon energy use does not vary over the development process. Table 10 shows regressions of the share of carbon emissions from agricultural fuel consumption relative to total carbon emissions versus the log of GDP per worker (columns 1-3) as well as versus the share of agricultural employment in the economy (with and without time and country fixed effects). Notice that the share of emissions coming from agriculture is low (the constant term in columns 1 and 4) and more importantly that this proportion is largely invariant with the changing size of agriculture and per worker income.

[70] Notice that other sources of greenhouse gases in agriculture are crop residues, cultivation of organic soils, enteric fermentation, manure applied to soils, manure left on pastures, manure management, rice cultivation and synthetic fertilizers. However, according to FAOSTAT (2012), these processes emit only methane (CH_4) and nitrous oxide (N_2O) and *not* carbon dioxide. As mentioned above, the only other source of carbon dioxide emissions from agriculture are land-use changes, which again are not the focus of this paper

	(1) Peak Intensity rel. to UK			(2) Growth in Intensity after Peak		
	Obs	Mean	Median	Obs	Mean	Median
All	129	1.56	1.03	128	-0.0239	-0.0169
		[1.21,1.91]	[0.85,1.20]		[-0.0277,-0.0201]	[-0.0201,-0.0136]
		0.18	0.09		0.0019	0.0017
No OPEC	121	1.31	0.97	120	-0.0244	-0.0169
		[1.05,1.57]	[0.78,1.15]		[-0.0284,-0.0204]	[-0.0204,-0.0133]
		0.13	0.09		0.0020	0.0018
No OPEC	85	0.83	0.78	84	-0.0164	-0.0117
& No Comm		[0.69,0.97]	[0.63,0.93]		[-0.0196,-0.0131]	[-0.0147,-0.0086]
		0.07	0.08		0.0017	0.0016
OECD	22	0.83	0.86	22	-0.0128	-0.0120
		[0.67,0.98]	[0.64,1.08]		[-0.0153,-0.0102]	[-0.0157,-0.0082]
		0.07	0.11		0.0012	0.0019

Table 9: Evidence of the 'envelope-pattern' in carbon emission intensity data. The first set of columns shows the mean and median of the maximum emission intensity of each country relative to that of the UK in the same year. The second set of columns shows the mean and median growth rates of emission intensity subsequent to a country's emission intensity having peaked. The groups of countries considered are: all countries, all countries excluding OPEC countries, all countries excluding OPEC countries and excluding (former) communist states, all OECD countries. See the Appendix for data sources.

Thus, the assumption not to include agricultural carbon emissions arising from energy in the model does not seem to be quantitatively important.

Direct Comparison with IEA and IMF data In the body of the paper I construct a price-gap measure of subsidies and compare it with the subsidy estimates arising from my model. Whilst my price-gap measure closely follows the methodology of the IMF (2013) and the IEA (2010) it is necessarily somewhat different.

First, the IEA (2010) and the IMF (2013) 'left-censor' their data. This means that when they find local prices of carbon energy that are higher than the international benchmark price, instead of reporting the corresponding 'negative-subsidy' (i.e. a tax) they report a subsidy of zero instead. Given that their positive subsidy estimates capture net-subsidies, this left-censoring of the data is somewhat arbitrary, results in a loss of information and introduces an upward bias in the average levels of their subsidies. Second, the IMF (2013) price-gap subsidy measure is only carried out for the year 2011, but my subsidy dataset extends only up to 2010.[71] As to the IEA (2010) data, it offers information for only 31 countries for the years 2009 and 2010. This is a relatively limited sample of data against which to test the implications of my model. Furthermore, neither the IMF nor the IEA data provide much variation over time, further limiting my ability to test my model's predictions. Third, neither the IEA (2010) nor the IMF (2013) provide data on subsidy *rates*. Instead, both papers only publish total subsidies in (current year) US dollars. Since these are not unit-less measures of subsidies and depend on the year of measurement, the quantity of energy used in a country and the level of the undistorted price of energy, this makes a clean comparison harder since their data needs to be transformed into comparable units. For the above reasons, in

[71] This is largely because a number of databases that I make use of in my model - such as the comparable, global carbon emission data from the CDIAC - stop in 2010.

	(1) agrCarbSh	(2) agrCarbSh	(3) agrCarbSh	(4) agrCarbSh	(5) agrCarbSh	(6) agrCarbSh
log(gdppw)	-0.0014*	-0.0017**	0.0020			
	(0.0008)	(0.0008)	(0.0034)			
agrEmpSh				0.0037	0.0056	0.0175
				(0.0038)	(0.0038)	(0.0195)
Cons.	0.0498***	0.0483***	-0.0326	0.0352***	0.0263***	-0.0159
	(0.0077)	(0.0096)	(0.0465)	(0.0015)	(0.0060)	(0.0308)
Obs.	2,828	2,828	2,828	2,834	2,834	2,834
R^2	0.0011	0.0093	0.6745	0.0003	0.0086	0.6746
Time FE	no	yes	yes	no	yes	yes
Country FE	no	no	yes	no	no	yes

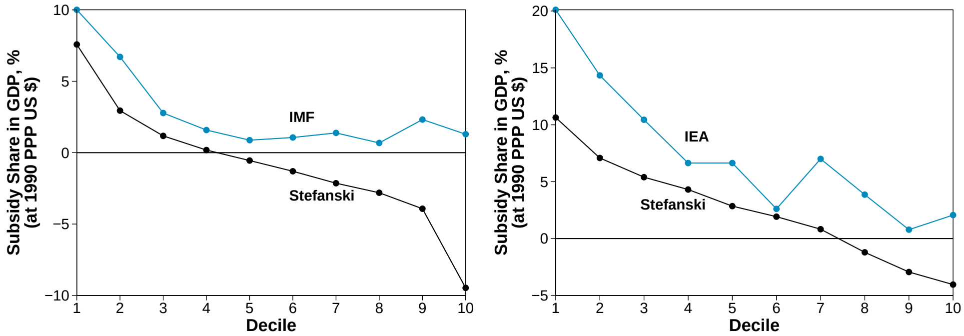
Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 10: Evolution of agricultural carbon emissions with development. The regressions relate the share of a country's total carbon emissions from energy use in agriculture to the log of GDP per worker (in PPP 1990 US $) in columns 1-3 and to a country's agricultural employment share in columns 4-6. Data is for all countries and the years 1970-2010. See Appendix for construction details.

the previous section, I choose to construct my own price-gap measure of fossil-fuel subsidies.

Admittedly, a drawback of my price-gap subsidy estimates is that they are based on only one carbon energy price - the price of petrol at the pump. This means that I implicitly assume that all carbon energy prices are subsidized at the same rate as petrol. The price-gap subsidy rates estimated in the literature however, are usually weighted averages of individual product subsidy rates. The IMF (2013), for example, calculates subsidy rates implied by the price-gap approach for gasoline, diesel, kerosene, coal, natural gas and electricity. It then takes a consumption-weighted average of these subsidy rates to obtain an overall 'aggregate' energy subsidy-rate. To calculate the total value of subsidies (in millions of dollars) it multiplies this consumption-weighted aggregate subsidy-rate by the total value of carbon-energy consumption (in US dollars). Ideally I would want to perform the exact same exercise, leaving data un-censored and comparing my implied subsidy rates to the IMF implied 'aggregate' subsidy rates. However, the (IMF, 2013) does not publish its 'aggregate' subsidy rates and it turns out that it is also difficult to obtain data on individual final energy prices and consumption levels for many of the fuels used by the IMF (2013). In particular, we read in the IMF (2013) paper that data for a number of countries on consumer prices of kerosene, coal, natural gas and electricity were "provided by country authorities to IMF staff" or resulted from "IMF staff estimates". Since neither this data nor the exact methodology has - in general - been made publicly available, I need to restrict myself to data from the Deutsche Gesellschaft fuer Internationale Zusammenarbeit (GIZ) (as reported by the WDI) that *is* available publicly.

Nonetheless, to remain consistent I present a direct comparison of measures of my subsidies and those of the (IMF, 2013) and the IEA (2010). Since the (IMF, 2013) data is for 2011 and my data series stops at 2010, for the IMF exercise I compare 2011 (IMF, 2013) data with my 2010 data. For the IEA exercise, I compare my data to the 31 countries in the IEA exercise in 2009 and 2010. Since data from the IMF (2013) and the IEA (2010) is in current US$ dollars, to make it comparable with



(a) IMF and this paper (2010/2011). (b) IEA and this paper (2009 and 2010).

Figure 19: Value of subsidies as a share of GDP (at 1990 PPP USD) by decile.

my data, I transform the value of subsidies into 1990 PPP dollars, using exchange rates from the WDI. Then, I convert the resulting values into subsidy shares of GDP (measured in constant 1990 US$) in order to make the subsidy measures unit-less. I then calculate the corresponding measure of subsidy shares of GDP in my model. Finally, I sort my subsidy-share data from highest to lowest and divide the resulting data into deciles. I then compare the average subsidy share of each decile in my data with the corresponding IMF and IEA data. I present my findings for the IMF data in Figure 19(a) and for the IEA data in Figure 19(b).

Subsidy-shares estimated using my technique tend to be lower than those of either the IMF and the IEA. In the highest decile, my measures predict that subsidies constitute approximately 7.5% of GDP versus 10% of GDP in the IMF data and 11% versus 20% in the IEA data. The difference is greater in the lowest deciles where I find net-subsidy shares of GDP of on average -9% versus 1.3% for the IMF and -4% versus 2.1% in the IEA data. Neither of these facts is particularly surprising since the IEA and the IMF left-censor their data and I do not. Thus whilst I include 'negative' subsidies amongst my estimates, the lowest estimates in the IMF and IEA data will be zero. Thus - if anything - my data tends to underestimate mean subsidy-shares across countries in comparison to those from the IMF/IEA. Importantly however, there is a strong correlation between my measure of subsidies and those in the IMF and the IEA. Thus - in general - both methodologies are picking up similar trends in cross-country subsidies.

Finally, even though I find that subsidy shares generally tend to be lower using my methodology, I nonetheless find that the value of total global subsidies (in dollar terms) are comparable or even higher than in the IMF/IEA data. The difference stems from predominantly three countries: China, the US and Russia. The IMF find total subsidies in China, Russia and the US to be 46 billion dollars in 2011 (in 1990 PPP US dollars), whilst in the rest of the world they find subsidies to be 583 billion dollars (in 1990 PPP US dollars). On the other hand I find subsidies in China, Russia and the US to be 673 billion dollars (62 percent of which comes from China) and subsidies in all remaining countries considered by the IMF to be 273 billion dollars in 2010. Similarly the IEA paper finds that China and Russia (the IEA do not have data on the US) spent 62 billion dollars (in 1990 PPP US dollars) on subsidies in 2010 whilst the remaining 29 countries spent 555 billion dollars

	(1) Koplow (2003)	(2) OECD (2005)	(3) OECD (2010)	(4) OECD (2014)	(5) OMB (2015)	(6) DOT (2010)	(7) DOT (2015)	(8) EIA (2010)
Pre-production	0.5	0.4	2.7	0.4				0.5
Production	11.0	3.4	4.0	2.4	2.9	1.9	2.8	2.3
Consumption	1.6	3.0	4.3	4.6	2.1			
Post-production	1.6							
Energy security	16.5	0.1	0.1	0.1				
Environment, health, safety	2.4							
Road infrastr. & usage	6.2							
Housing/building infrastr.	91.0							
TOTAL	130.8	6.9	11.1	7.4	5.0	1.9	2.8	2.8

Table 11: Directly measured US fossil-fuel subsidies by sector, various sources (billions, 1990 PPP USD). See Appendix 11.1 for data sources.

(in 1990 PPP US dollars). For the corresponding countries in 2010, my measure of subsidies in China and Russia was 503 billion dollars (in 1990 PPP US dollars) whilst subsidies in the remaining 29 countries totalled 220 billion dollar (in 1990 PPP US dollars). Thus, my methodology predicts lower subsidies in most countries than the methodology of the IMF or the IEA, but picks up larger subsidies in China, the US and Russia than the price-gap approach.

US Directly Measured Fossil Fuel Subsidies Table 11 shows the value of more recent directly measured US fossil-fuel subsidies from studies by: Koplow (2004), the OECD (2015), the Office of Management and Budget (OMB, 2015), the Joint Committee on Taxation and the Department of the Treasury (Sherlock and Stupak, 2015) as well as the U.S. Energy Information Administration (EIA, 2011). Detailed data sources and descriptions are given in Appendix 11.1. The highest and the lowest estimates vary by nearly three orders of magnitude. The table presents a disaggregation of subsidies by target sector which highlights that the main reason for this dispersion are significant differences with respect to which policies are counted as fossil-fuel subsidies. For example, estimates by the DOT only focused on federal subsidies to production sectors. The EIA, counted federal production subsidies but also included some estimates of pre-production (mostly research and development) subsidies. The OMB, did not include subsidies to pre-production but did focus on federal subsidies to production and consumption. The OECD included subsidies at both the federal *and* the state level to pre-production, production and consumption sectors as well as some limited subsidies towards energy security (e.g. subsidies to the Northeast home heating oil reserve). Koplow (2004) focused only on federal subsidies but considered the broadest set of sectors and the largest number of policies. Unlike other studies he also included subsidies to 'Activities that promoted increased energy consumption' in the form of pro-rated subsidies to road, housing and building infrastructure - which were substantial. He also counted the costs of maintaining a strategic petroleum reserve and the (pro-rated) costs of defending oil shipments to the US from the Middle East.

11.3 Theoretical Appendix

Proof Of Proposition 1 Given preferences, equations (3), (4) and (9) imply that:

$$y_{At} = \bar{a} \text{ and } y_{Ct} = \begin{cases} y_{Ct} = (1-\alpha_C)^{\frac{\sigma}{\sigma-1}} B_{Et}B_{eCt}(1+x_{Ct})^{-1}(1+x_{Ct}/(1-\tau_t))^{\frac{\sigma}{\sigma-1}} l_{Ct} & \text{if } \sigma \neq 1 \\ \alpha_C^{\alpha_C}(1-\alpha_C)^{1-\alpha_C}\frac{(1-\tau_t)^{\alpha_C}}{1-\alpha_C\tau_t}(B_{lCt})^{\alpha_C}(B_{Et}B_{eCt})^{1-\alpha_C} l_{Ct} & \text{if } \sigma = 1 \end{cases} \tag{30}$$

where, $l_{Ct} \equiv L_{Ct}/g_N^t$, $y_{Ct} \equiv Y_{Ct}/L_t$ and $y_{At} \equiv Y_{At}/L_t$. Given Assumption 1, the above can be simplified by setting $\tau_t = 0$. Notice also that $d_t \equiv \frac{p_{Ct^*}Y_{Ct}}{p_{At^*}Y_{At}+p_{Ct^*}Y_{Ct}} = \frac{p_{Ct^*}y_{Ct}}{p_{At^*}\bar{a}+p_{Ct^*}y_{Ct}}$. When $L_{At} = L_t$, by the labor market clearing condition $L_{Ct} = 0$ and hence $l_{Ct} = 0$ which - by equation (30) - implies that $y_{Ct} = 0$ and hence $d_t = 0$. Now, suppose $L_{At} < L_t$, then $l_{Ct} > 0$ and hence $y_{Ct} > 0$ (and $d_t > 0$). Given $y_{Ct} > 0$, I show that $\frac{y_{Ct+1}}{y_{Ct}} > 1$ and $\lim_{t\to\infty}\frac{y_{Ct+1}}{y_{Ct}} > 1$, which I will subsequently use to describe the evolution of d_t. There are three cases to consider. First, suppose $0 < \sigma < 1$. Then, given $\frac{g_E g_{eC}}{g_{lC}} > 1$, it holds that $\frac{x_{Ct+1}}{x_{Ct}} > 1$ and hence $\frac{y_{Ct+1}}{y_{Ct}} = g_{lC}\frac{l_{Ct+1}}{l_{Ct}}\left(\frac{1+1/x_{Ct}}{1+\left(\frac{g_{lC}}{g_E g_{eC}}\right)^{1-\sigma}/x_{Ct}}\right)^{\frac{1}{1-\sigma}} > 1$. Notice also that $\lim_{t\to\infty}\frac{y_{Ct+1}}{y_{Ct}} = g_{lC} > 1$. Second, suppose $\sigma > 1$. Then, given $\frac{g_E g_{eC}}{g_{lC}} > 1$, it holds that $\frac{x_{Ct+1}}{x_{Ct}} < 1$ and hence $\frac{y_{Ct+1}}{y_{Ct}} = g_E g_{eC}\left(\frac{1+x_{Ct+1}}{1+x_{Ct}}\right)^{\frac{1}{\sigma-1}}\frac{l_{Ct+1}}{l_{Ct}} > 1$. Notice also that $\lim_{t\to\infty}\frac{y_{Ct+1}}{y_{Ct}} = g_E g_{eC} > 1$. Finally, suppose $\sigma = 1$. Then, $\frac{y_{Ct+1}}{y_{Ct}} = (g_{lC})^{\alpha_C}(g_E g_{eC})^{1-\alpha_C}\frac{l_{Ct+1}}{l_{Ct}} > 1$. Notice also that $\lim_{t\to\infty}\frac{y_{Ct+1}}{y_{Ct}} = (g_{lC})^{\alpha_C}(g_E g_{eC})^{1-\alpha_C} > 1$. Since for all values of σ, $\frac{y_{Ct+1}}{y_{Ct}} > 1$ and $\lim_{t\to\infty} y_{Ct} = \infty$, from the above expression for d_t, $d_{t+1}/d_t > 1$ and $\lim_{t\to\infty} d_t = 1$.

