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Income, resources, and electricity mix

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Abstract

This paper presents evidence on a national-level electricity ladder which sees countries transition toward coal and natural gas, and finally nuclear power and modern renewables such as wind power, for their electricity needs as they develop. The extent to which countries climb the electricity ladder is dependent on energy endowments. The results imply that the environmental implications of economic development differ in countries with different energy resource endowments. An effective global carbon mitigation strategy will require developing countries to leapfrog the middle rungs of the electricity ladder.

JEL Codes: O11, O13, Q43

Keywords: economic development, electricity mix, energy, substitution, transition

1. Introduction

Electricity plays a vital role in modern economic activity. As countries develop, they typically experience a significant expansion in their production and consumption of electricity. Further, sustained rising per capita income of the sort associated with economic development generally sees an evolution of a country's electricity supply mix (hereafter "electricity mix", i.e. the bundle of sources used in generating electricity). There is little formal evidence on the impact of national income on the electricity mix.

Low-income countries have electricity sectors dominated by hydroelectricity and oil-fired electricity generation. High-income countries have more diversified electricity sectors that are more reliant on coal, natural gas, and nuclear power, with recent adoption of modern renewables such as wind power. This paper develops a parsimonious model of income, energy resource endowments, and electricity mix capable of explaining these patterns. The model implies an "electricity ladder" that countries climb as they develop, but that countries rich in energy resources are less likely to climb this ladder than otherwise similar countries. The impact of income on the electricity mix is formally tested using cross-sectional and panel data for a sample of 133 countries. Results support the idea of an electricity ladder that sees imported fuels and then modern generation sources (nuclear, modern renewables) become increasingly significant contributors to total electricity production as a country's income per capita increases. Results also confirm that the extent to which countries climb the electricity ladder is conditional on energy resource endowments.

The generation of electricity has important environmental implications. Of particular contemporary importance, given concerns about global climate change, are emissions of carbon dioxide and other greenhouse gases. That higher incomes typically involve substitution toward coal-fired electricity has serious implications for global greenhouse gas emission trajectories, and suggests a need for policy intervention to facilitate leapfrogging to the (low-carbon) upper rungs of the electricity ladder. That the impact of economic development on the electricity mix differs for countries with different resource endowments indicates that the environmental impacts of the economic development process also differ between countries, a result with important implications for the environmental Kuznets curve (EKC) literature.

The reason for focusing on the impact of income on the electricity mix, rather than the impact of income on the energy mix, is that concentrating on the electricity mix allows for an analysis of the supply mix used in the production of a homogenous output (electricity), which facilitates a direct test of the supply-side model developed in this paper. The focus on the electricity mix permits the exclusion of changes in energy demand composition which, while important for the energy mix, do not affect the electricity mix (as demand for electricity is for a homogenous good, whereas demand for energy is typically tied to an energy type). Excluding changes in energy demand composition is advantageous because these changes are correlated with national income, and potentially endogenous to the energy mix.[1] The electricity mix also varies more widely across countries and time than the energy mix in, for example, the transportation sector.[2] The electricity sector is also common to all countries, is a

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[1] For instance, the relative sizes of industries such as agriculture and manufacturing are a function of national income, and may be endogenous to energy supply options, making the consistent estimation of income effects difficult if output composition variables are controlled for.

[2] The average oil share of the energy mix in the transportation sector was between 95 and 98 percent in every year of the period 1971-2005 in Organisation for Economic Co-operation and Development (OECD) countries, and between 85 and 91 percent in every year of this period in other countries (International Energy Agency [IEA] 2007a, 2007b).

large and rapidly expanding user of energy and source of greenhouse gas emissions, and offers some of the most cost-effective opportunities to reduce these emissions, and so warrants particular research attention (Stern 2006, Energy Information Administration (EIA) 2009a). Results are also of relevance to the energy mix more broadly.[3]

The increasing importance of electricity generation in global energy use and for global carbon dioxide emissions from fossil fuel use is shown in Fig. 1. The generation of electricity and heat is the primary source of global carbon dioxide emissions from fossil fuel use, contributing 41 percent of these emissions in 2005 (IEA 2007c). (The second largest source is the transport sector, responsible for 23 percent of carbon dioxide emissions from fossil fuels.) That the electricity sector is such an important contributor to carbon dioxide emissions means that electricity mix transitions which affect the carbon intensity of electricity generation may have important implications for total carbon dioxide emissions, and may even be responsible for EKC-type downturns in per capita carbon dioxide emissions. If recent trends continue, the electricity sector will account for half of total global energy use within 25 years. This rapid expansion of the electricity sector makes its study of high relevance to energy sector policymakers more generally.

-Fig. 1 here-

[3] As for the electricity mix, higher incomes on average increase the natural gas, nuclear, and wind shares of the energy mix. However, the income effect on the energy mix differs to that on the electricity mix in important ways. There is a strong negative impact of income on the biomass and waste share of the energy mix, for example, whereas there is a positive impact of income on the biomass and waste share of the electricity mix, indicating that biomass and waste is on a low rung of the energy ladder (poor countries rely heavily on biomass for energy needs), but a high rung of the electricity ladder (richer countries are more likely to generate electricity from biomass and waste). Results on income and the energy mix are available from the author on request.

The remainder of this paper is organized as follows. In section 2, a review of initial evidence on the impact of income on the electricity mix is presented. Section 3 presents a parsimonious model of energy resources, income, and electricity mix capable of explaining a national-level electricity ladder that is conditional on energy resources. In section 4, the econometric approach for testing the income effect on the electricity mix, and data issues, are discussed. Section 5 presents cross-sectional and panel results. In section 6, cross-sectional instrumental variable (IV) estimates using historical income as an instrument for current income are presented. The implications of the results for the EKC literature are explored in section 7. The final section concludes.

2. Income and electricity mix: initial evidence

2.1. Existing literature

There is strong evidence that the mix of energy sources consumed at the household level evolves according to an “energy ladder” (see Leach 1992, Barnes and Floor 1996, Goldemberg 1998, Heltberg 2004, Hosier 2004). The energy ladder typically sees households switch from traditional fuels (such as animal dung, agricultural waste, and wood) to transition fuels (such as kerosene, coal, and charcoal), and then to modern energy sources (liquefied petroleum gas, natural gas, and electricity), as their incomes increase.

The implications of economic growth for energy mix at the national level have received less formal attention. The model of Tahvonen and Salo (2001) features a transition from renewable energy toward fossil fuels as countries develop, and then finally a reversion to renewable energy as fossil fuel supplies become increasingly constrained. Grübler (2004) and Marcotullio and Schulz (2007) describe an evolutionary progression of aggregate energy mix, from the biomass used to meet energy needs in agrarian countries, to fossil fuels, and finally to modern sources of energy, such as nuclear power and modern renewables. There is little econometric evidence on the importance of income in explaining the energy progression, or on whether there is an energy ladder for the electricity sector.