Proof Of Proposition 2 Equations (3), (4) and (9) imply that: $Y_{Ct} = (1-\alpha_C)^{\frac{\sigma}{\sigma-1}} B_{Et}B_{eCt}(1+x_{Ct})^{-\frac{1}{1-\sigma}} L_{Ct}$. Whilst equations (7), (4) and (9) imply that $P_{Ct} = \eta_C E_{Ct} = \eta_C B_{eCt} L^e_{Ct} = \left(\frac{\eta_C B_{eCt}}{1+x_{Ct}}\right) L_{Ct}$. Combining these, non-agricultural emission intensity becomes:

$$N_{Ct} \equiv \frac{P_{Ct}}{p_{Ct^*}Y_{Ct}} = \frac{\eta_C\left(B_{Et}^{\frac{\sigma-1}{\sigma}} + B_{Et}^{\frac{\sigma-1}{\sigma}} x_{Ct}\right)^{\frac{\sigma}{1-\sigma}}}{p_{Ct^*}(1-\alpha_C)^{\frac{\sigma}{\sigma-1}}}. \tag{31}$$

Consequently by Assumption 1, $N_{Ct+1}/N_{Ct} = \left(\frac{g_E^{\frac{\sigma-1}{\sigma}} + g_E^{\frac{\sigma-1}{\sigma}} x_{Ct+1}}{1+x_{Ct}}\right)^{\frac{\sigma}{1-\sigma}}$. Since $\sigma < 1$, N_{Ct+1}/N_{Ct} is less than one if and only if the term in brackets is less than one, that is:

$$g_E^{\frac{\sigma-1}{\sigma}} + g_E^{\frac{\sigma-1}{\sigma}} x_{Ct+1} < 1 + x_{Ct}. \tag{32}$$

Notice that $g_E^{\frac{\sigma-1}{\sigma}} x_{Ct+1} < x_{Ct}$ follows directly from the assumption that $\sigma < \frac{\log(g_E)}{\log(g_E)+\log(g_{eC})-log(g_{lC})}$. Thus, $1 + x_{Ct} > 1 + g_E^{\frac{\sigma-1}{\sigma}} x_{Ct+1} > g_E^{\frac{\sigma-1}{\sigma}} + g_E^{\frac{\sigma-1}{\sigma}} x_{Ct+1}$, where the last inequality follows from the fact that, given $\sigma < 1$ and $g_E > 1$ then $g_E^{\frac{\sigma-1}{\sigma}} < 1$. Thus, the inequality (32) is satisfied and $N_{Ct+1}/N_{Ct} < 1$. To show that intensity approaches zero in the limit, notice that $N_{Ct+1}/N_{Ct} = \frac{1}{g_E}\left(\frac{\frac{1}{x_{Ct}}+\left(\frac{g_E g_{eC}}{g_{lC}}\right)^{1-\sigma}}{\frac{1}{x_{Ct}}+1}\right)^{\frac{\sigma}{1-\sigma}}$. Since, $\lim_{t\to 0}\frac{1}{x_{Ct}} = 0$, $g_{NC} \equiv \lim_{t\to 0} N_{Ct+1}/N_{Ct} = \frac{1}{g_E}\left(\frac{g_E g_{eC}}{g_{lC}}\right)^{\sigma} < 1$, from the assumption that $\sigma < \frac{\log(g_E)}{\log(g_E)+\log(g_{eC})-log(g_{lC})}$. Hence, $\lim_{t\to\infty} N_{Ct} = \lim_{t\to\infty}\left(\frac{N_{Ct+1}}{N_{Ct}}\right)^t N_{C0} = \lim_{t\to\infty} g_{NC}^t N_{C0} = 0$, since $g_{NC} < 1$.

Proof Of Proposition 3 For this proof, I will make use of the solutions for the UK provided in section 3. Since I will be considering a country i with wedges D^i_{At}, D^i_{Ct} and $\bar{\tau}^i_t$, to use the UK solutions one simply needs to replace the corresponding UK productivity terms with their country i equivalents. Thus, for example, when I see B_{jt} in the UK solution, I replace that with $B^i_{jt} = D^i_{At} B_{jt}$ and so on. I now prove the theorem. First, I prove part 1). From equation (10) that $\frac{\partial l_{At}}{D^i_{At}} < 0$ where $l_{At} \equiv L_{At}/g^t_N$. Since $l_{Ct} = 1 - l_{At}$ from the labor market clearing condition, this implies that $\frac{\partial l_{Ct}}{D^i_{At}} > 0$. Using the expression for y_{Ct} from equation (30), this then implies that $\frac{\partial y_{Ct}}{D^i_{At}} > 0$. Notice however that from the proof of proposition 1, $d_t \equiv \frac{p_{Ct^*} y_{Ct}}{p_{At^*} \bar{a} + p_{Ct^*} y_{Ct}} = \frac{1}{1 + \frac{p_{At^*} \bar{a}}{p_{Ct^*} y_{Ct}}}$. As such, combining this with the above inequality, this implies $\frac{\partial d_t}{\partial D^i_{At}} > 0$. Next, notice from equation (31) that non-agricultural intensity does not depend on agricultural productivity terms. As such, $\frac{\partial N_{Ct}}{\partial D^i_{At}} = 0$. Next, I prove part 2). Using the expression for y_{Ct} from equation (30), and the expression for x_{Ct} derived in section 3 and assuming that $\sigma < 1$, it is easy to show that $\frac{\partial y_{Ct}}{\partial D^i_{Ct}} > 0$. Then, using the expression for d_t derived in the proof of part 1) above, it then follows that $\frac{\partial d_t}{\partial D^i_{Ct}} > 0$. Next, taking equation (31) and substituting for x_{Ct} from the expression derived in section 3 and assuming that $\sigma < 1$, it follows that $\frac{\partial N_{Ct}}{\partial D^i_{At}} < 0$. Finally, I prove part 3). Notice from the expression for x_{Ct} derived in section 3 that $\frac{\partial x_{Ct}}{\partial \bar{\tau}^i_t} < 0$. Using the expression for y_{Ct} from equation (30) and assuming that $\sigma < 1$, this then implies that $\frac{\partial y_{Ct}}{\partial \bar{\tau}^i_t} < 0$. Then, using the expression for d_t derived in the proof of part 1) above, it then follows that $\frac{\partial d_t}{\partial \bar{\tau}^i_t} < 0$. Finally, taking equation (31) and substituting for x_{Ct} from the expression derived in section 3 and assuming that $\sigma < 1$, it follows that $\frac{\partial N_{Ct}}{\partial \bar{\tau}^i_t} > 0$.

Proof Of Proposition 4 The proof involves comparing the solutions of the detailed and the baseline models. Government policy in either model does not affect employment in agriculture. Thus, given the same vector of productivities in both models, $\hat{L}^y_{At} = L^y_{At}$, $\hat{L}^e_{At} = L^e_{At}$, $\hat{L}_{At} = L_{At}$, $\hat{L}_{Ct} = L_{Ct}$, $\hat{Y}_{At} = Y_{At}$, $\hat{E}_{At} = E_{At}$ and $\hat{a}_t = a_t$. The policies however do influence the division of labor in non-agriculture between energy and non-energy output. In particular, from the firms problems, it is easy to show that $\hat{L}^e_{Ct} = \frac{1}{1+\hat{x}_{Ct}} \hat{L}_{Ct}$ and $\hat{L}^y_{Ct} = \frac{\hat{x}_{Ct}}{1+\hat{x}_{Ct}} \hat{L}_{Ct}$ where $\hat{x}_{Ct} \equiv \left(\frac{\alpha_C}{1-\alpha_C}\right)^{\sigma} \left(\frac{\hat{B}_{Et} \hat{B}_{eCt}}{\hat{B}_{lCt}}\right)^{1-\sigma} \left(\frac{(1-\hat{\tau}^L_{Et})(1-\hat{\tau}^E_{Ct})}{(1+\hat{\tau}_{Et})(1-\hat{\tau}^L_{Ct})}\right)^{\sigma}$. Thus, from the solution of the baseline model in equation (8), $\hat{x}_{Ct} = x_{Ct}$ if and only if the condition in equation (28) is satisfied. If this condition is satisfied, since $\hat{L}_{Ct} = L_{Ct}$, then $\hat{L}^e_{Ct} = L^e_{Ct}$ and $\hat{L}^y_{Ct} = L^y_{Ct}$ from equation (9). Given this and the various market clearing conditions and production functions, it follows that $\hat{Y}_{Ct} = Y_{Ct}$, $\hat{E}_{Ct} = E_{Ct}$, $\hat{P}_{Ct} = P_{Ct}$ and $\hat{c}_t = c_t$.

Approximate subsidy equivalence between detailed and baseline models Here I show the approximate equivalence between the value of expenditures on fossil-fuel subsidies in the detailed and baseline models. First, normalize the wage in both models to one: $\hat{w}_t = w_t = 1$. Second, use the modern energy firm's profit maximization problem in the detailed and baseline models to obtain, $\hat{p}_{eCt} = \frac{(1-\hat{\tau}^L_{Et})}{(1+\hat{\tau}_{Et})\hat{B}_{eCt}}$ and $p_{eCt} = \frac{1}{B_{eCt}}$. Third, suppose that productivities are the same in both models ($\hat{B}_{eCt} = B_{eCt}$ etc.) and that policies in the baseline and detailed model satisfy condition (28) so that proposition 4 holds and allocations in both models are the same (i.e. $L_{Et} = \hat{L}_{Et}$, $\hat{E}_{Ct} = E_{Ct}$ etc.). It then follows that: $\hat{p}_{eCt} = p_{eCt} \frac{(1-\hat{\tau}^L_{Et})}{(1+\hat{\tau}_{Et})}$, $1 = p_{eCt} B_{eCt}$ and $B_{eCt} \hat{L}_{Et} = E_{Ct}$. The value of fossil-fuel subsidies in the detailed model is then given by:

$$\begin{aligned}\hat{V}_t^E &\equiv \hat{p}^e_{Ct}\hat{E}_{Ct}(\hat{\tau}^E_{Ct}+\hat{\tau}_{Et})+\hat{w}_t\hat{\tau}^L_{Et}\hat{L}^e_{Et}-\hat{w}_t\hat{\tau}^L_{Ct}\hat{L}^y_{Ct}\left(\frac{\hat{L}^e_{Ct}}{\hat{L}^y_{Ct}}\right)\\ &= p^e_{Ct}E_{Ct}\left(\frac{\hat{\tau}_{Et}+\hat{\tau}^L_{Et}+\hat{\tau}^E_{Ct}-\hat{\tau}^L_{Ct}\hat{\tau}^E_{Ct}}{1+\hat{\tau}_{Et}}-\hat{\tau}^L_{Ct}\right)\\ &\approx p^e_{Ct}E_{Ct}(\hat{\tau}_{Et}+\hat{\tau}^E_{Ct}+\hat{\tau}^L_{Et}-\hat{\tau}^L_{Ct}),\end{aligned}$$

where the second equality follows from the above reasoning whilst the approximation holds from a first order Taylor expansion of the policies around zero. Finally, the value of subsidies calculated using the baseline model, V_t^E, is given by:

$$\begin{aligned}V_t^E &\equiv p^e_{Ct}E_{Ct}\tau\\ &= p^e_{Ct}E_{Ct}\left(1-\frac{(1-\hat{\tau}^L_{Et})(1-\hat{\tau}^E_{Ct})}{(1+\hat{\tau}_{Et})(1-\hat{\tau}^L_{Ct})}\right)\\ &\approx p^e_{Ct}E_{Ct}(\hat{\tau}_{Et}+\hat{\tau}^E_{Ct}+\hat{\tau}^L_{Et}-\hat{\tau}^L_{Ct}),\end{aligned}$$

where the second equality follows from condition (28) whilst the approximation follows from a first order Taylor expansion of the policies around zero. Thus, it follows that $V_t^E \approx \hat{V}_t^E$.

11.4 Robustness Appendix

11.4.1 Capital

Consider a model similar to the baseline but with capital as an input in non-agriculture and with a number of additional government policies. Denote all prices, allocations and productivities of this so-called 'detailed capital model' with a tilde-symbol over the corresponding variable. I suppose that preferences are identical to the baseline, that the consumer owns an initial endowment of capital, $\tilde{k}_0$, and chooses to accumulate capital over time according to $\tilde{k}_{t+1}=(1-\delta)\tilde{k}_t+\tilde{i}_t$, where δ is the depreciation rate of capital and $\tilde{i}_t$ is investment in new capital. In the non-agricultural sector I suppose that there are subsidy wedges to energy $\tilde{\tau}^E_{Ct}$ and to non-energy inputs, $\tilde{\tau}^{NE}_{Ct}$, such that the non-agricultural firm's problem is:

$$\max_{\tilde{L}^y_{Ct},\tilde{K}^y_{Ct},\tilde{E}_{Ct}} \tilde{p}^C_t\tilde{Y}_{Ct}-\tilde{w}_t(1-\tilde{\tau}^{NE}_{Ct})\tilde{L}^y_{Ct}-\tilde{r}_t(1-\tilde{\tau}^{NE}_{Ct})\tilde{K}^y_{Ct}-\tilde{p}^e_{Ct}(1-\tilde{\tau}^E_{Ct})\tilde{E}_{Ct}, \tag{33}$$

where, $\tilde{Y}_{Ct}=\left(\alpha_C(\tilde{B}_{lCt}(\tilde{L}^y_{Ct})^{1-\lambda}(\tilde{K}^y_{Ct})^{\lambda})^{\frac{\sigma-1}{\sigma}}+(1-\alpha_C)(\tilde{B}_{Et}\tilde{E}_{Ct})^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$. In this equation, $0<\lambda<1$ and is the share of capital in non-energy inputs in non-agriculture. In the modern energy sector, suppose there are subsidy wedges to the price of energy, $\tilde{\tau}_{Et}$, as well as to both non-energy inputs, $\tilde{\tau}^{NE}_{Et}$, that the modern energy firm's problem is:

$$\max_{\tilde{L}^e_{Ct},\tilde{K}^e_{Ct}} \tilde{p}_{eCt}(1+\tilde{\tau}_{Et})\tilde{E}_{Ct}-\tilde{w}_t(1-\tilde{\tau}^{NE}_{Et})\tilde{L}^e_{Et}-\tilde{r}_t(1-\tilde{\tau}^{NE}_{Et})\tilde{K}^e_{Et}, \tag{34}$$

where, $\tilde{E}_{Ct}=\tilde{B}_{eCt}(\tilde{L}^e_{Ct})^{1-\lambda}(\tilde{K}^e_{Ct})^{\lambda}$. Notice that I that λ is common across the non-agricultural output and energy sub-sectors. Whilst this is clearly a simplification, this allows for nearly analytic solutions that lend insight in to the working of the model with capital. Finally suppose the government budget constraint balances period by period:

$$\tilde{w}_t\tilde{\tau}_{Ct}^{NE}\tilde{L}_{Ct}^{y}+\tilde{r}_t\tilde{\tau}_{Ct}^{NE}\tilde{K}_{Ct}^{y}+\tilde{p}_{Ct}^{e}\tilde{\tau}_{Ct}^{E}\tilde{E}_{Ct}+\tilde{w}_t\tilde{\tau}_{Et}^{NE}\tilde{L}_{Et}^{e}+\tilde{r}_t\tilde{\tau}_{Et}^{NE}\tilde{K}_{Et}^{e}+\tilde{p}_{eCt}\tilde{\tau}_{Et}\tilde{E}_{Ct}=\tilde{T}_t. \tag{35}$$

Competitive Equilibrium A (tax-distorted) competitive equilibrium of this economy consists of: (i) Sequences of goods prices, wage rates, capital rental rates as well as energy $\{\tilde{p}_{At},\tilde{p}_{Ct},\tilde{w}_t,\tilde{r}_t,\tilde{p}_{eAt},\tilde{p}_{eCt}\}_{t=0}^{\infty}$; (ii) household allocations: $\{\tilde{a}_t,\tilde{c}_t,\tilde{i}_t,\tilde{k}_t\}_{t=0}^{\infty}$; (iii) firm allocations and emissions $\{\tilde{L}_{At}^{y},\tilde{L}_{At}^{e},\tilde{L}_{Ct}^{y},\tilde{L}_{Ct}^{e},\tilde{K}_{Ct}^{y},\tilde{K}_{Ct}^{e},\tilde{P}_{Ct}\}$; and (iv) government policies $\{\tilde{\tau}_{Ct}^{NE}\tilde{\tau}_{Ct}^{E},\tilde{\tau}_{Et}^{NE},\tilde{\tau}_{Et},\tilde{T}_t\}$ such that:

(a) Given prices, policies and initial capital stock, households' allocations maximize their utility, $\sum_{t=0}^{\infty}\beta^t U(\tilde{a}_t,\tilde{c}_t)$, subject to their budget constraint: $\sum_{t=0}^{\infty}(\tilde{p}_{At}\tilde{a}_t+\tilde{p}_{Ct}\tilde{c}_t+\tilde{p}_{Ct}\tilde{i}_t)=\sum_{t=0}^{\infty}(\tilde{w}_t+\tilde{r}_t\tilde{k}_t-\tilde{T}_t)$; and the accumulation of capital equation: $\tilde{k}_{t+1}=(1-\delta)\tilde{k}_t+\tilde{i}_t$.

(b) Given prices and policies, firms' allocations solve the firms' problems in output and energy subsectors for agriculture: $\max_{\{\tilde{L}_{At}^{y},\tilde{E}_{At}\}}\tilde{p}_t^{A}\tilde{Y}_{At}-\tilde{w}_t\tilde{L}_{At}^{y}-\tilde{p}_{eAt}\tilde{E}_{At}$ and $\max_{\tilde{L}_{At}^{e}}\tilde{p}_{eAt}\tilde{E}_{At}-\tilde{w}_t\tilde{L}_{At}^{e}$; and for non-agriculture in equations (33) and (34). Firms emit carbon according to $\tilde{P}_{Ct}=\tilde{\eta}_{Ct}\tilde{E}_{Ct}$.

(c) The government period budget constraint is given by (35).

(d) Goods, labor and capital markets clear: $\tilde{Y}_{At}=L_t\tilde{a}_t$, $\tilde{Y}_{Ct}=L_t(\tilde{c}_t+\tilde{i}_t)$. $\tilde{L}_{At}^{y}+\tilde{L}_{At}^{e}+\tilde{L}_{Ct}^{y}+\tilde{L}_{Ct}^{e}=L_t$. $\tilde{K}_{Ct}^{y}+\tilde{K}_{Ct}^{e}=L_t\tilde{k}_t\equiv\tilde{K}_t$.

The sectoral allocations can be obtained as in the baseline and written with respect to sectoral productivities, policies, total capital stock and labor force. Sectoral employment is given by:

$$\tilde{L}_{At}^{e}=(1-\alpha_A)\tilde{L}_{At}\ ,\ \tilde{L}_{At}^{y}=\alpha_A\tilde{L}_{At}\ ,\ \tilde{L}_{Ct}^{e}=\left(\frac{1}{1+\tilde{x}_{Ct}}\right)\tilde{L}_{Ct}, \tag{36}$$

where $\tilde{x}_{Ct}\equiv\left(\frac{\alpha_C}{1-\alpha_C}\right)^{\sigma}\left(\frac{\tilde{B}_{Et}\tilde{B}_{eCt}}{\tilde{B}_{lCt}}\right)^{1-\sigma}\left(\frac{(1-\tilde{\tau}_{Et}^{NE})(1-\tilde{\tau}_{Ct}^{E})}{(1+\tilde{\tau}_{Et})(1-\tilde{\tau}_{Ct}^{NE})}\right)^{\sigma}$. Employment in agriculture is derived exactly as in the baseline and is given by:

$$\tilde{L}_{At}=\frac{\bar{a}}{{\alpha_A}^{\alpha_A}(1-\alpha_A)^{1-\alpha_A}\tilde{B}_{At}\tilde{B}_{eAt}^{1-\alpha_A}}\tilde{L}_t \text{ and } \tilde{L}_{Ct}=\tilde{L}_t-\tilde{L}_{At}. \tag{37}$$

Equating the wage-rental rate ratios emerging from the (non-agricultural) energy and non-energy firm I obtain sectoral capital levels:

$$\tilde{K}_{Ct}^{e}=\left(\frac{1}{1+\tilde{x}_{Ct}}\right)\tilde{K}_t \text{ and } \tilde{K}_{Ct}^{y}=\left(\frac{\tilde{x}_{Ct}}{1+\tilde{x}_{Ct}}\right)\tilde{K}_t. \tag{38}$$

Thus, the above allows me to calculate the values of sectoral output $(\tilde{Y}_{At},\tilde{Y}_{Ct})$ and sectoral energy production $(\tilde{E}_{At},\tilde{E}_{Ct})$ given productivities, government policies, the aggregate stock of capital and the aggregate labor force.[72] The evolution of the aggregate capital stock can be pinned down by

[72] For example, one can show that $\tilde{Y}_{Ct}=\tilde{B}_{lCt}(\tilde{x}_{Ct}/(\tilde{x}_{Ct}+\frac{(1-\tilde{\tau}_{Et}^{NE})(1-\tilde{\tau}_{Ct}^{E})}{(1+\tilde{\tau}_{Et})(1-\tilde{\tau}_{Ct}^{NE})}))^{\frac{\sigma}{1-\sigma}}\alpha_C^{\frac{\sigma}{\sigma-1}}(\tilde{L}_{Ct})^{1-\lambda}(\tilde{K}_t)^{\lambda}$.

the following Euler equation obtained by combining the first order condition for capital from the household problem and the non-agricultural goods firm problem:

$$\frac{u'(\tilde{c}_t)}{\beta u'(\tilde{c}_{t+1})} = \frac{1}{(1-\tilde{\tau}^{NE}_{Ct})}\frac{\partial \tilde{Y}_{Ct+1}}{\partial \tilde{K}^y_{Ct+1}} - (1-\delta). \tag{39}$$

In the above, I can show that $\frac{\partial \tilde{Y}_{Ct}}{\partial \tilde{K}^y_{Ct}} = \tilde{B}_{lCt}\left(\frac{\tilde{x}_{Ct}}{\tilde{x}_{Ct}+\frac{(1-\tilde{\tau}^{NE}_{Et})(1-\tilde{\tau}^{E}_{Ct})}{(1+\tilde{\tau}_{Et})(1-\tilde{\tau}^{NE}_{Ct})}}\right)^{\frac{1}{1-\sigma}} \alpha_C^{\frac{\sigma}{\sigma-1}}\frac{\tilde{x}_{Ct}}{1+\tilde{x}_{Ct}}\lambda(\tilde{L}_{Ct})^{1-\lambda}(\tilde{K}_t)^{\lambda-1}$, and $\tilde{c}_t = \tilde{Y}_{ct}/L_t - (\tilde{K}_{t+1}/\tilde{L}_{t+1} - (1-\delta)\tilde{K}_t/L_t)$. Finally, the following theorem establishes a mapping from the detailed model with capital to the standard baseline model.

Proposition 5. *Given a vector of productivities $\{\tilde{B}_{At}, \tilde{B}_{eAt}, \tilde{B}_{lCt}, \tilde{B}_{Et}, \tilde{B}_{eCt}\}_{t=0}^{\infty}$, government policies $\{\tilde{\tau}^{NE}_{Ct}, \tilde{\tau}^{E}_{Ct}, \tilde{\tau}^{E}_{Ct}, \tilde{\tau}^{NE}_{Et}, \tilde{\tau}_{Et}\}_{t=0}^{\infty}$ and equilibrium aggregate capital allocations, $\{\tilde{K}_t\}_{t=0}^{\infty}$, the allocations from the detailed capital model are identical to baseline economy if productivities in the baseline are specified by:*

$$B_{lCt} = \tilde{B}_{lCt}(1 - \tilde{K}_{t+1}/\tilde{Y}_{Ct} + (1-\delta)\tilde{K}_t/\tilde{Y}_{Ct})(\tilde{K}_t/\tilde{L}_{Ct})^{\lambda} \tag{40}$$

$$B_{Et} = \tilde{B}_{Et}(1 - \tilde{K}_{t+1}/\tilde{Y}_{Ct} + (1-\delta)\tilde{K}_t/\tilde{Y}_{Ct}) \text{ and } B_{eCt} = \tilde{B}_{eCt}(\tilde{K}_t/\tilde{L}_{Ct})^{\lambda} \tag{41}$$

$$B_{At} = \tilde{B}_{At} \text{ and } B_{eAt} = \tilde{B}_{eAt} \tag{42}$$

and the energy-price wedge in the baseline, is specified by:

$$\tau_t = 1 - \frac{(1-\tilde{\tau}^{NE}_{Et})(1-\tilde{\tau}^{E}_{Ct})}{(1+\tilde{\tau}_{Et})(1-\tilde{\tau}^{NE}_{Ct})}. \tag{43}$$

The proof of the above follows that of Proposition 4 and is left out for brevity's sake. Notice from equation (43) that if the only distortion in the detailed capital model is an energy-price wedge, $\tilde{\tau}^{E}_{Ct}$, then this wedge is identical to the energy-price wedge found in the baseline, $\tilde{\tau}^{E}_{Ct} = \tau_t$. Furthermore, comparing equations (43) and (28) in section 6 shows that the detailed model with capital captures the same set of wedges as a model without capital. In particular Propositions 4 and 5 show that the baseline energy-price wedge captures the effect of *all* policies that impact energy demand - including non-energy price wedges.[73] Finally, notice that constructing a more detailed model could potentially allow for tighter estimates of baseline subsidies. For example, choosing a λ that potentially varies across sectors, or imposing additional restrictions that would allow us to infer separate distortions on capital and labor could lead to better estimates of subsidy wedges in the baseline. Both steps however would require more data and greatly reduce the tractability and simplicity of the baseline model. Since the goal of the baseline is to obtain subsidy estimates for as many countries and years as possible, this extension is not undertaken in the current paper and is left for future research.

[73] Notice that the above setup also highlights a limitation of the counterfactual emission exercise in the baseline model. In that exercise I assume energy-price wedges and sectoral labor productivities are independent. The above theorem shows that this is not necessarily the case as distortions can influence capital accumulation through the Euler equation and effect labor productivity. Thus, the counterfactual emission exercise in the baseline likely *underestimates* the role of energy price wedges on emissions.

11.4.2 Sub-Sectors

I largely follow Ngai and Pissarides (2007), Duarte and Restuccia (2007) and Stefanski (2014b) in the construction of the three sector model. Utility is now defined over per-capita consumption of agricultural goods (a_t), industrial goods (m_t) and service-sector goods (s_t). As in Duarte and Restuccia (2007), I take preferences to be:

$$U(a_t, m_t, s_t) = \begin{cases} \bar{a} + \left(\nu m_t^{\frac{\rho-1}{\rho}} + (1-\nu) s_t^{\frac{\rho-1}{\rho}}\right)^{\frac{\rho}{\rho-1}} & \text{if } a_t > \bar{a} \\ a_t & \text{if } a_t \leq \bar{a}. \end{cases} \tag{44}$$

In the above, ρ is the elasticity of substitution between industry and service sector goods, whilst ν is the weight of industry in the CES aggregator.

The setup of agricultural side of the model, remains exactly as in the baseline. Non-agriculture is replaced by industrial (M) and service (S) sectors, and output in each of these sectors (Y_{it}) is produced using labor (L^y_{it}) and a modern energy inputs (E_{it}) for $i = M, S$:

$$Y_{it} = \left(\alpha_i (B_{lit} L^y_{it})^{\frac{\sigma_i - 1}{\sigma_i}} + (1-\alpha_i)(B_{Eit} E_{it})^{\frac{\sigma_i - 1}{\sigma_i}}\right)^{\frac{\sigma_i}{\sigma_i - 1}}. \tag{45}$$

In the above, α_i is the weight of labor in production, σ_i is the elasticity of substitution between labor and energy, whilst B_{lit} and B_{Eit} are exogenous labor and energy augmenting productivity terms at time t in sector $i = M, S$ respectively. Total modern energy used in industry and services, $E_{Ct} = E_{Mt} + E_{St}$, is then produced using the same production function as in the baseline in equation (4). Notice that I continue to assume that traditional energy is only used in agriculture, whilst modern energy is used only in non-agriculture (i.e. in industry and services).

Finally, I allow government to potentially subsidize or tax modern energy consumption in both industry and the service sectors at the same rate, τ_t. As before, this policy is supported by lump sum taxes/transfers on the household.

Competitive Equilibrium (Sub-Sectors) The (tax-distorted) competitive equilibrium of the economy for every t is defined as the: (1) Price of agricultural, industry and service sector goods, wage rates, as well as traditional and modern energy prices, $\{p_{At}, p_{Mt}, p_{St}, w_t, p_{eAt}, p_{eCt}\}$; (2) household allocations: $\{a_t, m_t, s_t\}$; (3) firm allocations and emissions $\{L^y_{At}, L^e_{At}, L^y_{Mt}, L^y_{St}, L^e_{Ct}, P_{Ct}\}$; and (4) energy policy $\{\tau_t, T_t\}$ such that:

(a) Given prices and policy, households' allocations maximize equation (44) subject to the budget constraint of the household: $p_{At}a_t + p_{Mt}m_t + p_{St}s_t = w_t - T_t$.