It follows that there is little evidence on whether the impact of economic development on the electricity mix is affected by energy resource endowments. Marcotullio and Schulz (2007) provide evidence of heterogeneity in energy mix transitions across countries. They identify resource endowments as an important explanator of this heterogeneity, but caution that "confirmation of these trends demand further analysis" (p. 1676). As far as I am aware, no prior paper provides formal evidence of a national electricity ladder that is conditional on energy resources.

2.2. A first look at the data

That income is important for the electricity mix is evident from Fig. 2, which plots the hydroelectricity share of total electricity generation against gross domestic product (GDP) per capita in purchasing power parity (PPP) terms for the year 2003. It appears that hydroelectricity is on a bottom rung of the electricity ladder (i.e. is utilized first), and becomes a less important contributor to the electricity mix as per capita incomes rise. Nevertheless, several water-rich countries, such as Norway and Sweden, remain highly dependent on hydroelectricity, despite reaching high income levels. This suggests that resource endowments affect the degree to which countries climb the electricity ladder as their incomes increase.

- Fig. 2 here -

In Table 1, the 2003 electricity mix shares for eight electricity source types are shown for high-, middle-, and low-income countries, and for the world. The electricity source types consist of all sources that contribute more than 0.3 percent of global electricity production, and together make up 99.9 percent of global electricity generation. The electricity mix sources are ordered along the rungs of a general electricity ladder, from hydro (generated using domestic resources), to tradable fossil fuels (oil, coal, and natural gas), and finally to modern, capital-intensive technologies, such as nuclear power and non-hydro renewables.

- Table 1 here -

Hydroelectricity and oil contribute only 18 percent of electricity output in high-income countries, compared to 56 percent in low-income countries. These two fuels appear to be on low rungs of the electricity ladder, and tend to fall in relative importance as an economy develops. Hydro power is typically constrained by domestic hydro capacity, and oil generation, while favored by poor countries due to the relatively low capital costs of oil-fired plants, typically loses competitiveness as economic development relaxes capital constraints. As countries switch from hydro and oil-fired electricity as they develop, it appears that they substitute strongly toward coal. Coal accounts for 38 percent of electricity generated in high-income countries, compared to only 6 percent in low-income countries. High-income countries are also more likely to generate electricity from natural gas than poorer countries, in part reflecting its suitability in meeting intra-day peak loads in modern electricity networks.[4]

[4] The share of electricity generated from natural gas-fired plants is larger in low-income countries than high-income countries, but this reflects high natural gas shares of electricity generation in a number of the largest low-income countries, including Bangladesh, Nigeria, Pakistan, Uzbekistan, and Vietnam. On average, high-income countries have a higher proportion of gas in the electricity mix than low-income countries (Panel B of Table 1).

Nuclear power is primarily a developed country technology, contributing 23 percent of the electricity generated in high-income countries in 2003. Nuclear power is also an important electricity source in a number of middle-income countries, particularly former Soviet states such as Lithuania, and makes a small contribution to the electricity mix in one low-income country, Pakistan. Biomass, waste, and wind power contribute 2 percent of electricity generation in high-income countries, but a negligible amount in low-income countries. The data in Table 1 provide no evidence that income level is important for the use of geothermal power, indicating that factors such as geothermal resource potential may be a more important determinant of geothermal uptake than income level.

3. A model of electricity mix

3.1. Model set-up

In this section, a simple, stylized model of income, resource endowments, and electricity mix that is capable of providing an analytical framework for explaining these initial observations on income and electricity mix is presented. Consider a representative small, open economy with a social planner tasked with choosing from a basket of three electricity sources, D (domestic), F (imported fuel), and M (modern). Domestic sources include hydroelectricity and indigenous fuel reserves. Imported fuel sources include fossil fuels (oil, coal, natural gas). Modern sources are capital-, human capital-, and institution-intensive energy sources, such as nuclear power and modern renewables (including wind and solar). The social planner decides to invest in electricity generation capacity on the basis of the unit cost (C) of electricity from a new plant. Cost is defined broadly to include various factors of potential concern to the social planner, as will become evident, and is in levelized net present value terms.[5] Income (*Y*) is exogenous, and electricity demand (*Q*), a derived demand, is a positive function of income,

$$Q = f(\underset{+}{Y}) \qquad (1)$$

Assumption 1: At the early stages of the development process, the domestic energy source is the cheapest of the three sources to develop, and the modern energy source is the most expensive i.e. $C_D(Y \approx 0) < C_F(Y \approx 0) < C_M(Y \approx 0)$.

There are a number of reasons why domestic energy resources might initially be considered the preferred (lowest net cost) option for electricity generation by the social planner. First, domestic resources might initially be relatively cheap to exploit (the best options for hydroelectricity production are developed first, and the most accessible fuels are accessed first). Second, where available, domestic resources are able to be utilized with lower transactions costs (primarily, transport costs) than imported energy resources. Third, the use of domestic resources minimizes requirements for foreign exchange, access to which is costly and constrained in poor countries. Fourth, the use of domestic energy resources has more favorable domestic employment, income, and government revenue implications than the use of imported energy sources. Fifth, the use of domestic resources reduces exposure to energy security risks associated with reliance on imported energy sources. Hydro capacity, where available, is likely to be favored for electricity generation over even domestic fossil fuels, because it is renewable, not exportable (apart from as electricity), and of little utility in satisfying energy demand in other sectors of the economy (such as transportation).

[5] Levelized cost includes capital, operating, fuel, and other costs over the whole operating life of a plant using a given discount rate (IEA 2002).

Assumption 2: There are diminishing returns to domestic energy resources i.e. $\frac{\partial C_D}{\partial Q_D} > 0$.

From Assumption 2 and Equation 1,

$$\frac{\partial C_D}{\partial Y} > 0 \qquad (2)$$

Assumption 3: The cost of electricity from plants using "modern" energy sources decreases at higher incomes, i.e. $\frac{\partial C_M}{\partial Y} < 0$.

There are several reasons why the unit cost of modern electricity sources might fall with greater income.[6] Modern electricity sources are capital-, labor-, and institution-intensive, meaning that they require large amounts of capital investment, a highly skilled workforce, and an enabling governance environment characterized by mature energy-sector institutions. As countries develop, they typically experience reductions in the costs of financing, improved access to foreign exchange, and growth in human and institutional capital. As a result, modern electricity sources become increasingly viable as incomes increase. Further, wealthier countries are better able to exploit the economies of scale available in electricity generation (due to larger market size), which favor capital-intensive modern electricity sources.[7]

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[6] A countervailing factor is that small-scale use of renewable electricity generation technologies is particularly advantageous in countries with weak electricity infrastructure, such as India. Nevertheless, distributed generation remains a small share of total electricity generation, and predominately fossil fuel-based (Banerjee 2006).

[7] Modern electricity generation sources such as nuclear, wind, and solar power also involve the use of imported and/or domestic inputs (for example, imported or domestic uranium; domestic sunlight or wind endowments), but generation costs are dominated by capital costs (IEA 2005). Sunlight or wind endowments are essentially

Assumption 4: C_F is independent of income.

A summary of the model is presented in Table 2. For parsimony, the model ignores features of electricity sector investment, such as learning effects and uncertainties over costs. It also ignores distinctions between, for instance, the different fossil fuel types. Nevertheless, the model captures important reasons for why a general electricity ladder may exist.

- Table 2 here -

The relationship between income and the cost of new plants of the three electricity source types for the representative economy is presented in Fig. 3. From Assumptions 1-4, the unit cost of electricity from a plant based on domestic resources is initially low but increasing, that for modern plants is initially high but decreasing, and that for plants using imported fuels is an intermediate case, assumed constant.[8] The result of these different cost structures is an "electricity ladder". Initially, when income and electricity demand are low, the cheapest energy source is the domestic source (perhaps hydroelectricity). As income and electricity demand rise, increasingly marginal domestic energy resources are exploited until income level $Y^{\#}_{D,F}$, from which point the social planner switches investment toward plants using imported fuels. Once income level $Y^{\#}_{F,M}$ is reached, electricity plants of type *M* become

renewable, non-rivalrous, and non-excludable, meaning that they are not subject to the same within-country diminishing returns as domestic hydro and fossil fuels.

[8] The model result does not strictly require there always to be diminishing returns to domestic resources (i.e. unit costs of electricity generation may fall for a period), but that there is eventually diminishing returns.

economically competitive, and the social planner begins to invest in modern technologies, such as nuclear or wind power.

- Fig. 3 here -

The cost curves in Fig. 3 are likely to be affected by country- and time-specific factors. The magnitude of energy endowments would strongly affect C_D: in a country with few hydro or fossil fuel energy reserves, for instance, C_D would likely be high, and the initial energy source of choice may be imported fuels. (This reflects the situation in countries such as Cyprus, and amounts to a relaxation of Assumption 1.) Changes in technologies and prices also affect electricity generation costs, meaning that the cost curves are likely to shift over time. If global energy prices increase over time, this would place upward pressure on C_F and delay electricity mix transitions from domestic energy sources to imported fuels. The levels of the three cost curves may vary geographically within countries, so that at any time there may be concurrent investments in different energy sources within any one country. (For instance, hydroelectricity may be a relatively cheap energy source in some areas of a country, but prohibitively expensive in others.) As a result, measures of a country's scale (land area and population size) may be important controls in the regressions.

3.2. Parameterization

Assuming a fixed quantity of potential domestic energy resources, $R > 0$, a parameterization of the model is provided below.

$$C_D = d\left(\frac{Q_D}{R}\right)^{\alpha} \quad (3)$$

$$C_F = f \quad (4)$$

$$C_M = mY^{-\beta} \quad (5)$$

with $d, \alpha, f, m, \beta > 0$

In (3), the cost of new plants of type *D* is a decreasing function of *R* – i.e. electricity generation is cheaper in countries with more energy resources. The cost of plants of type *D* is also an increasing function of the quantity of electricity generated from domestic energy sources, reflecting diminishing returns i.e. $\partial C_D / \partial Q_D > 0$.[9]

Adopting the function $Q = lY \qquad (l > 0) \qquad (6)$

and because the initial electricity supply is plant type *D* (from Assumption 1), we have:

$$C_D = d\left(\frac{lY}{R}\right)^{\alpha} \quad (7)$$

From equations 4 and 7, the social planner will choose to switch from domestic energy sources to imported fossil fuel sources when:

$$C_D = C_F$$

$$\Rightarrow Y^{\#}_{D,F} = f^{\frac{1}{\alpha}} d^{-\frac{1}{\alpha}} l^{-1} R > 0 \quad (8)$$

The social planner will choose to switch from domestic to modern energy sources when:

$$C_D = C_M$$

[9] The extent to which returns are diminishing is also a negative function of *R* i.e. countries with large energy resource endowments have smaller diminishing returns. In countries with very large domestic energy resources, diminishing returns approach zero.

$$\Rightarrow Y^{\#}_{D,M} = \left(\frac{m}{d}\right)^{\frac{1}{\alpha+\beta}} l^{\left(\frac{-\alpha}{\alpha+\beta}\right)} R^{\left(\frac{\alpha}{\alpha+\beta}\right)} > 0 \qquad (9)$$

Finally, the social planner will switch from imported fossil fuels to modern sources when:

$$C_F = C_M$$

$$\Rightarrow Y^{\#}_{F,M} = \left(\frac{m}{f}\right)^{\frac{1}{\beta}} > 0 \qquad (10)$$

In countries with $R < lm^{\frac{1}{\beta}} d^{\frac{1}{\alpha}} f^{\frac{-(\alpha+\beta)}{\alpha\beta}}$, then $Y^{\#}_{D,F} < Y^{\#}_{D,M} < Y^{\#}_{F,M}$, and the cost curves will resemble those in Fig. 3 (so that the country will transition from domestic sources toward imported fuels and then, in turn, from imported fuels toward modern energy sources). If a country has sufficient energy reserves (*R* is large), it may not transition to imported fuels, and instead eventually transition directly from domestic sources to modern sources, albeit at a relatively high income level.

Income has an important impact on the electricity mix in the model: countries are more likely to switch toward imported fossil fuels and modern technologies as their incomes increase. Of interest is that $\partial Y^{\#}_{D,F} / \partial R,\ \partial Y^{\#}_{D,M} / \partial R > 0$, meaning that the switching points from domestic to either imported fossil fuels or modern electricity generation will be at higher income levels for countries with larger energy resource endowments. The model thus provides an important insight: the extent to which a country moves up the electricity ladder as it develops is contingent on energy resource endowments. A country with large capacity for producing hydroelectricity, for example, is less likely to adopt nuclear power as it develops than a country with few indigenous energy sources.

Reliable data on the costs of electricity generation by source and country are difficult to obtain. As a result, and given that the primary focus in this paper is on the determinants of the electricity mix, the empirical investigation will focus on the model's implications for electricity output. Whether a national-level electricity ladder exists, and whether it is contingent on energy resource endowments, are explored in the remainder of the paper.