(b) Given prices and policy, firms' allocations, (3), solve the firms' problems: $\max_{\{L^y_{At}, E_{At}\}} p^A_t Y_{At} - w_t L^y_{At} - p_{eAt}E_{At}$ and $\max_{\{L^e_{At}\}} p_{eAt}E_{At} - w_t L^e_{At}$ in agricultural output and energy sub-sectors; $\max_{\{L^y_{Mt}, E_{Mt}\}} p^M_t Y_{Mt} - w_t L^y_{Mt} - p^e_{Ct}(1-\tau_t)E_{Mt}$ and $\max_{\{L^y_{St}, E_{St}\}} p^S_t Y_{St} - w_t L^y_{St} - p^e_{Ct}(1-\tau_t)E_{St}$ in industry and service output sub-sectors and $\max_{\{L^e_{Ct}\}} p_{eCt}E_{Ct} - w_t L^e_{Ct}$ in modern energy sub-sector. Also, firms emit carbon according to equation (7).

(c) The government period budget constraint is balanced and given by $L_t T_t = \tau_t p^e_{Ct} E_{Ct}$.

(d) Goods, labor and energy markets clear: $Y_{At} = L_t a_t$, $Y_{Mt} = L_t m_t$ and $Y_{St} = L_t s_t$; $E_{Ct} = E_{Mt} + E_{St}$; $L^y_{At} + L^e_{At} + L^y_{Mt} + L^y_{St} + L^e_{Ct} = L_t$.

Solution Like the baseline, the problem is solved in two parts. For non-agriculture, it helps to abuse sectoral definitions somewhat and to define L_{Mt} and L_{St} as total employment in the production of sectoral output *and* sectoral energy, so that $L_{it} = L^e_{it} + L^y_{it}$ where $E_{it} = L^e_{it} B_{eCt}$ for $i = M, S$ and hence $L^e_{Ct} = L^e_{Mt} + L^e_{St}$. In short, it is helpful to assume that there are identical (but separate) modern energy firms providing energy for industry and services and attribute employment in each energy firm to an artificial M and S sector. Importantly, this is completely equivalent to having one modern energy firm, however it simplifies the solution process. When taking the model to the data, it is also of course necessary to remain consistent in sectoral definitions. Thus energy production from both industry and services will be classed as part of the industrial sector in the data, however temporarily abstracting from this in the solution, simplifies calculation. Having done this, the first step takes L_{At}, L_{Mt} and L_{St} as given and allocates this labor between energy and output production, by equating the wage-to-energy price ratios derived from the first-order conditions of output and energy firms in each sector. For agriculture, the solution remains unchanged and is given by equation (8).

For non-agriculture, I obtain very similar expressions as before for $i = M, S$:

$$L^e_{it} = \left(\frac{1}{1 + x_{it}}\right) L_{it} \text{ and } L^y_{it} = \left(\frac{x_{it}}{1 + x_{it}}\right) L_{it} \tag{46}$$

where, $x_{it} \equiv \left(\frac{\alpha_i}{1-\alpha_i}\right)^{\sigma_i} \left(\frac{B_{Eit} B_{eCt}}{B_{lit}}\right)^{1-\sigma_i} (1 - \tau_t)^{\sigma_i}$. In the above, total employment in the modern energy sector is simply given by $L^e_{Ct} = L^e_{Mt} + L^e_{St}$, whilst total employment in non-agriculture is given by $L_{Ct} = L_{Mt} + L_{St}$.

Finally, the proportion of workers in agriculture and non-agriculture is derived as in the baseline and given by equation (10). The division of non-agricultural workers between sectors is obtained by combining the household's first-order condition for industry and service sector goods:

$$\frac{p^m_t}{p^s_t} = \frac{\nu}{1 - \nu} \left(\frac{c_{Mt}}{c_{St}}\right)^{-\frac{1}{\rho}}. \tag{47}$$

Then, using goods market clearing conditions, substituting for sectoral output and using the solutions in (46), I can show that

$$L_{Mt} = \left(\frac{1}{1 + x_{Ct}}\right) L_{Ct} \text{ and } L_{St} = \left(\frac{x_{Ct}}{1 + x_{Ct}}\right) L_{Ct}, \tag{48}$$

where,

$$x_{Ct} = \frac{B_{EMt}}{B_{ESt}} \left(\frac{(1 - \nu) p^m_t}{\nu p^s_t}\right)^{\rho} \frac{1 + x_{St}}{1 + x_{Mt}} \frac{\left((1 - \alpha_S)(1 + \frac{x_{St}}{1-\tau_t})\right)^{\frac{\sigma_S}{1-\sigma_S}}}{\left((1 - \alpha_M)(1 + \frac{x_{Mt}}{1-\tau_t})\right)^{\frac{\sigma_M}{1-\sigma_M}}}. \tag{49}$$

To obtain an exact solution to the above, all that remains is to specify prices. This is done exactly as in the baseline. Normalizing the wage rate to one, final good firms' first-order conditions imply that the price of sector $s = A, S, M$ goods is $p_{st} = 1/\frac{\partial Y_{st}}{\partial L_{st}^y}$. Using the above results:

$$p_{At} = \frac{1}{\alpha_A^{\alpha_A}(1-\alpha_A)^{1-\alpha_A} B_{At} B_{eAt}^{(1-\alpha_A)}} \text{ and } p_{it} = \frac{1}{\alpha_i^{\frac{\sigma_i}{\sigma_i - 1}} B_{lit} \left(1 + \frac{(1-\tau_t)}{x_{it}}\right)^{\frac{1}{\sigma_i - 1}}}, \tag{50}$$

where $i = M, S$.

The model achieves structural transformation by combining two different effects. First, the reallocation of labor from agriculture to non-agriculture is driven - as in the baseline - by non-homothetic preferences. Second, the reallocation of workers from industry to services is largely driven by substitution effects caused by an elasticity of substitution that is different from one, $\rho \neq 1$, in conjunction with different (exogenous) productivity growth rates across industry and service sectors. If TFP growth rates are higher (on average) in industry than in services, then setting a low elasticity, $\rho < 1$, results in labor moving away from industry towards services. Intuitively, with a low elasticity, consumers enjoy goods in relatively fixed proportions. With unbalanced TFP growth, the only way to maintain fixed proportions in consumption is for labor to move from the faster to the slower growing sectors. Conversely, if TFP growth rates are higher in services than in industry, an elasticity greater than one is needed to induce labor to move towards services.

Calibration The model is calibrated to reproduce: 1) traditional and modern energy use; 2) modern energy use in industry and services 2) agricultural, industrial and service sector employment; 3) total GDP; 4) the (after subsidy, current price) share of modern energy in non-agricultural value added and 5) the impurity of modern energy; in the UK. Due to the additional data restrictions imposed by the more detailed structure of the model, I shall only focus on the 1980-2010 period.

In general, the calibration is similar to that of the baseline. However, an additional challenge arises which was not present in the baseline and highlights why the baseline structure of the model may after all be preferable to this extension. In particular, there are difficulties in the construction of modern energy consumption data in the industry and service sectors that is compatible with the ISIC classification used in the rest of the paper. The best source of this type of data is Mulder and de Groot (2012), who derive sectoral energy consumption data from EU-KLEMS national accounts and create a database that covers a period between 1980 and 2005. However, since this data comes from national accounts it excludes non-market activities and, does not include energy use by households and the personal transport sector. It thus refers to non-residential energy use only. Consequently, a non-trivial choice must be made as to how to allocate non-market (residential) energy consumption between industry and service sectors. This is a difficult problem and one that goes significantly beyond the scope of this paper. For now, and for lack of a better alternative, I assume that residential and personal transport energy is allocated between industry and service sectors in the same proportion as energy used by market activities. I thus take the proportion of non-agricultural energy used by industry, s_{Mt}, and services, $1 - s_{Mt}$, in the UK from Mulder and de Groot (2012) and multiply it by the total UK consumption of modern energy previously used and derived from DUKES (2012). Since the data stops at 2005, I extrapolate s_{Mt} to 2010, by assuming a constant rate of decline in s_{Mt}. This gives me an estimate of the total modern energy consumption of the industry and service sectors using the ISIC classification. Importantly, this also sums to total modern energy consumption I had in the baseline. This perhaps underestimates the energy used by the service sector (due to the presumably disproportionate use of energy for private transportation), but this is the best that can be done given the limited data.

First, L_{1990}, E_{C1990} and η_{C1990} are normalized to 1 and L_t, L_{At}, L_{Ct}, L^y_{St}, E_{At}, E_{Mt}, E_{St} and η_{Ct} are fed into the model directly from the data.[74] As before, η_{Ct} is modern-energy impurity and is derived as the ratio of carbon-emissions to modern (non-biofuel) energy use. The parameters α_A, B_{eAt}, $\bar{a}$, B_{At} and τ_t are calibrated exactly as in the baseline.

Second, using equations (46), (48) and (50) as well as the expressions for sectoral output, the (after subsidy, current price) share of modern energy in non-agricultural value added, s^e_{Ct}, can be expressed as:

$$s^e_{Ct} \equiv \frac{p_{eCt}(1-\tau_t)(E_{St}+E_{Mt})}{p_{Mt}Y_{Mt}+p_{St}Y_{St}} = \frac{1}{1+\frac{1}{1-\tau_t}\frac{x_{Mt}+(x_{Ct}+x_{Mt}+x_{Mt}x_{Ct})x_{St}}{1+x_{Ct}+x_{Mt}x_{Ct}+x_{St}}}. \tag{51}$$

The ratio of modern energy used in industry and services can be expressed as:

$$\frac{E_{Mt}}{E_{St}} = \frac{L^e_{Mt}B_{eCt}}{L^e_{St}B_{eCt}} = \frac{\left(\frac{1}{1+x_{Mt}}\right)L_{Mt}}{\left(\frac{1}{1+x_{St}}\right)L_{St}} = \frac{1+x_{St}}{(1+x_{Mt})x_{Ct}}. \tag{52}$$

From equations (48) and using the labor market-clearing condition, I can express x_{Ct} as:

$$x_{Ct} = \frac{L_{St}}{L_{Ct}-L_{St}} = \frac{L^y_{St}(1+x_{St})}{L_{Ct}x_{St}-L^y_{St}(1+x_{St})}. \tag{53}$$

Taking s^e_{Ct} from the data and substituting equation (53) into equations (51) and (52), I can then simultaneously solve equations (51) and (52) for x_{Mt} and x_{St}:

$$x_{Mt} = \frac{(E_{Mt}+E_{St})(L_{Ct}-L^y_{St})(1-\tau_t) - s^e_{Ct}\left((1-\tau_t)L_{Ct}+L^y_{St}\tau_t\right)}{E_{Mt}L_{Ct}s^e_{Ct}} \tag{54}$$

$$x_{St} = \frac{(E_{Mt}+E_{St})L^y_{St}(1-\tau_t+s^e_{Ct}\tau_t)}{E_{St}L_{Ct}s^e_{Ct}}. \tag{55}$$

Given these values of x_{Mt} and x_{St}, I then obtain the value of x_{Ct} from equation (53). Finally, this allows me to derive the values of L_{Mt} and L_{St} from equation (48).[75] Consequently, from the modern energy production function, the fact that $L^e_{Ct} = L^e_{Mt} + L^e_{St}$ and equation (46), I can extract the labor productivity of the modern energy sector, period by period:

$$B_{eCt} = \frac{E_{Ct}}{\left(\frac{1}{1+x_{Mt}}\right)L_{Mt} + \left(\frac{1}{1+x_{St}}\right)L_{St}}. \tag{56}$$

Third, I set the elasticity of substitution between labor and energy in both industry and services to $\sigma_M = \sigma_s = 0.76$, so that elasticity of substitution in non-agriculture remains 0.76 - as in the baseline and in accordance with the estimates cited in the calibration above. I also experimented

[74] The construction and sources of E_{Mt} and E_{St} are discussed in the main body of the paper.
[75] Recall, that L_{Mt} and L_{St} are artificial sectoral constructs that are used to help solve the model and are not equivalent to total industry and service sector employment in the data.

with choosing different elasticities in each sector, but in such a way that the weighted average of the elasticity of substitution of both sectors remained at 0.76. This however this had very little effect on estimated subsidies, and so I chose to retain the same elasticities in both sectors.[76]

Fourth, I normalize industry and service sector labor productivity and energy specific productivity in 1990 to one, so that: $B_{lM1990} = B_{lS1990} = 1$ and $B_{EM1990} = B_{ES1990} = 1$. This then allows me to infer that $1 - \alpha_M = 0.09$ and $1 - \alpha_S = 0.05$ from equations (54) and (55) evaluated for 1990 after substituting for x_{Mt} and x_{St}:

$$\alpha_i = \frac{1}{1 + (1 - \tau_{1990})^{\frac{\sigma_i - 1}{\sigma_i}} B_{ei1990}^{\frac{1-\sigma_i}{\sigma_i}} x_{i1990}^{-\frac{1}{\sigma_i}}}. \tag{57}$$

Fifth, I set the elasticity of substitution between industry and services, ρ. To do this one can estimate the relationship between relative consumption and relative sectoral prices derived in (47). This exercise has been carried out by, for example, Stockman and Tesar (1995) who find the elasticity to be 0.44 or Duarte and Restuccia (2007) who find it to be 0.4. I have also experimented with estimating this elasticity directly using data from the World Bank's 2005 International Comparison Program (ICP) database. In particular, I calculate the ratios of sectoral consumption and prices for 140 countries in 2005.[77] I then take logs of equation (47) and regress relative sectoral consumption on relative sectoral prices. The slope of this regression is an estimate of the elasticity of substitution between industry and service sector goods. In my sample I find an elasticity of 0.54, which matches well with the above literature. In order to remain consistent with the other papers, however, in the calibration I set $\rho = 0.40$.

Sixth, given the normalizations made above, and the value for x_{Ct}, I evaluate equation (49) for $t = 1990$ and solve for $\nu = 0.22$.

Seventh, using equation (49), I can relate the two energy specific technological progress terms via $B_{EMt} = rel(x_{Mt}, x_{St}, x_{Ct}, \tau_t) B_{ESt}$, where

$$rel(x_{Mt}, x_{St}, x_{Ct}, \tau_t) \equiv x_{Ct} \left(\frac{(1-\nu) p_t^m}{\nu p_t^s} \right)^{\rho} \frac{1 + x_{St}}{1 + x_{Mt}} \frac{\left((1 - \alpha_S)(1 + \frac{x_{St}}{1-\tau_t}) \right)^{\frac{\sigma_S}{1-\sigma_S}}}{\left((1 - \alpha_M)(1 + \frac{x_{Mt}}{1-\tau_t}) \right)^{\frac{\sigma_M}{1-\sigma_M}}}. \tag{58}$$

This then allows me to extract labor- and energy-specific technological progress in the industry and service sectors in exactly the same way as in the baseline. I feed into the the model - period-by-period - the constant price GDP found in the data so that $GDP_t^{Data} = p_{A1990} Y_{At} + p_{M1990} Y_{Mt} + p_{S1990} Y_{St}$. As in the baseline, I can then show that:

$$B_{ESt} = \frac{GDP_t^{Data} - p_{A1990} \bar{a} L_t}{p_{S1990} E_{St} (1 - \alpha_S)^{\frac{\sigma_S - 1}{\sigma_S}} (1 + \frac{x_{St}}{(1-\tau_t)})^{\frac{\sigma_S - 1}{\sigma_S}} + p_{M1990} E_{Mt} rel(\cdot) (1 - \alpha_M)^{\frac{\sigma_M - 1}{\sigma_M}} (1 + \frac{x_{Mt}}{(1-\tau_t)})^{\frac{\sigma_M - 1}{\sigma_M}}}, \tag{59}$$

[76] In particular I experimented with setting values for $\sigma_M = 0.56, 0.66, 0.86, 0.96$ and then choosing $\sigma_S = 0.86, 0.81, 0.71, 0.66$ respectively so that the weighted average of the elasticity of substitution of both sectors was 0.76. As weights, I took the UK sectoral employment shares in industry and service sectors in 1990.