4. Estimation approach and data

To estimate the income effect on the electricity mix, and investigate whether this effect is conditional on energy endowments, regression estimations using both cross-sectional and panel data are carried out. The model for estimation is of the form:

$$S_{j,c,t} = \alpha_j \ln Y_{c,t} + \mathbf{x}'_{c,t}\boldsymbol{\beta}_j + I_{j,c} + I_{j,t} + \varepsilon_{j,c,t} \qquad (11)$$

where the dependent variable is the percentage share of electricity source (*S*) type *j* in total electricity generation in country *c* in year *t*. The standard regression assumptions, including $E(\varepsilon_{j,c,t}) = 0$, are applied. $Y_{c,t}$ is real GDP per capita in PPP terms, and $\mathbf{x}'_{c,t}$ is a vector of additional determinants of electricity mix. This vector includes the following country characteristics: 1) the logarithms of population and land area, to control for a scale effect of country size on electricity type; 2) a dummy for transition economies; 3) dummies for the members of the United Nations Security Council and for countries with nuclear weapon capabilities, as these countries may have larger nuclear power sectors and/or more substantial energy security concerns than otherwise similar countries; and 4) six variables that measure indigenous energy reserves (as proxies of endowments). These variables are per capita: a) renewable internal freshwater resources, as a proxy for hydroelectricity potential; b) oil reserves; c) coal reserves; d) natural gas reserves; e) uranium reserves; and f) volcanoes, as a proxy for the potential to produce geothermal electricity. These six energy reserve types are relevant for electricity generation sources that contribute 98.3 percent of global electricity production. Given availability constraints, data on reserves are for recent years. This is not a drawback if current reserves are strongly correlated to historical endowments, or if electricity-sector investment has been affected by expectations of resource availability and cost.[10]

Both country and year fixed effects are included in panel estimations, represented by $I_{j,c}$ and $I_{j,t}$ respectively. The inclusion of these fixed effects is important because time-invariant and time-specific factors may affect both a country's electricity mix and its income level. Time-invariant factors include institutional quality, climate, geography, cultural preferences, and exposure to energy security risks. Time-specific factors include changes in energy prices, technologies, and perceived energy security risks, as well as the effects of incidents such as the Three Mile Island and Chernobyl nuclear accidents, which reduced the attractiveness of investments in nuclear power. Interactions between income and energy reserves are included in panel estimations to test whether the within-country impact of income on the electricity mix is dependent on resources, as implied by the model.

Estimations are carried out for the eight electricity source types in Table 1. Given that the same set of control variables is included in each equation, the efficient estimator is single-equation ordinary least squares (OLS) rather than system equation estimation (Greene 2000).

[10] Nevertheless, fossil fuel exploration, the large costs of which are affected by government policies related to the energy sector, may be endogenous to the electricity mix (via, for example, preferences concerning energy sources), or may be a function of income. As a robustness check, I explored results using the 1971 value of fossil fuel resource stocks from Norman (2008). Results, available on request, are similar.

Robust standard errors are presented. Panel data standard errors are clustered at the country level to account for possible serial correlation.

A list of data sources and definitions for all variables is provided in the Appendix. Panel regressions are for a sample of 4,002 observations for the period 1960-2004. Countries are included in the sample for an average of 30 years each. The large size of the panel data set, particularly in dimension *N* (133 countries), means that issues related to spurious regressions in the panel data context are not of significant concern (Wooldridge 2002). Cross-sectional regressions are for 2003, as this year allows broad country coverage.

5. Results

5.1. Cross-sectional estimates

Results from the estimation of (11) using cross-sectional data, without controls, are presented in Table 3. The estimated income effect is negative for the hydro and oil shares of the electricity mix, and positive for coal, natural gas, nuclear, biomass and waste, and wind (significant at the 5 percent level or higher). The estimated income effect on the geothermal share of the electricity mix is statistically insignificant. The results are consistent with an electricity ladder that sees countries substitute, in relative terms, from hydroelectricity and oil toward coal, natural gas, nuclear, and modern renewables as they develop.[11] The estimated coefficient on income of -11.48 in the hydro regression has the following interpretation: on average, one percent more income reduces the hydro share of the electricity mix by 0.11 percentage points.

[11] Regressions in 1971-2003 first differences give similar results in sign and significance for all regressions except biomass and waste, but missing 1971 electricity mix and GDP data reduce the estimation sample. Results are similar if OPEC countries are excluded from the estimation sample.

- Table 3 here -

Results with the set of control variables are presented in Table 4. Estimated coefficients on income per capita are identical in sign to those in Table 3, larger in absolute magnitude, and remain statistically significant (with the exception of the geothermal estimate). The income effect on the electricity mix observed from cross-sectional data is thus robust to the consideration of other country-specific characteristics. The coefficients of determination (*R*-squared) are reasonably high for most of the electricity source types, and the regression *F* statistics are mostly significant. For instance, 42 percent of the cross-country variation in the hydro share of the electricity mix is explained by the variables included in the model.

- Table 4 here -

The estimated coefficients on the control variables in Table 4 provide additional information on the determinants of the electricity mix. Smaller countries tend to have electricity sectors that are more oil-dependent than otherwise similar countries, likely reflecting the relatively low capital costs of oil-fired generation and that oil is cheaper to transport than coal or natural gas (Heron 1985). Transition economies are more likely to use nuclear power, and have smaller dependence on oil and modern renewables. There is no evidence that nuclear-armed countries are more likely to use nuclear power than comparable countries. Unreported estimates that control for the ratio of electricity generation to total primary energy supply are similar.

The estimated coefficients for control group B in Table 4 indicate the importance of energy reserves for the electricity mix. The bold diagonal is the set of own-resource coefficients. The prior for these variables is that they are positive: countries are likely to use domestic resources in electricity production, when available. The results indicate that for electricity generated from hydro, oil, coal, natural gas, and geothermal sources, this is indeed the case. Countries with large geothermal resources (as proxied by the number of volcanoes per capita), for instance, are significantly more likely to generate geothermal electricity than otherwise similar countries. Countries with large endowments of fresh water are more likely to base their electricity sectors on hydro power, and countries are likely to base their electricity sectors on fossil fuels that are domestically available. There is thus strong evidence of an "endowment effect" on the electricity mix. It is only the case of nuclear power for which the relationship between domestic energy resources (in nuclear's case, uranium) and electricity production is insignificant.[12]

The cross-resource coefficients in control group B indicate the effect of other energy reserves on the electricity share of any one electricity source. The expectation is that these coefficients will typically be negative: reserves of R_1 reduce the likelihood of electricity generation from source $S_{\neq 1}$. The results in Table 4 generally agree with this expectation. The cross-coefficients reveal an important result: all else equal, additional reserves of oil, coal, or natural gas significantly reduce the likelihood that a country invests in modern electricity sources such as nuclear power, biomass and waste, or wind power. This result is in line with

[12] That uranium endowments are insignificant determinants of nuclear adoption is likely in part a function of the low share of fuel costs in total levelized costs of nuclear generated electricity (IEA 2005), and provides support to the treatment of nuclear power in the model.

the model: additional energy endowments reduce the likelihood that a country will climb to the top rungs of the electricity ladder.

Both the income and endowment effects on the electricity mix are large. The estimates in Table 4 indicate that a doubling of GDP per capita on average results in a 23 percentage point reduction in the hydro and oil share of the electricity mix, with substitution toward coal, natural gas, and nuclear power (and also minor substitution toward biomass, waste, and wind). But large endowment effects mean that countries with similar income levels may have very different electricity mixes. Countries with per capita coal reserves as large as those of Australia on average source 72 additional percentage points of their electricity mix from coal, and have much smaller dependence on hydro, natural gas, nuclear, and modern renewables, than otherwise similar countries with no coal reserves. Countries with per capita water resources as large as those of Norway on average source 64 additional percentage points of their electricity mix from hydroelectricity. The United Arab Emirates' natural gas and oil reserves imply that its share of the electricity mix accounted for by natural gas and oil is 53 percentage points higher than an otherwise similar country with no reserves of either fuel.

While the evidence using cross-sectional data indicates that endowments are important for the electricity mix and that countries' electricity mixes tend to evolve according to a common electricity ladder, there are exceptions. Mongolia, for instance, has reasonably large water endowments but has yet to develop hydroelectricity, despite hydroelectricity's position on the bottom rung of the general electricity ladder. Mongolia instead relies primarily on (domestic) coal to meet both electricity and heating needs. Others, such as Ireland and Luxembourg, have yet to adopt nuclear power, despite reaching high incomes and having few energy endowments. (Ireland and Luxembourg do have relatively high shares of other generation sources at the upper rungs of the electricity ladder, including natural gas, biomass and waste, and wind.) The electricity ladder is thus not climbed in a universally common manner. Additional factors, such as preferences, policies, climate, and geographical location relative to energy suppliers, also have important effects on any individual country's electricity mix and the manner in which it changes as that country develops.

5.2. Panel data estimates

Estimates on the impact of income on the electricity mix for a panel data set of 133 countries for the 45 year period 1960-2004 are presented in Table 5. Four estimations are presented: 1) pooled OLS; 2) pooled OLS with year fixed effects; 3) fixed effects estimations with year fixed effects; and 4) estimates using the between estimator. The estimates are generally similar to those obtained from cross-sectional regressions, indicating that the evidence on income and the electricity mix is statistically robust (and that regression issues related to the time series characteristics of the variables are of little concern). The fixed effects regressions presented in Panel C, which indicate the within-country impact of changes in income on the electricity mix, provide strong support for the evidence on the electricity mix obtained already: as a country's income increases, it is, on average, likely to substitute from hydro and oil toward coal, natural gas, nuclear, and wind. (The estimate of the impact of income on the biomass and waste share of the electricity mix is insignificant in the fixed effects estimation.) The between estimator has the advantage of being a consistent estimator of the long-run relationship between variables in panel data studies when the time series are stationary or stochastically trending, and being super-consistent for series that cointegrate (Pesaran and Smith 1995). Estimates using the between estimator are similar to the other results.

- Table 5 here -

In Table 6, fixed effects estimates that include interactions between income and energy resource reserves are presented. The motivation for this specification is to identify whether the within-country impact of income on the electricity mix differs for countries with different endowments. Interactions of log GDP per capita with reserves of water, oil, coal, and natural gas are included.[13] Results for energy sources at the top of the electricity ladder are particularly interesting. They suggest that the positive income effect on the adoption of nuclear power or modern renewables is significantly weaker in countries with large reserves of hydro resources or coal. This finding provides strong support for the implications of the model: countries with large energy resources are less likely to climb the electricity ladder as their incomes increase. The parameter estimate on the interaction term between coal reserves and log GDP per capita, for instance, indicates that the income effect on the nuclear share of the electricity mix is non-positive in countries with coal reserves of 0.41 thousand tons oil of equivalent per capita or above. Australia has per capita coal reserves that are almost five times this threshold. The results thus provide statistical support to the idea that countries that are rich in energy resources are less likely to climb to the top rungs of the electricity ladder.

- Table 6 here -

[13] These four energy sources are directly relevant to the lower four rungs of the electricity ladder, which contribute 82 percent of global electricity. Interactions of income with uranium reserves and volcanoes per capita are not included because uranium reserves have been found to be relatively unimportant for electricity mix (see Table 4), and geothermal electricity is a relatively minor and recent contributor to global electricity production.

6. Addressing the potential endogeneity of income

An issue of importance is that income may potentially be endogenous, i.e. correlated with $\varepsilon_{j,c,t}$. There are several avenues via which this endogeneity may emerge. Country-specific rates of technological change in the electricity sector may affect both income and the electricity mix, for example. Or resource extraction to feed electricity demand may have implications for economic growth (see Sachs and Warner 1995). Political factors, such as whether a government pursues an export-oriented development strategy, may also affect both the electricity mix and income. Further, environmental factors, such as localized air pollution problems or the occurrence of acid rain, may affect both national income and electricity mix choice. Moreover, security issues potentially affect both income and the electricity mix – for example, countries at higher risk of experiencing disruptions in their access to oil may have slower income growth, and would have an incentive to diversify away from oil-fired electricity. Finally, the relative cost of electricity – which is affected by fuel choice – may affect the economic growth rate. In any of these cases, both the dependent variable (electricity mix source) and the key independent variable (log GDP per capita) are correlated with an excluded variable.[14] A suitable IV approach will provide consistent estimates of the causal impact of income on the electricity mix, allowing a robustness check on the OLS results.

The IV strategy exploits the facts that 1) cross-sectional GDP per capita rankings display persistence over time; and 2) the great majority of investment in the global electricity sector has been in the post-World War II period, and post-War electricity capacity dominates the

[14] The fixed effects estimations control for time-invariant, but not time-varying, aspects of these mechanisms.

current electricity mix.[15] Historical GDP per capita thus fits the requirements of a good instrument for the cross-sectional regressions: it is highly correlated with current levels of GDP, but unlikely to be otherwise correlated with variables that may be in the error term, such as country-specific technical progress in the electricity sector, and whether countries have been affected by acid rain. I am unaware of any prior paper that has used historical income as an instrument for present income.