[77] The ICP provides cross-country data on the value of final household and government expenditures by sector for the year 2005. Expenditure data is given in current US dollars (at market exchange rates), as well as in PPP terms which allows me to extract country specific sectoral price levels (relative to the corresponding price level in the US).

and $B_{EMt} = rel(x_{Mt}, x_{St}, x_{Ct}, \tau_t) B_{ESt}$, according to the relationship derived above.

Finally, since $x_{it} \equiv \left(\frac{\alpha_i}{1-\alpha_i}\right)^{\sigma_i} \left(\frac{B_{Eit}B_{eCt}}{B_{lit}}\right)^{1-\sigma_i} (1-\tau_t)^{\sigma_i}$ for $i = M, S$, taking x_{it} from the data via equations (54) and (55), I can extract labor-specific productivity for $i = M, S$:

$$B_{lit} = \frac{B_{Eit}B_{eCt}}{\left(\frac{\alpha_i}{1-\alpha_i}\right)^{\frac{\sigma_i}{\sigma_i-1}} (1-\tau_t)^{\frac{\sigma_i}{\sigma_i-1}} x_{it}^{\frac{1}{1-\sigma_i}}}. \tag{60}$$

Table 13 shows the calibrated parameters as well as the average sectoral productivity growth rates over the 1980-2010 period.

Inferring Wedges Cross-country wedges for agriculture as well as energy prices are defined as in the baseline. Instead of the non-agricultural wedge, I now introduce a country-i-specific industrial wedge (D^M_{Ct}) and service wedge (D^S_{Ct}). The overall productivity of sector j, in each country, i, B^i_{jt}, is then the product of baseline (UK) productivity, B_{jt}, and the country-i-specific sectoral wedge. Thus I can write $B^i_{jt} = D^i_{At} B_{jt}$ for sectors $j = lM, EM, eC$ and $B^i_{jt} = D^i_{Ct} B_{jt}$ for sectors $j = lS, ES$. Taking the calibration for the UK as given, I then repeat the baseline experiment for the same panel of data as before. I set the *agricultural productivity* wedge, to match country i's agricultural employment share at time t. I set the *industrial productivity* wedge, to match country i's industrial employment share at time t and I choose the *service productivity* wedge, to match the ratio of GDP-per-worker between country i and the UK. Finally, I choose a *fossil-fuel subsidy* wedge, to match the ratio between emission intensity of country i and the UK.

11.4.3 Endowments

Here I allow countries to differ in their endowments of energy. I assume that countries have an exogenous fixed factor, D_t, which is owned by the household and captures the size of fossil-fuel energy reserves at time t. These reserves combine with labor to produce modern energy in a standard Cobb-Douglas fashion, replacing modern energy production function (4) in the baseline model with (29). All other aspects of the model remain identical to the baseline.

Competitive Equilibrium (Endowments) The (tax-distorted) competitive equilibrium of the economy for every period t is defined as the: (1) Price of agricultural and non-agricultural goods, wage rates, rental rate of endowments, as well as traditional and modern energy prices, $\{p_{At}, p_{Ct}, w_t, p_{Dt}, p_{eAt}, p_{eC}$ (2) household allocations: $\{a_t, c_t\}$; (3) firm allocations and emissions $\{L^y_{At}, L^e_{At}, L^y_{Ct}, L^e_{Ct}, P_{Ct}\}$; and (4) energy policy $\{\tau_t, T_t\}$ such that:

(a) Given prices and policy, households' allocations maximize equation (2) subject to the budget constraint of the household: $p_{At}a_t + p_{Ct}c_t = w_t + p_{Dt}\frac{D_t}{L_t} - T_t$.

(b) Given prices and policy, firms' allocations, (3), solve the firms' problems in output and energy sub-sectors: $\max_{\{L^y_{At}, E_{At}\}} p^A_t Y_{At} - w_t L^y_{At} - p_{eAt} E_{At}$ and $\max_{\{L^e_{At}\}} p_{eAt} E_{At} - w_t L^e_{At}$ in agriculture as well as $\max_{\{L^y_{Ct}, E_{Ct}\}} p^C_t Y_{Ct} - w_t L^y_{Ct} - p^e_{Ct}(1-\tau_t) E_{Ct}$ and $\max_{\{L^e_{Ct}, D_t\}} p_{eCt} E_{Ct} - w_t L^e_{Ct} - p_{Dt} D_t$ in non-agriculture and firms emit carbon according to equation (7).

(c) The government period budget constraint is given by $L_t T_t = \tau_t p^e_{Ct} E_{Ct}$.

(d) Goods and labor markets clear: $Y_{At} = L_t a_t$, $Y_{Ct} = L_t c_t$. $L^y_{At} + L^e_{At} + L^y_{Ct} + L^e_{Ct} = L_t$.

Solution In general there is no complete analytic solution to the above problem. The approach to solving the model however, remains similar to before. The agricultural side of the solution as well as the division of labor between agriculture and non-agriculture remains identical to equations (8) and (10). In order to find solutions to the non-agricultural side of the problem, I equate the modern-energy price-to-wage ratio implied by the profit maximization problem of the modern-energy firm with the corresponding ratio from the profit maximization problem of the non-agricultural firm to obtain:

$$\left(\frac{B_{Et}}{B_{lCt}}\right)^{1-\frac{1}{\sigma}} \left(\frac{E_{Ct}}{L^y_{Ct}}\right)^{-\frac{1}{\sigma}} \left(\frac{1-\alpha_C}{\alpha_C}\right) \frac{1}{1-\tau_t} = \frac{1}{\gamma B_{eCt} D_t^{1-\gamma} (L^e_{Ct})^{\gamma-1}} \tag{61}$$

Substituting from equation (29) for modern energy production (E_{Ct}) and using market clearing to write $L^y_{Ct} = L_{Ct} - L^e_{Ct}$, I can express the above as an implicit equation describing L^e_{Ct} as a function of productivities and total employment in non-agriculture, L_{Ct}. It is then easy to show, using the implicit function theorem, that as long as $\sigma < 1$, $\partial L^e_{Ct}/\partial D_t > 0$. Thus higher endowment entail higher modern-energy production and hence (in a closed economy model) higher energy use.

Calibration The calibration is similar to that of the baseline with the exception of modern energy endowments, D_t, and the endowment share in modern energy production, $1-\gamma$.

I assume that D_t is exogenous and I choose the value of endowments to match estimates of recoverable reserves of coal as well as proved reserves of crude oil and natural gas for countries around the world provided by the EIA (2014). I transform this reserve data into the same units (billions of barrels of oil equivalent) and calculate the total reserves of carbon energy in each country over time for the period 1980-2010.[78] There is a large variation in per-capita endowment of natural resources across countries. Normalizing UK (per worker) endowments to 1 and focusing on the 114 countries with non-zero endowments in 2010, countries in the bottom, median and top quintiles have (per worker) modern fuel endowments that are respectively 0.046, 3.18 and 117.77.

To estimate the impact this variation in endowments will have on modern energy production however, I first need to choose the reserve share parameter, $1-\gamma$, in modern energy production. Since data on the rental rate of reserves is hard to come by, I will choose $1-\gamma$ by regressing the (log of) constant price (PPP) value added of mining and utilities on (the log of) reserves as well as the log of a combined capital-labor mix used the mining-utilities sector.[79] In the regression I include time-fixed effects and I focus on OECD countries over the period 1980 to 2007. Details of construction and summary statistics on the data can be found in Kuralbayeva and Stefanski (2013). Since I am

[78] The coal reserve data is available only for 2011 and so I assume that total coal reserves stay constant for the period 1980-2010. In principle it would also be interesting to consider the wind, hydro and nuclear potential of different countries, but this proves difficult due to the scarcity of data and the difficulties of interpreting such data.

[79] The value added data comes from Kuralbayeva and Stefanski (2013) with the original sources being the UN (2014), Heston et al. (2012) and WDI (2013). See this paper for more detail. The reason for including capital in the regressions is that the only factors in the model are reserves and non-reserves (i.e. labor) and excluding capital would over-emphasize the role of the fixed factor (i.e. the reserves) with respect to the reproducible factors (i.e. labor).

estimating shares, I restrict parameters to sum to one. I define the capital-labor mix employed by the mining-utilities sector as $\kappa_t^i \equiv (K_t^i)^{\chi}(L_t^i)^{1-\chi}$ where K_t^i and L_t^i are the capital and employment used by the mining and utilities sector in country i at time t. Furthermore, I set $\chi = 2/3$ to capture the stylized fact that the (non-endowment) labor share tends to be roughly 66% in the data.[80]

The results of the regression are shown in the first column of Table 12. The share of reserves is approximately 15%. For completeness, I also present the results of the regression of the (log of) constant price (PPP) value added of mining and utilities on (the log of) reserves, employment and capital used in mining and utilities and time dummies (focusing on the same countries and time periods and restricting the sum of coefficients to one, as above). In this regression the share of reserves is roughly 10% - or even smaller than in the previous example. Finally, I also report regression results for all countries in the data. The values of γ are slightly higher than before. This however, does not significantly influence the results. Furthermore, since there are major issues with reserve data coming from non-OECD countries, I take my initial estimate of $1-\gamma = 0.15$ as the preferred value of reserve share.[81] The variance of $(D_t/L_t)^{1-\gamma}$ is much smaller than of per-capita endowments: the ratio between the highest and the lowest quintile is 3.24 $(= (117.77/0.0462)^{0.15})$.

Given the above, the model is then calibrated to reproduce: 1) traditional and modern energy use; 2) agricultural and non-agricultural employment; 3) total GDP; 4) the (after subsidy, current price) share of modern energy in non-agricultural value added; 5) the impurity of modern energy in the UK between 1980 and 2010 and 6) carbon energy endowments in the UK between 1980 and 2010. As before, I obtain net fossil-fuel subsidies directly from UK data.

First, L_{1990}, E_{C1990}, η_{C1990} and D_{1990} are normalized to 1 and L_t, L_{At}, L_{Ct}, E_{Ct}, E_{At}, η_{Ct} and D_t are fed into the model directly from the data. As before, η_{Ct} is modern-energy impurity and is derived as the ratio of carbon-emissions to modern (non-biofuel) energy use. The parameters α_A, B_{eAt}, $\bar{a}$, B_{At}, τ_t, σ are calibrated exactly as in the baseline.

Second, normalizing the wage rate to one, final good firms' first-order conditions imply that the price of sector $s = A, C$ goods is $p_{st} = 1/\frac{\partial Y_{st}}{\partial L_{st}^y}$ whilst modern energy prices are $p_{eCt} = 1/\frac{\partial E_{Ct}}{\partial L_{Ct}^e}$. Using these relationships as well as equations (3) and (29), the (after subsidy, current price) share of modern energy in non-agricultural value added, s_{Ct}^e, can be expressed as:

$$s_{Ct}^e \equiv \frac{p_{eCt}(1-\tau_t)E_{Ct}}{p_{Ct}Y_{Ct}} = \frac{1}{1+\bar{x}_{Ct}}, \tag{62}$$

where $\bar{x}_t \equiv \left(\frac{\alpha_C}{1-\alpha_C}\right)\left(\frac{B_{lCt}L_{Ct}^y}{B_{Et}E_{Ct}}\right)^{1-\frac{1}{\sigma}}$. Taking s_{Ct}^e from the data, I can thus infer that $\bar{x}_t = \frac{1-s_{Ct}^e}{s_{Ct}^e}$. Given this, using equation (29) and (61) I can write employment in modern energy production as:

$$L_{Ct}^e = \frac{\gamma}{(1-\tau_t)\bar{x}_t + \gamma} L_{Ct}. \tag{63}$$

[80] Quantitatively this last assumption is not very important and my results are not very sensitive to changes in χ. I impose this restriction to maintain a positive role for labor in the regression. As a robustness check, I also examine the case where capital and labor enter separately. As can be seen in columns 3 and 4 of Table 12, the reserve share is even smaller in this case, however labor share becomes statistically insignificant.

[81] Reserve data is usually self-reported by governments and hence may have political undertones. For example, OPEC countries base their production quotas on the reported reserve data of countries. This leads to large jumps in reported oil reserves after quotas are tightened that are not likely connected to changes in endowments.

	(1) $\log(VA_{MU})$	(2) $\log(VA_{MU})$	(3) $\log(VA_{MU})$	(4) $\log(VA_{MU})$
$\log(D_t)$	0.15***	0.26***	0.10***	0.19***
	(0.01)	(0.01)	(0.01)	(0.01)
$\log(\kappa_t)$	0.85***	0.74***		
	(0.01)	(0.01)		
$\log(L_t)$			-0.04	0.01
			(0.03)	(0.02)
$\log(K_t)$			0.93***	0.80***
			(0.03)	(0.02)
Obs.	617	1,088	617	1,088
Time FE	yes	yes	yes	yes
Sample	OECD	All	OECD	All

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

Table 12: Estimating the share of endowments in modern energy production.

Consequently, from equations (9) and (29), I extract the labor productivity of the modern energy sector, period by period:

$$B_{eCt} = \frac{E_{Ct}}{(D_t)^{1-\gamma}(L^e_{Ct})^{\gamma}}. \tag{64}$$

Third, I normalize non-agricultural labor productivity and energy specific productivity in 1990 to one, so that: $B_{lC1990} = 1$ and $B_{E1990} = 1$. This then allows me to infer α_C from equation (62) evaluated for 1990 after substituting for $\bar{x}_t$:

$$\alpha_C = \frac{1}{1 + \frac{1}{\bar{x}_{1990}}\left(\frac{L^y_{C1990}}{E_{C1990}}\right)^{1-\frac{1}{\sigma}}}. \tag{65}$$

Finally, I extract labor- and energy-specific technological progress in the non-agricultural sector. I feed into the the model - period-by-period - the constant price GDP found in the data so that $GDP^{Data}_t = p_{A1990}Y_{At} + p_{C1990}Y_{Ct}$.[82] In this expression sectoral outputs can be shown to be $Y_{At} = \bar{a}L_t$ and $Y_{Ct} = B_{Et}E_{Ct}(1-\alpha_C)^{\frac{\sigma}{\sigma-1}}(1+\bar{x}_t)^{\frac{\sigma}{\sigma-1}}$, whilst 1990 sectoral prices come from firms' first-order conditions evaluated at 1990 and the fact that $B_{lC1990} = B_{E1990} = 1$. Consequently, I extract energy-specific technological progress in the non-agricultural sector:

$$B_{Et} = \frac{GDP^{Data}_t - p_{A1990}\bar{a}L_t}{p_{C1990}E_{Ct}(1-\alpha_C)^{\frac{\sigma}{\sigma-1}}(1+\bar{x}_t)^{\frac{\sigma}{\sigma-1}}}. \tag{66}$$

Furthermore, since $\bar{x}_t \equiv \left(\frac{\alpha_C}{1-\alpha_C}\right)\left(\frac{B_{lCt}L^y_{Ct}}{B_{Et}E_{Ct}}\right)^{1-\frac{1}{\sigma}}$, taking $\bar{x}_t$ from the data, I can extract labor-specific productivity in the non-agricultural sector:

$$B_{lCt} = B_{Et}\frac{E_{Ct}}{L^y_{Ct}}\left(\bar{x}_t\frac{1-\alpha_C}{\alpha_C}\right)^{\frac{\sigma}{\sigma-1}}. \tag{67}$$

[82] Since the wage rate in the model is normalized to one in each period, I ensure that the implied level of GDP in the model and the data in 1990 match, by normalizing constant price GDP in the data in 1990 by the level of GDP in the model, $GDP^{model}_{1990} \equiv w_{1990}\left(L_{A1990} + \frac{(1-\tau_{1990})(1+\bar{x}_{1990})}{\gamma+\bar{x}_{1990}(1-\tau_{1990})}L_{C1990}\right)$.

Finally, it is worth highlighting some issues with the above calibration. Most importantly, endowment data is very limited - including endowments gives nearly 40% less price wedge observations than in the baseline. Second, the endowment data itself is patchy. Detailed reserve data is often a state secret in many countries whilst officially published data is usually self-reported and may have political undertones in some countries. More detailed examinations of energy and mineral reserves, such as the estimates of natural capital derived by the World Bank (WB, 2006), carry the risk of other endogeneity issues - see, for example, the criticisms of van der Ploeg and Poelhekke (2010). Consequently, the wedges derived from this particular extension should be approached with caution.

Inferring Wedges Taking the calibration for the UK as given, but varying in each country the per-worker endowment of natural resources (taken directly from the data), I repeat the baseline experiment for the same panel of data as in the baseline. Productivity and energy price wedges are defined exactly as in the baseline. I then set the *agricultural productivity* wedge, to match country i's agricultural employment share at time t. I choose the *non-agricultural productivity* wedge, to match the ratio of GDP-per-worker between country i and the UK. Finally, I choose a *fossil-fuel subsidy* wedge, $\bar{\tau}_t^i$, to match the ratio between emission intensity of country i and the UK.

11.4.4 Endowments and Trade

I now allow trade in the model with endowments. I assume that total modern energy (E_{Ct}) is produced using the same production function as in equation (29) with both labor (L_{Ct}^e) and fuel reserves (D_t). Modern energy however, can now be traded. Denote the quantity of modern energy (net-)exports as E_{Xt} (potentially negative) and the quantity of local modern energy consumption by E_{Lt}. We can then write:

$$E_{Ct} = E_{Lt} + E_{Xt}. \tag{68}$$

For simplicity, assume that trade is balanced period-by-period and that in exchange for energy exports (imports), consumers in the country can import (export) non-agricultural goods. Thus, in this version of the model, the following trade balance condition holds period-by-period:

$$p_{Ct} IM_{Ct} = p_{eCt}^* E_{Xt}, \tag{69}$$

where p_{Ct} is the price of non-agricultural goods, IM_{Ct} is the quantity of imported non-agricultural goods and p_{eCt}^* is the international price of modern energy. The imported goods are perfect substitutes for the locally produced non-agricultural goods, so that:

$$c_t L_t = Y_{Ct} + IM_{Ct}. \tag{70}$$

Of course, in the above, if IM_{Ct} is negative, this implies that part of the non-agricultural output of the country is exported in exchange for modern energy imports. To remain consistent with the data, the emissions of an economy are based on total modern energy consumption (rather than production), so that:

$$P_{Ct} = \eta_{Ct} E_{Lt}. \tag{71}$$

To close the model, the country is assumed to be a small open economy which takes the international price of modern energy, p^*_{eCt}, as given.[83] In addition, there are now two types of subsidy wedges. First, as before, there is a modern energy consumption subsidy, τ_t, which is paid to firms who use modern energy as an input. There is now also a modern-energy production subsidy, τ^T_t, which is paid to firms who produce modern energy. Thus, the consumer and producer prices of energy are respectively given by:

$$p^C_{eCt} = (1-\tau_t)p^*_{eCt} \text{ and } p^P_{eCt} = (1+\tau^T_t)p^*_{eCt}. \tag{72}$$

Both subsidies are financed by a lump-sum tax on the consumer. The reason for having two types of distortions is that the consumption subsidies influence the level of energy consumed in a country and hence the quantity of emissions produced by a country, whereas producer subsidies influence the quantity of energy produced and hence the extent of energy-net exports. Thus, when calibrating the model, I will be able to infer both production and consumption energy subsidies using data on emissions and on energy trade. Notice that this producer wedge - besides capturing direct producer subsidies - also captures costs associated with international trade - like transport or tariffs. All other aspects of the model (including production and preference functions) are identical to the baseline.

Competitive Equilibrium (Endowments and Trade) For every period t, given the international price of modern energy p^*_{eCt}, the (tax-distorted) competitive equilibrium of the economy with endowments and trade is defined as the: (1) Price of agricultural and non-agricultural goods, wage rates, rental rates of endowments, traditional energy prices as well consumer and producer modern energy prices, $\{p_{At}, p_{Ct}, p_{Dt}, w_t, p_{eAt}, p^C_{eCt}, p^P_{eCt}\}$; (2) household allocations: $\{a_t, c_t\}$; (3) firm allocations and emissions $\{L^y_{At}, L^e_{At}, L^y_{Ct}, L^e_{Ct}, P_{Ct}\}$; and (4) government policies $\{\tau_t, \tau^T_t, T_t\}$ such that:

(a) Given prices and policies, households' allocations maximize equation (2) subject to the budget constraint of the household: $p_{At}a_t + p_{Ct}c_t = w_t + p_{Dt}\frac{D_t}{L_t} - T_t$.

(b) Given prices and policy, firms' allocations, (3), solve the firms' problems in output and energy sub-sectors: $\max_{\{L^y_{At}, E_{At}\}} p^A_t Y_{At} - w_t L^y_{At} - p_{eAt}E_{At}$ and $\max_{\{L^e_{At}\}} p_{eAt}E_{At} - w_t L^e_{At}$ in agriculture and $\max_{\{L^y_{Ct}, E_{Lt}\}} p^C_t Y_{Ct} - w_t L^y_{Ct} - p^C_{eCt}E_{Lt}$ and $\max_{\{L^e_{Ct}, D_t\}} p^P_{eCt}E_{Ct} - w_t L^e_{Ct} - p_{Dt}D_t$ in non-agriculture and firms emit carbon according to $P_t = \eta_{Ct}E_{Lt}$.

(c) International and local (after subsidy) modern energy prices are equalized: $p^C_{eCt} = (1-\tau_t)p^*_{eCt}$ and $p^P_{eCt} = (1+\tau^T_t)p^*_{eCt}$.

(d) Trade is balanced period by period: $p_{Ct}IM_{Ct} = p^*_{eCt}E_{Xt}$.

(e) The government period budget constraint is given by $L_tT_t = \tau_t p^*_{eCt}E_{Lt} + \tau^T_t p^*_{eCt}E_{Ct}$.

[83] Whilst this might seem like a restrictive assumption, especially for large countries, recall that the model presented in this section is *not* used for counterfactual experiments, but only for measurement. Since I match observed levels of production and consumption at the global level, the price implied by the model will implicitly be the general-equilibrium 'market clearing' price at the international level. Consequently, nothing should be lost by assuming an exogenous price.

(f) Goods, energy and labor markets clear: $Y_{At} = L_t a_t$, $Y_{Ct} + IM_{Ct} = L_t c_t$. $E_{Ct} = E_{Lt} + E_{Xt}$. $L^y_{At} + L^e_{At} + L^y_{Ct} + L^e_{Ct} = L_t$.

Solution The approach to solving the model is similar to both the baseline and the model with endowments but no trade. The agricultural side of the solution as well as the division of labor between agriculture and non-agriculture remains identical to equations (8) and (10). Since this is a small open economy model, I take international modern energy prices as given. Since government policies are also exogenous, I also take local consumer and producer modern energy prices as given and exogenous. I then normalize the wage rate to one, and solve for L^e_{Ct} from the profit maximization problem of the modern-energy firm:

$$L^e_{Ct} = D_t \left(\gamma p^P_{eCt} B_{eCt}\right)^{\frac{1}{1-\gamma}} . \tag{73}$$

Total modern energy produced by the country is then simply obtained by substituting this expression into (29) to obtain:

$$E_{Ct} = D_t B_{eCt}^{\frac{1}{1-\gamma}} \left(\gamma p^P_{eCt}\right)^{\frac{\gamma}{1-\gamma}} . \tag{74}$$

Recalling that $L^y_{Ct} = L_{Ct} - L^e_{Ct}$ and substituting (73) into the expression for the modern energy price-to-wage ratio from the maximization problem of the non-agricultural firm, I can also solve for local energy consumption:

$$E_{Lt} = (p^C_{eCt})^{-\sigma} \left(\frac{1-\alpha_C}{\alpha_C}\right)^{\sigma} \left(\frac{B_{lCt}}{B_{eCt}}\right)^{1-\sigma} (L_{Ct} - D_t \left(\gamma p^P_{eCt} B_{eCt}\right)^{\frac{1}{1-\gamma}}). \tag{75}$$

Notice from the above, that in a model with energy endowments *as well as trade*, the result from the closed economy model that higher endowments cause higher consumption of modern energy is overturned. Whilst from equation (74), we see that higher endowments result in higher production of modern energy, from equation (75) we observe that they nonetheless result in a lower consumption of modern energy. Countries with high endowments export modern energy and import non-agricultural goods instead. Finally, from market clearing, (net) exports of energy are given by $E_{Xt} = E_{Ct} - E_{Lt}$ and hence by the trade balance condition in (69), net-imports of non-agricultural goods are given by $IM_{Ct} = \frac{p^*_{eCt}}{p_{Ct}} E_{Xt}$, where $p_{Ct} = 1/\frac{\partial Y_{Ct}}{\partial L_{Ct}}$ after normalizing the wage to one. All other quantities and prices can be derived similarly as in the baseline.

Calibration The model is calibrated to reproduce: 1) traditional and modern energy consumption as well as modern energy production (and hence the net imports of modern energy); 2) agricultural and non-agricultural employment; 3) total GDP; 4) the (after subsidy, current price) share of modern energy in non-agricultural value added; 5) the impurity of modern energy in the UK between 1980 and 2010 and 6) carbon energy endowments in the UK between 1980 and 2010. Ideally, I could calibrate both the consumer and producer subsidies directly to the data in the UK. It is however difficult to find disaggregated producer and consumer subsidies in the United Kingdom. As such, for simplicity, I assume that all subsidies in the UK are energy consumption subsidies and that producer subsidy are zero. Given this, as before, I obtain net fossil-fuel subsidies directly from UK data.

First, I obtain data on net energy import share of non-renewable energy, nm_t, defined as total non-renewable energy consumption less total non-renewable energy production divided by total energy consumption.[84] Given these shares, I can take the baseline modern energy consumption data (denote this by E_{Lt}) and calculate the implicit net-exports of modern energy $E_{Xt} = -nm_t E_{Lt}$. Hence, total production of energy can then be denoted by $E_{Ct} = (1 - nm_t)E_{Lt}$.

Second, as before, L_{1990}, E_{L1990}, η_{C1990} and D_{1990} are normalized to 1 and L_t, L_{At}, L_{Ct}, E_{Lt}, E_{Xt}, E_{At}, η_{Ct} and D_t are fed into the model directly from the data. The parameters η_{Ct}, α_A, B_{eAt}, $\bar{a}$, B_{At}, τ_t, σ are calibrated exactly as in the baseline whilst γ is calibrated exactly as in the model with endowments but no trade.

Third, normalizing the wage rate to one, final good firms' first-order conditions imply that the price of non-agricultural goods is $p_{Ct} = 1/\frac{\partial Y_{Ct}}{\partial L^y_{Ct}}$ whilst modern energy prices of consumers are $p^C_{eCt} = 1/\frac{\partial Y_{Ct}}{\partial L^e_{Ct}}$. Combining these conditions I obtain:

$$\left(\frac{B_{Et}}{B_{lCt}}\right)^{1-\frac{1}{\sigma}} \left(\frac{E_{Lt}}{L^y_{Ct}}\right)^{-\frac{1}{\sigma}} \left(\frac{1-\alpha_C}{\alpha_C}\right) = p^C_{eCt}. \tag{76}$$

Notice from the modern energy price-equalization condition that $p^C_{eCt} = \frac{1-\tau_t}{1+\tau^T_t} p^P_{eCt}$. Furthermore, notice that $p^P_{eCt} = \frac{1}{\gamma B_{eCt}(D_t)^{1-\gamma}(L^e_{Ct})^{\gamma-1}} = \frac{L^e_{Ct}}{\gamma E_{Ct}} = \frac{L^e_{Ct}}{\gamma(1-nm_t)E_{Lt}}$, where the first equality follows the modern-energy firm's profit maximization problem, the second equality follows from the production function of modern energy and the third equality follows from the fact that $E_{Ct} = (1 - nm_t)E_{Lt}$. Then, defining, $\tilde{x}_t \equiv \left(\frac{\alpha_C}{1-\alpha_C}\right)\left(\frac{B_{lCt}L^y_{Ct}}{B_{Et}E_{Lt}}\right)^{1-\frac{1}{\sigma}}$, recalling from labor market clearing that $L^y_{Ct} = L_{Ct} - L^e_{Ct}$ and substituting for p^C_{eCt}, I can rewrite equation (76) as:

$$L^e_{Ct} = \frac{\gamma(1-nm_t)}{(1-\tau_t)\tilde{x}_t + \gamma(1-nm_t)} L_{Ct}. \tag{77}$$

Given the above it is then easy to show that:

$$p_{eCt}E_{Ct} = \frac{L^e_{Ct}}{\gamma} = \frac{1-nm_t}{\gamma(1-nm_t) + (1-\tau_t)\tilde{x}_t} L_{Ct} \tag{78}$$

$$p_{eCt}E_{Lt} = \frac{p_{eCt}E_{Ct}}{(1-nm_t)} = \frac{1}{\gamma(1-nm_t) + (1-\tau_t)\tilde{x}_t} L_{Ct} \tag{79}$$

and

$$p_{Ct}Y_{Ct} = \frac{(1+\tilde{x}_t)(1-\tau_t)}{\gamma(1-nm_t) + (1-\tau_t)\tilde{x}_t} L_{Ct}. \tag{80}$$

Notice, also that the (current-price) value added of non-agriculture is defined as $VA_{Ct} \equiv p_{Ct}Y_{Ct} - p_{eCt}E_{Lt} + p_{eCt}E_{Ct}$. Substituting equations (78)-(80) into this expression, I obtain:

$$VA_{Ct} = \frac{(1+\tilde{x}_t)(1-\tau_t) - nm_t}{\gamma(1-nm_t) + (1-\tau_t)\tilde{x}_t} L_{Ct}.$$

[84] The data comes from the U.S. Energy Information Administration and International Energy Statistics and is conveniently presented by the Shift Project Data Portal (http://www.tsp-data-portal.org/) for all of the world's countries.