To instrument for log GDP per capita in 2003, I use 1950 log GDP per capita from Maddison (2009). Ideally, historical GDP levels prior to the adoption of electricity would be used as an instrument for current GDP, but 1950 is the earliest year for which the data allow broad country coverage. Two-stage least squares estimates are presented in Table 7. 1950 log GDP per capita explains 51 percent of the cross-country variation in 2003 log GDP per capita, and safely passes the Stock and Yogo (2005) weak instruments test.

- Table 7 here -

The estimated coefficients in Table 7 are generally similar to earlier results, and strengthen the case that there is an important income effect on the electricity mix. The exception is the coal regression, in which a negative and statistically insignificant IV coefficient estimate on the income variable is obtained, in contrast to the positive and significant estimate obtained in the OLS regressions. This result is largely a product of the poor post-1950 growth performance of countries such as Kuwait and Venezuela, which generate no coal-fired

[15] Electricity generation extends from the 19th century, but global electricity generation in 1950 was equal to only 6 percent of generation in 2003 (Khatib 1993, IEA 2007a). Further, generation plants have limited life-spans. Consequently, the bulk of existing electricity generating plants is the product of post-1950 investment.

electricity, and the strong post-1950 growth performance of countries such as Botswana and China, which have electricity sectors that are heavily dependent on coal. Despite the insignificant IV estimate for the income effect on the coal share of the electricity mix, the weight of the evidence, including the panel data results, indicate that coal on average becomes an increasingly important share of the electricity mix as countries develop.

7. Implications of results for the environmental impact of development

Each of the electricity generation source types is associated with a bundle of environmental effects. Hydro generation normally requires the damming of rivers and the flooding of large areas. Fossil fuel-fired generation involves emissions of air pollutants, including greenhouse gases. Nuclear power has a low carbon footprint, but produces radioactive waste, and is associated with a risk of serious accidents. Modern renewables are low-carbon, but have other implications for the environment. Wind power, for instance, often raises concerns relating to issues such as aesthetics and impacts on local ecosystems. The differing environmental impacts of the electricity sources mean that electricity mix transitions may have profound implications for environmental trends.

There is a large literature on the environmental impacts of economic development. Since the early 1990s, the EKC hypothesis – that environmental degradation eventually reduces as countries develop – has attracted particular attention. Much of the literature has centered on estimating a globally-common income level at which environmental degradation begins to reduce with further income increases. Given increasing concerns about the impact of atmospheric emissions of carbon dioxide on the global climate, many recent studies have focused on testing the EKC hypothesis in the context of carbon dioxide emissions (see, for instance, Schmalensee et al. 1998, Dijkgraaf and Vollebergh 2005, Azomahou et al. 2006).

The results presented in this paper have two implications of importance to the carbon EKC literature. First, transitions to low-carbon electricity sources on the top rungs of the electricity ladder as income increases may be an important cause of EKC-type downturns in carbon dioxide emissions. Second, the likelihood of such transitions depends on energy resource endowments. Energy endowments are thus one potential source of cross-country heterogeneity in the long-run relationship between income and carbon dioxide emissions. Many studies in the EKC literature have allowed for country-to-country differences in emissions paths by including country fixed level effects in EKC regressions. But the results in this paper indicate that countries are likely to differ in their emissions-income trajectories as well as in their emissions levels.[16] If this is the case, a globally-common emissions-income turning point is unlikely to exist. The effects of heterogeneity in energy resource endowments and electricity mix on emissions-income paths are a valuable area for further research.

8. Conclusion

The model presented in this paper features diminishing returns to electricity generation from domestic energy resources and increasing affordability of modern energy sources as countries develop, and implies a general electricity ladder that sees countries transition from domestic resources, to imported fuels, and finally to capital-intensive modern electricity sources, as per capita incomes rise. The model also implies that the extent to which any country climbs the electricity ladder as it develops is a negative function of domestic energy endowments.

[16] The point that different countries are unlikely to follow a common emissions-income path has been made by others, most notably Brock and Taylor (2004), and tests reject parameter homogeneity in carbon Kuznets curve studies (Dijkgraaf and Vollebergh 2005). The importance of energy endowments for the income effect on the electricity mix is a potentially important, and overlooked, source of cross-country parameter heterogeneity in the carbon-income relationship.

Empirical results for a large sample of countries provide strong support for the implications of the model. Similar results are obtained in cross-sectional and panel data estimates, and in estimates in which historical income is used as an instrument for current income. The results indicate that as per capita incomes increase, countries typically transition from hydro and oil-fired electricity toward electricity generated from coal, natural gas, nuclear, and modern renewables such as wind power. The evidence indicates that countries do not follow a common electricity mix path, and that the extent to which countries climb the rungs of the electricity ladder is dependent on domestic energy resource endowments.

Important implications emerge, the most significant of which relate to the environmental implications of economic development. The results highlight a dilemma arising from the non-uniform impact of income on carbon dioxide emissions. Higher incomes lead to substitution toward fossil fuel-fired electricity (coal and natural gas), which is carbon-intensive. On the other hand, higher incomes also eventually facilitate the adoption of low-carbon electricity sources, such as nuclear power and wind power, particularly in countries that are poor in fossil fuels. On average, the impact of higher incomes in increasing the fossil fuel share of the electricity mix dominates the impact of higher incomes in increasing the nuclear and modern renewables share of the electricity mix, implying that the carbon intensity of electricity generation is likely to increase with continued economic development in a business-as-usual scenario. Nevertheless, the adoption of nuclear power and modern renewables may, in certain instances, be a cause of EKC-type downturns in carbon dioxide emissions as income per capita increases. Countries that are poor in fossil fuel resources may be best placed to achieve reductions in carbon dioxide emissions with rising incomes.

The results also imply a need for low- and middle-income countries to leap out of, or over, the middle rungs of the electricity ladder (fossil fuels) if global carbon mitigation efforts are to be successful. Without leapfrogging, greenhouse gas emissions from electricity generation are likely to accelerate as the coal share of the electricity mix increases. Adequate pricing of greenhouse gas emissions may be effective in diverting investment from coal-fired electricity generation. Research and development aimed at improving the cost-competitiveness of low-carbon electricity options may also potentially facilitate leapfrogging. External assistance in the form of cash, training, and access to technologies may also be able to improve the ability of low- and middle-income countries to adopt low-carbon electricity generation sources at the upper rungs of the electricity ladder.