Consequently, the (after subsidy, current price) share of modern energy in non-agricultural value added, s^e_{Ct}, can be expressed as:

$$s^e_{Ct} \equiv \frac{p_{eCt}(1-\tau_t)E_{Lt}}{VA_{Ct}} = \frac{1-\tau_t}{(1+\tilde{x}_t)(1-\tau_t)-nm_t}. \tag{81}$$

Taking s^e_{Ct}, τ_t and nm_t from the data, I can thus infer that

$$\tilde{x}_t = \frac{nm_t s^e_{Ct} + (1-s^e_{Ct})(1-\tau_t)}{s^e_{Ct}(1-\tau_t)}.$$

This then allows me to infer L^e_{Ct} from (77) and hence to extract the labor productivity of the modern energy sector, period by period:

$$B_{eCt} = \frac{E_{Ct}}{(D_t)^{1-\gamma}(L^e_{Ct})^{\gamma}}. \tag{82}$$

Fourth, I normalize non-agricultural labor productivity and energy specific productivity in 1990 to one, so that: $B_{lC1990} = 1$ and $B_{E1990} = 1$. This then allows me to infer α_C from equation (81) evaluated for 1990 after substituting for $\tilde{x}_t$:

$$\alpha_C = \frac{1}{1+\frac{1}{\tilde{x}_{1990}}\left(\frac{L^y_{C1990}}{E_{L1990}}\right)^{1-\frac{1}{\sigma}}}. \tag{83}$$

Finally, I extract labor- and energy-specific technological progress in the non-agricultural sector. I feed into the the model - period-by-period - the constant price GDP found in the data so that $GDP^{Data}_t = p_{A1990}Y_{At} + p_{C1990}Y_{Ct}$.[85] In this expression sectoral outputs can be shown to be $Y_{At} = \bar{a}L_t$ and $Y_{Ct} = B_{Et}E_{Lt}(1-\alpha_C)^{\frac{\sigma}{\sigma-1}}(1+\tilde{x}_t)^{\frac{\sigma}{\sigma-1}}$, whilst 1990 sectoral prices come from firms' first-order conditions evaluated at 1990 and the fact that $B_{lC1990} = B_{E1990} = 1$. Consequently, I extract energy-specific technological progress in the non-agricultural sector:

$$B_{Et} = \frac{GDP^{Data}_t - p_{A1990}\bar{a}L_t - p_{eC1990}(E_{Ct}-E_{Lt})}{p_{C1990}E_{Lt}(1-\alpha_C)^{\frac{\sigma}{\sigma-1}}(1+\tilde{x}_t)^{\frac{\sigma}{\sigma-1}}}. \tag{84}$$

Furthermore, since $\tilde{x}_t \equiv \left(\frac{\alpha_C}{1-\alpha_C}\right)\left(\frac{B_{lCt}L^y_{Ct}}{B_{Et}E_{Lt}}\right)^{1-\frac{1}{\sigma}}$, taking $\tilde{x}_t$ from the data, I can extract labor-specific productivity in the non-agricultural sector:

$$B_{lCt} = B_{Et}\frac{E_{Lt}}{L^y_{Ct}}\left(\tilde{x}_t\frac{1-\alpha_C}{\alpha_C}\right)^{\frac{\sigma}{\sigma-1}}. \tag{85}$$

Inferring Wedges Taking the calibrated values for the UK (including the implied international modern energy price), but varying each country's per-worker endowment of natural resources (taken directly from the data), I repeat the baseline experiment with the same data. Productivity wedges for country i are defined exactly as in the baseline. I also define wedges to modern energy consumer prices ($\bar{\tau}^i_t$) and modern energy producer prices ($\bar{\tau}^{Ti}_t$). The consumer energy price wedge in country

[85] Since the wage rate in the model is normalized to one in each period, I ensure that the implied level of GDP in the model and the data in 1990 match, by normalizing constant price GDP in the data in 1990 by the level of GDP in the model, $GDP^{model}_{1990} \equiv w_{1990}\left(L_{A1990} + \frac{(1-\tau_{1990})(1+\tilde{x}_{1990})-nm_{1990}}{\gamma(1-nm_{1990})+\tilde{x}_{1990}(1-\tau_{1990})}L_{C1990}\right)$.

i is the sum of the baseline (UK) consumer energy price wedge, τ_t, and the country-i-specific price-wedge $\bar{\tau}_t^i$: $\tau_t^i = \bar{\tau}_t^i + \tau_t$. The producer energy price wedge in country i is the sum of the baseline (UK) producer energy price wedge, τ_t^T, and the country-i-specific price-wedge $\bar{\tau}_t^{Ti}$: $\tau_t^{Ti} = \bar{\tau}_t^{Ti} + \tau_t^T$. I then set the *agricultural productivity* wedge to match country i's agricultural employment share at time t. I choose the *non-agricultural productivity* wedge, to match the ratio of GDP-per-worker between country i and the UK. I choose the *producer fossil-fuel price* wedge, $\bar{\tau}_t^{Ti}$, to match the net import share of modern energy in each country i.[86] Finally, I choose the *consumer fossil-fuel price* wedge, $\bar{\tau}_t^i$, to match the ratio between emission intensity of country i and the UK.

11.4.5 Population Density, Climate and Urbanization

Suppose that the production function in non-agriculture is now given by:

$$Y_{Ct} = \left(\alpha_C (B_{lCt} L_{Ct}^y)^{\frac{\sigma-1}{\sigma}} + (1-\alpha_C)(\bar{B}_{Et} Z_{Ut} \left(Z_{Ht} E_{Ht}\right)^{\alpha_H} \left(Z_{Tt} E_{Tt}\right)^{\alpha_T} \left(E_{Ot}\right)^{\alpha_O})^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \quad (86)$$

where Z_{Ht} and Z_{Tt} refers to heating and transport energy specific productivity, whilst Z_{Ut} captures the energy productivity benefits of urbanization, E_{Ht} refers to the energy used in heating (or cooling), E_{Tt} refers to the energy used in transport, E_{Ot} refers to all other energy, whilst $0 < \alpha_s < 1$ for $s = H, T, O$ are weights of heating/cooling, transport and other energy use in the energy bundle such that $\sum_s \alpha_s = 1$. Finally, $\bar{B}_{Et}$ is the overall productivity of the energy-bundle. If, E_{Ct} is the total energy consumed by the non-agricultural firm (so that $E_{Ct} = E_{Ht} + E_{Tt} + E_{Ot}$), then it is easy to show that the allocation of energy between the different activities that maximizes effective energy (and hence the allocation that a profit maximizing firm would choose) will be $E_{st} = \alpha_s E_{Ct}$ for $s = H, T, O$. Consequently, the above non-agricultural production function can be written as:

$$Y_{Ct} = \left(\alpha_C (B_{lCt} L_{Ct}^y)^{\frac{\sigma-1}{\sigma}} + (1-\alpha_C)(B_{Et} Z_{Et} E_{Ct})^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}, \quad (87)$$

where, $B_{Et} \equiv \bar{B}_{Et} \sum_s {\alpha_s}^{\alpha_s}$ and $Z_{Et} \equiv Z_{Ut} Z_{Ht}^{\alpha_H} Z_{Tt}^{\alpha_T}$. This however, is just the baseline non-agricultural production function with an additional distortions to energy use. Thus the definition of competitive equilibrium and the solution are identical to the baseline, with the exception that B_{Et} is replaced with $B_{Et} Z_t$. Notice however, that I normalize $Z_{Et} = 1$ for the UK thus the calibration will also be identical to that of the baseline.

Inferring Wedges The overall productivity of sector j, in country, i, B_{jt}^i, is the product of UK productivity and the country-i-specific sectoral wedge. As in the baseline, I will have $B_{jt}^i = D_{At}^i B_{jt}$ for sectors $j = A, eA$ and $B_{jt}^i = D_{Ct}^i B_{jt}$ for sectors $j = lC, eC$. However, now allow for an additional wedge, Z_{Et}^i, to impact the modern-energy consumption sub-sector so that $B_{Et}^i = D_{Ct}^i Z_{Et}^i B_{Et} Z_{Et}$. In this last expression, as mentioned Z_{Et} is normalized to one. Subsidy wedges are defined in an identical manner to those of the baseline. Agricultural, non-agricultural and subsidy wedges will all be chosen exactly as in the baseline. However, in addition, I now calculate measures of Z_{Ht}^i, Z_{Tt}^i and Z_{Ut}^i directly from the data which - given α_H and α_T will allow me to calculate Z_{Et}^i for each country. I now describe how these measures are constructed.

[86] Data for this also comes from the Shift Project Data Portal.

First, consider the impact of temperature on energy demand. In regular atmospheric conditions, heating and cooling a space by one degree requires (for all intents and purposes) identical quantities of energy. Consequently, as a rough estimate, I calculate the sum of monthly absolute deviations from an 'ideal' room temperature, $\overline{temp} = 23^oC$, in the UK relative to country i:

$$Z_{Ht}^i = \frac{\sum_{k=1}^{12} |temp_{kt}^{UK} - \overline{temp}|}{\sum_{k=1}^{12} |temp_{kt}^{i} - \overline{temp}|}. \tag{88}$$

If $Z_{Ht}^i > 1$, countries will require less energy for heating (or cooling) than the UK and if $Z_{Ht}^i < 1$, countries will require more energy for heating (or cooling) than the UK to get to the 'ideal' temperature. I obtain monthly temperature data from WB (2011) and calculate Z_{Ht}^i for each country at each point in time.

Second, I consider the role that the area (and hence the population density) of a country plays. I assume that the main benefit of having a smaller area is the fact that less energy has to be spent in transporting goods and individuals since - on average - travel distances will be shorter. Suppose - for simplicity - that the (per worker) area of country i, A^i, is represented by a square with sides of length L^i such that, $A^i = L^i \times L^i$. It is then relatively easy to show that the distance between two randomly selected points in this square will be $L^i\sqrt{\frac{2}{3}}$.[87] Thus I can define the following:

$$Z_{Tt}^i = \frac{L^{UK}\sqrt{\frac{2}{3}}}{L^i\sqrt{\frac{2}{3}}} = \sqrt{\frac{A^{UK}}{A^i}}. \tag{89}$$

This will be a rough estimate of how much shorter the average journey in country i will be relative to the UK. If $Z_{Tt}^i > 1$ the average trip will be $1/Z_{Tt}^i$ times shorter than in the UK and hence less energy will be needed to make the trip. If, on the other hand, $Z_{Tt}^i < 1$ more energy will be needed to conduct the average trip than in the UK. I obtain data annual data on the (per-worker) land area of each country from the WDI (2013) and calculate Z_{Tt}^i for each country and at each point in time.

Third, I consider the role that urbanization plays in energy demand. A number of studies have shown that greater urbanization can result in improvements in energy efficiency. For example see Jones (1991), Liu (2009), Sadorsky (2013) or Morikawa (2012). Consequently, I define the following:

$$Z_{Ut}^i = (u_t^i/u_t^{UK})^{\alpha_U}, \tag{90}$$

where u_t^i and u_t^{UK} are the fraction of the (non-agricultural) labor force living in urban areas and α_U determines by how much energy efficiency improves given differences in urbanization rates across countries. If $Z_{Ut}^i > 1$, countries will require less overall energy than the UK given the extent of their urbanization and if $Z_{Tt}^i < 1$, countries will require more energy than the UK. I obtain the fraction of the population living in urban areas from the WDI (2013) (where urban areas are defined by national statistical offices). Then, due to lack of data, I assume that the same fraction of the labor force as of the total population lives in urban areas. Using this assumption I calculate the proportion of the non-agricultural population living in urban areas for each country at each point

[87] This assumes that the probability of choosing any point in the square is uniform and that each point (and each coordinate) is chosen independently.

in time, u_t^i. Determining α_U is relatively tricky, as estimates can vary widely. I turn to the the results of Morikawa (2012) who uses establishment-level micro-data from Japan for the years 2007 and 2008 and shows that doubling of urban density results in the efficiency of energy consumption in service establishments to increase by approximately 12%. I then assume that this 12% increase applies to all of non-agriculture and I choose $\alpha_U = 0.62$ so that a doubling of urbanization in the baseline UK model will increase non-agricultural modern energy intensity by 12% on average for the years 1980-2010.

Finally, I turn to data from Gov.uk (2012) (publication URN 14D/207) to calculate the fraction of energy used for transport and for heating/cooling in the UK in 2010. Using data from Table 1.02 in that publication I calculate the (primary energy equivalent) fraction of energy used for transport in 2010 which is approximately 27%. Primary energy equivalent data for heating and cooling is not available, however data on final energy consumption for heating/cooling and transport is available (Table 1.10). As such I calculate the ratio between final energy consumption share of heating/cooling and the final energy consumption share of transport and multiply it by the 27% found above which gives an estimate of the primary energy equivalent fraction of energy used for heating/cooling in 2010 as approximately 21%. Consequently, I set $\alpha_H = 0.21$ and $\alpha_T = 0.27$. Then, for each country i I construct $Z_{Et}^i \equiv Z_{Ut}^i {Z_{Ht}^i}^{\alpha_H} {Z_{Tt}^i}^{\alpha_T}$. Recalling that Z_{Et}^{UK} is normalized to one, the median observation of Z_{Et}^i is 0.98, the mean is 1.09, the highest percentile is 3.17 and the lowest percentile is 0.43.

11.4.6 All Factors

In this section I consider the version of the model that has endowments and trade, a non-agricultural sector disaggregated into industry and services as well as cross-country variation in population density, climate and urbanization rates.

Utility is defined over per-capita consumption of agricultural goods (a_t), industrial goods (m_t) and service-sector goods (s_t) and preferences are identical to those in the multi-sector version of the model in equation (44). The setup of the agricultural side of the model remains exactly as in the baseline case with the extension for population density, climate and urbanization rates. Non-agriculture is replaced by industry (M) and service (S) sectors, and output in each of these sectors (Y_{jt}) is produced using labor (L_{jt}^y) and modern energy inputs (E_{jt}) for $j = M, S$ according to:

$$Y_{jt} = \left(\alpha_j (B_{ljt} L_{jt}^y)^{\frac{\sigma_j - 1}{\sigma_j}} + (1-\alpha_j)(\bar{B}_{Ejt} Z_{Ut} \left(Z_{Ht} E_{jHt}\right)^{\alpha_H} \left(Z_{Tt} E_{jTt}\right)^{\alpha_T} \left(E_{jOt}\right)^{\alpha_O})^{\frac{\sigma_j - 1}{\sigma_j}} \right)^{\frac{\sigma_j}{\sigma_j - 1}}, \tag{91}$$

In the above, each term is defined as in (86) but is sector $j = M, S$ specific. Notice, I assume that α_H, α_O and α_T are common across the M and the S sector (and satisfy the same restrictions as before) as are the distortions Z_{Ut}, Z_{Ht} and Z_{Tt}. This assumption is largely made due to a lack of disaggregated data. As in the baseline model with cross-country variation in population density, climate and urbanization rates, the above non-agricultural production function can be written as:

$$Y_{jt} = \left(\alpha_j (B_{ljt} L_{jt}^y)^{\frac{\sigma_j - 1}{\sigma_j}} + (1-\alpha_j)(B_{Ejt} Z_t E_{jt})^{\frac{\sigma_j - 1}{\sigma_j}} \right)^{\frac{\sigma_j}{\sigma_j - 1}}, \tag{92}$$

where, $B_{Ejt} \equiv \bar{B}_{Ejt} \sum_{k=H,T,O} \alpha_k{}^{\alpha_k}$ and $Z_t \equiv Z_{Ut} Z_{Ht}^{\alpha_H} Z_{Tt}^{\alpha_T}$. As before, I normalize $Z_t = 1$ for the UK.

I assume that total modern energy (E_{Ct}) is produced using the same production function as in equation (29) with both labor (L^e_{Ct}) and fuel reserves (D_t). Modern energy however, can now be traded. Denote the quantity of modern energy (net-)exports as E_{Xt} (potentially negative) and the quantity of local modern energy consumption by E_{Lt}. We can then write:

$$E_{Ct} = E_{Lt} + E_{Xt}. \tag{93}$$

Notice that total modern energy consumption is simply the sum modern energy consumption in industry and services: $E_{Lt} = E_{Mt} + E_{St}$. I thus continue to assume that traditional energy is only used in agriculture, whilst modern energy is used only in non-agriculture.

For simplicity, assume that trade is balanced period-by-period and that in exchange for energy exports (imports), consumers in the country can import (export) industrial goods. Thus, in this version of the model, the following trade balance condition holds period-by-period:

$$p_{Mt} IM_{Mt} = p^*_{eCt} E_{Xt}, \tag{94}$$

where p_{Mt} is the price of industrial goods, IM_{Mt} is the quantity of imported industrial goods and p^*_{eCt} is the international price of modern energy. The imported goods are perfect substitutes for the locally produced industrial goods, so that:

$$m_t L_t = Y_{Mt} + IM_{Mt}. \tag{95}$$

Of course, in the above, if IM_{Mt} is negative, this implies that part of the non-agricultural output of the country is exported in exchange for modern energy imports. As before, the emissions of an economy are based on total modern energy consumption given by equation (71).

To close the model - as before - the country is assumed to be a small open economy which takes the international price of modern energy, p^*_{eCt}, as given. Also, as before, there are modern energy consumption subsidies, τ_t, paid to firms who use modern energy as an input and modern-energy production subsidies, τ_t^T, paid to firms who produce modern energy. Thus, the consumer and producer prices of energy are respectively given by equation (72). These are assumed to be paid for by lump sum taxes on the consumer.

Competitive Equilibrium (All Factors) For every period t, given the international price of modern energy p^*_{eCt}, the (tax-distorted) competitive equilibrium of the economy with endowments, trade as well as industry/service sub-sectors is defined as the: (1) Price of agricultural, industry and service sector goods, wage rates, rental rates of endowments, traditional energy prices as well as consumer and producer modern energy prices, $\{p_{At}, p_{Ct}, p_{Dt}, w_t, p_{eAt}, p^C_{eCt}, p^P_{eCt}\}$; (2) household allocations: $\{a_t, m_t, s_t\}$; (3) firm allocations and emissions $\{L^y_{At}, L^e_{At}, L^y_{Mt}, L^y_{St}, L^e_{Ct}, P_{Ct}\}$; and (4) government policies $\{\tau_t, \tau_t^T, T_t\}$ such that:

(a) Given prices and policies, households' allocations maximize equation (44) subject to the budget constraint of the household: $p_{At}a_t + p_{Mt}m_t + p_{St}s_t = w_t + p_{Dt}\frac{D_t}{L_t} - T_t$.

(b) Given prices and policies, firms' allocations, (3), solve the firms' problems: $\max_{\{L^y_{At},E_{At}\}} p^A_t Y_{At} - w_t L^y_{At} - p_{eAt}E_{At}$ and $\max_{\{L^e_{At}\}} p_{eAt}E_{At} - w_t L^e_{At}$ in agricultural output and energy sub-sectors; $\max_{\{L^y_{Mt},E_{Mt}\}} p^M_t Y_{Mt} - w_t L^y_{Mt} - p^e_{Ct}(1-\tau_t)E_{Mt}$ and $\max_{\{L^y_{St},E_{St}\}} p^S_t Y_{St} - w_t L^y_{St} - p^e_{Ct}(1-\tau_t)E_{St}$ in industry and service output sub-sectors and $\max_{\{L^e_{Ct},D_t\}} p_{eCt}E_{Ct} - w_t L^e_{Ct} - p_{Dt}D_t$ in modern energy sub-sectors and firms emit carbon according to $P_t = \eta_{Ct}E_{Lt}$.

(c) International and local (after subsidy) modern energy prices are equalized: $p^C_{eCt} = (1-\tau_t)p^*_{eCt}$ and $p^P_{eCt} = (1+\tau^T_t)p^*_{eCt}$.

(d) Trade is balanced period by period: $p_{Mt}IM_{Mt} = p^*_{eCt}E_{Xt}$.

(e) The government period budget constraint is given by $L_t T_t = \tau_t p^*_{eCt}E_{Lt} + \tau^T_t p^*_{eCt}E_{Ct}$.

(f) Goods, energy and labor markets clear: $Y_{At} = L_t a_t$, $Y_{Mt} + IM_{Mt} = L_t m_t$ and $Y_{St} = L_t s_t$; $E_{Lt} = E_{Mt} + E_{St}$; $E_{Ct} = E_{Lt} + E_{Xt}$; $L^y_{At} + L^e_{At} + L^y_{Mt} + L^y_{St} + L^e_{Ct} = L_t$.

Solution The model is solved similarly to the models above. Whilst an analytic solution is easily obtained, it is messy, and - given the above models - it does not contribute much to the discussion. Importantly, since this is a small open economy model, I take international modern energy price as exogenous. This then pins down the total quantity of modern energy produced in an economy. Then, like in the sub-sector model, by equating the wage-to-energy price ratios derived from the first-order conditions of output and energy firms in each sector and by combining the households first-order condition for industry and service sector goods, I can solve for employment in each of the firms. Given sectoral employment and energy production, I can infer the quantity of energy exports and hence - by the balanced trade condition - the quantity of imported industrial goods. This then allows me to disentangle sectoral consumption in the model. Sectoral prices are, once more, obtained from firm first order conditions.

Calibration Since the calibration is similar to that of the previous models I will only briefly outline the procedure. The model is calibrated to reproduce: 1) traditional and modern energy consumption as well as modern energy production (and hence the net imports of modern energy); 2) modern energy use in industry and services 2) agricultural, industrial and service sector employment; 3) total GDP; 4) the (after subsidy, current price) share of modern energy in non-agricultural value added; 5) the impurity of modern energy in the UK between 1980 and 2010 and 6) carbon energy endowments in the UK between 1980 and 2010. As before, I obtain net fossil-fuel subsidies directly from UK data and assume that all energy subsidies in the UK are consumer subsidies. Finally, as before, I normalize $Z_{Et} = 1$ in the UK. I can then choose the international price of energy to match the UK's net imports of modern energy. Due to the additional data requirements I again only focus on the 1980-2010 period.

Inferring Wedges Taking the calibrated values for the UK (including the implied international modern energy price), but varying each country's per-worker endowment of natural resources and their energy-specific wedges (both taken directly from the data and constructed above), I repeat the baseline experiment with the same data. The overall productivity of sector j, in country i, B^i_{jt}, is the product of UK productivity and the country-i-specific sectoral wedge. As before, I will have $B^i_{jt} = D^i_{At}B_{jt}$ for sectors $j = A, eA$ and $B^i_{jt} = D^i_{Ct}B_{jt}$ for sectors $j = lM, lS, eC$. However, I will also allow an additional wedge, Z^i_{Et}, to impact both modern-energy consumption sub-sectors so that $B^i_{Ejt} = Z^i_{Et}Z_{Et}D^i_{jt}B_{Ejt}$ for $j = M, S$. In this last expression, $Z_{Et} = 1$ in the UK, whilst the wedge Z^i_{Et} is constructed exactly as before.[88] I also define wedges to modern energy consumer and producer prices exactly as in the trade and endowment version of the model. I then set the *agricultural productivity* wedge to match country i's agricultural employment share at time t. I set the *industrial productivity* wedge, to match country i's industrial employment share at time t and I choose the *service productivity* wedge, to match the ratio of GDP-per-worker between country i and the UK. I choose the *producer fossil-fuel price* wedge, to match the net import share of modern energy consumption in each country i. Finally, I choose the *consumer fossil-fuel price* wedge, $\bar{\tau}^i_t$, to match the ratio between emission intensity of country i and the UK.

11.4.7 Analyzing results

A summary of the calibrated values from the robustness exercises are shown in Table 13. For productivity terms I also include average growth rates over the period to aid comparison.

Next, I turn to comparing the subsidy rates predicted by the various models. Table 14(a) replicates the results of Table 3 for each of the different models. In particular, they show the regression of the percent deviation of the modern energy consumer price from the undistorted consumer price in the model and the data.[89] As before, I focus on OECD countries since indirect subsidies in those countries are most likely to be small, and hence the price-gap approach is likely to capture most subsidies and hence be comparable to the estimates obtained form the model. The first column reproduces the regression for the baseline model. Notice that the results are slightly different to the result shown in column (1) of Table 3, since I now include only data points that are available for all robustness exercises. Column 2-7 then shows the corresponding regressions each of the extensions. The fit across models is generally good - with the slope parameters - in general - being near 1. The value of R^2 across the experiments is also high - ranging from 0.38 to 0.65. Notice that, adding endowments lowers the fit of the model - however allowing for endowments and trade results in the model with a fit almost as high as the baseline. This highlights the importance of trade in modern energy. Finally, disaggregation of non-agriculture lowers the fit - both when incorporated into the baseline model and when incorporated into a model with endowment and trade. This perhaps reflects the poor quality of disaggregated energy data. The addition of controls for temperature, population density and urbanization also lowers the fit. This again may be due to the relatively rough estimates of Z^i_{Et}.[90]

Next, Table 14(b), shows the regression of the percent deviation of the modern energy consumer price relative to the undistorted consumer price in the each of the models with respect to that of

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[88] I choose $\alpha_U = 0.93$ so that a doubling of urbanization in the baseline UK model will increase non-agricultural modern energy intensity by 12% on average for the years 1980-2010. Parameters α_H and α_T are chosen as before.

[89] To see this, recall that for country i, $\log\left(\frac{p^i_t}{p^{Ref}_t}\right) = \log(\frac{(1-\tau^i_t)p^{Ref}_t}{p^{Ref}_t}) = \log(1-\tau^i_t) \approx -\tau^i_t$.

[90] Notice that if I consider a broader sample of countries including these features results in a better fit.

Parameter	Baseline	Measured Productivity	Multi-Sector	Endowment	Endowment and Trade	Area, Temp. & Urb.	All
B_{lC1990},B_{E1990}, L_{1990},E_{C1990}, η_{C1990}	1	1	1	1	1	1	1
$\bar{a}$	1	0.16	1	1	1	1	1
$1-\alpha_A$	0.08	0.08	0.08	0.08	0.08	0.08	0.08
$1-\alpha_C$	0.06	0.06	-	0.06	0.06	0.06	-
$1-\alpha_M$	-	-	0.09	-	-	-	0.10
$1-\alpha_S$	-	-	0.05	-	-	-	0.04
α_H	-	-	-	-	-	0.21	0.21
α_T	-	-	-	-	-	0.27	0.27
α_U	-	-	-	-	-	0.62	0.93
$1-\gamma$	-	-	-	0.15	0.15	-	0.15
ρ	-	-	0.61	-	-	-	0.61
σ	0.76	0.76	-	0.76	0.76	0.76	-
σ_M	-	-	0.76	-	-	-	0.76
σ_S	-	-	0.76	-	-	-	0.76
ν	-	-	0.22	-	-	-	0.19
$\{D_t\}_{t=1980}^{2010}$	-	-	-	$\{\cdot\}$	$\{\cdot\}$	-	$\{\cdot\}$
Ave. gr., 1980-2010	-	-	-	-4.07%	-4.07%	-	-4.07%
$\{B_{At}\}_{t=1980}^{2010}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	
Ave. gr., 1980-2010	1.92%	2.56%	1.92%	1.92%	1.92%	1.92%	1.92%
$\{B_{lCt}\}_{t=1980}^{2010}$	$\{\cdot\}$	$\{\cdot\}$	-	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	-
Ave. gr., 1980-2010	2.01%	1.95%	-	2.02%	1.98%	2.01%	-
$\{B_{lMt}\}_{t=1980}^{2010}$	-	-	$\{\cdot\}$	-	-	-	$\{\cdot\}$
Ave. gr., 1980-2010	-	-	8.48%	-	-	-	8.18%
$\{B_{lSt}\}_{t=1980}^{2010}$	-	-	$\{\cdot\}$	-	-	-	$\{\cdot\}$
Ave. gr., 1980-2010	-	-	-1.25%	-	-	-	-0.98%
$\{B_{eAt}\}_{t=1980}^{2010}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$
Ave. gr., 1980-2010	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%	0.7%
$\{B_{eCt}\}_{t=1980}^{2010}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$
Ave. gr., 1980-2010	0.19%	4.48%	0.19%	0.83%	0.67%	0.19%	0.67%
$\{B_{Et}\}_{t=1980}^{2010}$	$\{\cdot\}$	$\{\cdot\}$	-	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	-
Ave. gr., 1980-2010	4.13%	4.10%	-	4.13%	4.29%	4.13%	-
$\{B_{EMt}\}_{t=1980}^{2010}$	-	-	$\{\cdot\}$	-	-	-	$\{\cdot\}$
Ave. gr., 1980-2010	-	-	9.67%	-	-	-	11.53%
$\{B_{ESt}\}_{t=1980}^{2010}$	-	-	$\{\cdot\}$	-	-	-	$\{\cdot\}$
Ave. gr., 1980-2010	-	-	-3.38%	-	-	-	-3.24%
$\{L_t\}_{t=1980}^{2010}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$
$\{\eta_{Ct}\}_{t=1980}^{2010}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$
$\{\tau_t\}_{t=1980}^{2010}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$	$\{\cdot\}$
$\{\tau_t^T\}_{t=1980}^{2010}$	-	-	-	-	$\{0\}_{t=1980}^{2010}$	-	$\{0\}_{t=1980}^{2010}$

Table 13: Robustness: Calibrated parameters

(a) Percent deviation of consumer modern energy prices from reference price in each extension and the data (OECD, 1980-2010).

	$\log(1-\tau^i_{Model,t})$						
	B	MP	S	E	ET	ATU	All
$\log(1-\tau^i_{Data,t})$	0.97***	0.96***	0.85***	0.70***	0.93***	0.90***	0.74***
	(0.06)	(0.06)	(0.09)	(0.08)	(0.06)	(0.06)	(0.09)
Obs	139	139	139	139	139	139	139
R^2	0.65	0.65	0.38	0.38	0.62	0.58	0.35
Sample	OECD	OECD	OECD	OECD	OECD	OECD	OECD

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

(b) Percent deviation of consumer modern energy prices from reference price in each extension and the baseline model. All countries, 1980-2010.

	$\log(1-\tau^i_{Model,t})$					
	MP	S	E	ET	ATU	All
$\log(1-\tau^i_{Baseline,t})$	0.98***	1.15***	0.85***	0.93***	0.95***	0.88***
	(0.00)	(0.01)	(0.01)	(0.00)	(0.00)	(0.01)
Obs.	1,660	1,660	1,660	1,660	1,660	1,660
R^2	1.00	0.86	0.81	0.96	0.98	0.80
Sample	All	All	All	All	All	All

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

Table 14: Results from the robustness exercise comparing predicted measure of subsidy rates in each model extension to the data (top) and the baseline model (bottom). In the above: B= Baseline; MP=Measured Productivity; E=Endowments; S=Sub-Sectors; ET=Endowments and Trade; ATU=Area, Temperature, Urbanization; ETS= Endowments, Trade and Sub-Sectors; All=Endowments, Trade, Sub-Sectors, Area, Temperature, Urbanization.

the baseline. In general, the prediction of most models is similar to the baseline, with the greatest differences - again - emerging in the models that disaggregate the non-agricultural sector. This is confirmed by Figure 20 which shows the density plots of the percent deviation of the modern energy consumer price relative to the undistorted consumer price (i.e. $\log(1-\tau^i_t)$) in each of the models in comparison to the density of the corresponding measures in the baseline. Notice that adding endowments, trade, population density, temperature and urbanization largely leaves the densities unchanged. However, sub-dividing the non-agricultural sector results in a leftward shift of density relative to the baseline - a small increase in implicit subsidy rates.

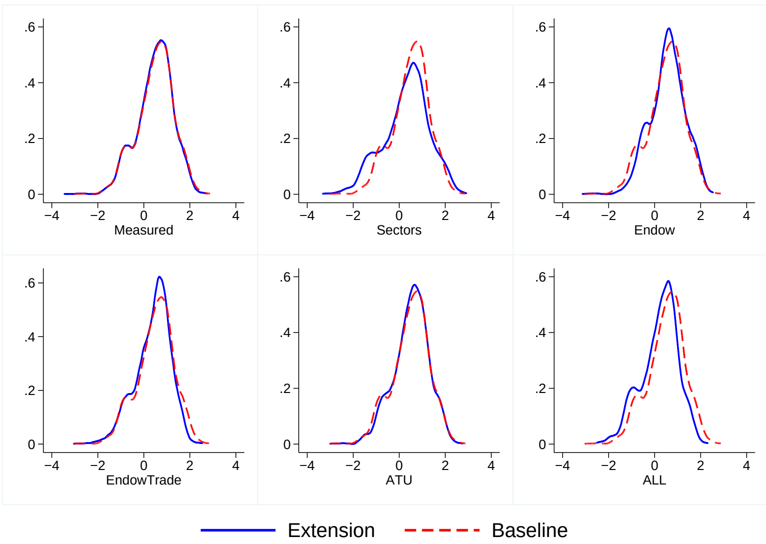

Figure 20: Kernel densities of the percent deviation of consumer modern energy prices from reference price in each extension and the baseline model (All Countries, 1980-2010).

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