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Table 1: Electricity source by income level, 2003

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	----------------------------> General electricity ladder ----------------------------->							
Type of source	Hydro		Fossil fuels		Nuclear	Modern renewables		
Source	Hydro	Oil	Coal	Natural gas	Nuclear	Geothermal	Biomass and waste	Wind
Panel A: Share of total electricity produced in each country group								
High-income countries	11.92	6.43	38.15	18.18	22.58	0.28	1.70	0.58
Middle-income countries	20.38	7.12	45.50	20.05	5.97	0.40	0.48	0.08
Low-income countries	45.45	10.73	6.31	36.63	0.52	0.20	0.11	0.00
World	15.80	6.78	40.35	19.26	15.84	0.32	1.20	0.38
Panel B: Mean of electricity-shares by country for country group								
High-income countries	13.88	14.92	24.67	30.09	13.70	0.59	1.41	0.70
Middle-income countries	32.30	21.74	18.70	21.42	3.90	1.10	0.71	0.12
Low-income countries	53.52	25.00	4.06	16.22	0.08	0.51	0.33	0.00
World	30.40	20.16	17.83	23.23	6.34	0.82	0.86	0.28

Notes: Current World Bank country classification used to classify countries into income groups. An additional 0.1 percent of global electricity production comes from “other sources”, such as solar and heat.

Table 2: Summary of model

Electricity source	Description	Characteristics	Examples	$C(Y_{\approx 0})$	$\partial C/\partial Y$	$C(Y_{\infty})$
Domestic (*D*)	Electricity generation based on domestic sources	Subject to (eventual) diminishing returns	Hydroelectricity, use of domestic reserves of fossil fuels	Low	>0	High
Imported fuels (*F*)	Electricity generation based on imported energy sources	Intermediate	Imported fossil fuels	Medium	0	Medium
Modern (*M*)	Modern electricity sources	Requires large capital investment, skilled workforce, developed institutions, large electricity grid	Nuclear power, modern renewables (e.g. wind, solar)	High	<0	Low

Table 3: Cross-sectional regression results, 2003

Dependent variable: Technology share of electricity generation in 2003

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Share of electricity generation (percent)	Hydro	Oil	Coal	Natural gas	Nuclear	Geothermal	Biomass and waste	Wind
Log GDP per capita	-11.482***	-6.765**	4.869***	8.140***	4.727***	-0.078	0.378**	0.262**
	(2.794)	(2.646)	(1.728)	(2.188)	(1.095)	(0.228)	(0.145)	(0.115)
R^2	0.143	0.066	0.040	0.085	0.110	0.001	0.046	0.055
F statistic	16.89***	6.54**	7.94***	13.84***	18.66***	0.12	6.81**	5.18**
Countries: 129								

Notes: ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels respectively. Robust standard errors are in parentheses. Coefficients on constants not reported.

Table 4: Cross-sectional regression results with controls, 2003

Dependent variable: Technology share of electricity generation in 2003

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Share of electricity generation (percent)	Hydro	Oil	Coal	Natural gas	Nuclear	Geothermal	Biomass and waste	Wind
Log GDP per capita	-12.564***	-10.127***	6.641***	9.627***	5.696***	-0.192	0.595***	0.375**
	(2.973)	(2.830)	(1.806)	(2.362)	(1.267)	(0.200)	(0.188)	(0.159)
Control group A: country characteristics								
Log population	-1.001	-1.951	-0.090	1.015	1.739	0.363	-0.063	0.014
	(3.236)	(2.600)	(4.444)	(3.799)	(1.233)	(0.347)	(0.192)	(0.075)
Log land	1.427	-5.022**	2.607	1.256	-0.156	-0.301	0.155	0.030
	(2.542)	(2.285)	(3.272)	(3.275)	(0.962)	(0.249)	(0.174)	(0.057)
Transition economy dummy	1.024	-23.197***	10.363	3.492	10.749**	-0.904*	-1.060***	-0.377*
	(6.303)	(5.028)	(6.985)	(7.606)	(4.463)	(0.468)	(0.284)	(0.194)
Security council dummy	5.165	14.355*	-30.391	-8.951	18.854	0.818	0.395	-0.360
	(7.704)	(8.246)	(24.797)	(18.775)	(12.895)	(0.683)	(0.529)	(0.327)
Nuclear weapon dummy	-9.750	-4.304	31.784	-8.318	-6.307*	-1.555*	-1.159***	-0.313
	(6.731)	(4.144)	(20.564)	(17.109)	(3.327)	(0.837)	(0.415)	(0.340)
Control group B: indigenous reserves variables								
Water reserves (thousand cubic meters per capita)	**0.761*****	-0.130	-0.262*	-0.290*	-0.058	-0.005	-0.008	-0.008
	(0.240)	(0.120)	(0.143)	(0.152)	(0.040)	(0.012)	(0.006)	(0.005)
Oil reserves (thousand tons oil equivalent [ttoe] per capita)	-1.863	**6.708***	-4.479***	2.523	-2.143***	-0.112	-0.428***	-0.191**
	(1.538)	**(3.966)**	(1.538)	(4.598)	(0.679)	(0.088)	(0.130)	(0.082)
Coal reserves (ttoe per capita)	-24.597***	13.287**	**37.437*****	-16.325*	-8.983**	0.184	-0.711**	-0.339
	(6.148)	(6.277)	**(11.635)**	(8.497)	(4.145)	(0.423)	(0.343)	(0.252)
Natural gas reserves (ttoe per capita)	0.122	-3.150***	-0.860*	**4.519*****	-0.486**	-0.016	-0.083**	-0.042*
	(0.359)	(0.795)	(0.489)	**(1.327)**	(0.230)	(0.039)	(0.034)	(0.024)
Uranium reserves (thousand tons per capita)	0.549**	-0.202	-0.087	-0.243	**-0.001**	0.002	-0.016	0.000
	(0.231)	(0.124)	(0.221)	(0.168)	**(0.054)**	(0.012)	(0.010)	(0.006)
Volcanoes per capita (*1,000,000)	-3.605***	0.553	1.239*	1.290*	0.251	**0.206*****	0.024	0.034
	(1.308)	(0.616)	(0.663)	(0.767)	(0.198)	**(0.069)**	(0.030)	(0.022)
R^2	0.416	0.298	0.318	0.211	0.277	0.224	0.142	0.107
F statistic	61.25***	5.62***	7.97***	7.71***	2.90***	9.49***	3.62***	0.88
Countries: 129								

Notes: ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels respectively. The bold diagonal is the set of own-resource coefficients. Robust standard errors are in parentheses. Coefficients on constants not reported.

Table 5: Panel data results

Dependent variable: Technology share of electricity generation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Share of electricity generation$_t$ (percent)	Hydro	Oil	Coal	Natural gas	Nuclear	Geothermal	Biomass and waste	Wind
Panel A: Pooled OLS								
Log GDP per capita	-10.864***	-5.118**	4.959***	7.146***	3.671***	-0.054	0.163*	0.075**
	(2.633)	(2.145)	(1.837)	(2.132)	(0.863)	(0.147)	(0.095)	(0.036)
R^2	0.113	0.033	0.040	0.081	0.096	0.000	0.008	0.019
F statistic	17.03***	5.69**	7.29***	11.23***	18.11***	0.14	2.92*	4.21**
Panel B: Pooled OLS with year fixed effects								
Log GDP per capita	-11.316***	-4.449**	4.383**	7.488***	3.701***	-0.072	0.176*	0.068*
	(2.581)	(2.210)	(1.807)	(2.226)	(0.890)	(0.143)	(0.097)	(0.034)
R^2	0.133	0.083	0.071	0.120	0.135	0.006	0.016	0.057
F statistic	4.31***	4.52***	2.79***	3.40***	1.34	0.510	2.78***	0.75
Panel C: Country fixed effects estimation with year fixed effects								
Log GDP per capita	-5.430**	-9.974**	5.221***	7.194**	2.996*	-0.383	0.279	0.107*
	(2.210)	(3.993)	(1.952)	(3.413)	(1.605)	(0.415)	(0.220)	(0.060)
R^2 (within)	0.134	0.236	0.093	0.188	0.217	0.022	0.047	0.071
F statistic	2.70***	3.30***	2.25***	2.53***	1.60**	0.47	4.66***	0.88
Panel D: Between estimator								
Log GDP per capita	-10.749***	-5.283**	4.901**	7.477***	3.511***	-0.039	0.125	0.046**
	(2.704)	(2.430)	(2.198)	(2.133)	(1.017)	(0.232)	(0.126)	(0.019)
R^2 (between)	0.108	0.035	0.037	0.086	0.083	0.000	0.008	0.044
F statistic	15.80***	4.73**	4.97**	12.29***	11.91***	0.03	0.99	6.02**
Observations: 4,002								
Years: 1960-2004								
Countries: 133								

Notes: ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels respectively. Standard errors are in parentheses. The standard errors in panels A-C are robust standard errors clustered by country. Coefficients on constants not reported.

Table 6: Panel data fixed effects results with interaction terms

Dependent variable: Technology share of electricity generation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Share of electricity generation$_t$ (percent)	Hydro	Oil	Coal	Natural gas	Nuclear	Geothermal	Biomass and waste	Wind
Log GDP per capita$_t$	-6.474**	-8.771**	5.171**	6.722**	3.633**	-0.763	0.356	0.134*
	(2.554)	(3.836)	(2.316)	(3.103)	(1.827)	(0.481)	(0.260)	(0.072)
Log GDP per capita$_t$*Water reserves (thousand cubic meters per capita)	0.024**	0.016	0.012	-0.036***	-0.033***	0.020***	-0.002*	-0.001*
	(0.012)	(0.012)	(0.011)	(0.011)	(0.010)	(0.002)	(0.001)	(0.001)
Log GDP per capita$_t$*Oil reserves (ttoe per capita)	1.180*	-5.704	-0.329	5.038	-0.281	0.187	-0.076	-0.023
	(0.600)	(5.106)	(0.541)	(4.583)	(0.421)	(0.152)	(0.061)	(0.017)
Log GDP per capita$_t$*Coal reserves (ttoe per capita)	3.457	7.947*	7.241**	-8.032	-8.908**	-0.216	-1.010**	-0.328
	(3.651)	(4.104)	(3.656)	(6.416)	(3.713)	(0.217)	(0.404)	(0.214)
Log GDP per capita$_t$*Natural gas reserves (ttoe per capita)	0.268	1.472*	-0.070	-1.756**	0.027	0.069*	-0.012	-0.001
	(0.175)	(0.880)	(0.111)	(0.802)	(0.104)	(0.038)	(0.019)	(0.004)
R^2 (within)	0.141	0.248	0.096	0.211	0.233	0.063	0.050	0.074
F statistic	4.19***	3.70***	3.01***	4.18***	1.19	112.86***	10.00***	0.97
Country and year fixed effects: Yes								
Observations: 4,002								
Years: 1960-2004								
Countries: 133								

Notes: ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels respectively. Robust standard errors clustered by country are in parentheses. Coefficients on constants not reported.

Table 7: Instrumental variables results, 2003

Dependent variable: Technology share of electricity generation in 2003

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Share of electricity generation (percent)	Hydro	Oil	Coal	Natural gas	Nuclear	Geothermal	Biomass and waste	Wind
Panel A: No controls								
Log GDP per capita	-6.455*	-6.814**	-1.019	8.233**	5.307***	-0.094	0.563***	0.294*
	(3.619)	(3.374)	(3.250)	(3.625)	(1.670)	(0.298)	(0.188)	(0.176)
Second-stage R^2	0.023	0.034	0.001	0.044	0.071	0.001	0.052	0.036
Second-stage F statistic	3.13*	4.02**	0.10	5.08**	9.95***	0.10	8.89***	2.77*
Panel B: With controls								
Log GDP per capita	-7.589*	-8.548**	-1.330	7.800**	7.843***	-0.065	1.251***	0.616*
	(4.283)	(3.410)	(3.918)	(3.863)	(2.288)	(0.246)	(0.278)	(0.315)
Control group A: country characteristics								
Log population	-1.168	-2.004	0.177	1.076	1.667	0.359	-0.085	0.006
	(3.085)	(2.448)	(4.300)	(3.570)	(1.214)	(0.331)	(0.201)	(0.086)
Log land	2.805	-4.585**	0.399	0.750	0.438	-0.266	0.337*	0.096
	(2.539)	(2.307)	(2.631)	(3.233)	(1.048)	(0.238)	(0.177)	(0.083)
Transition economy dummy	1.136	-23.161***	10.183	3.451	10.797**	-0.901**	-1.046***	-0.372*
	(6.232)	(4.763)	(6.890)	(7.241)	(4.364)	(0.442)	(0.304)	(0.191)
Security council dummy	-1.713	12.172	-19.369	-6.425	15.887	0.641	-0.511	-0.694
	(8.246)	(8.619)	(25.566)	(18.210)	(12.185)	(0.636)	(0.665)	(0.485)
Nuclear weapon dummy	-10.837	-4.649	33.526	-7.919	-6.776*	-1.583**	-1.302**	-0.366
	(6.715)	(3.920)	(21.665)	(15.716)	(3.672)	(0.787)	(0.572)	(0.386)
Control group B: indigenous reserves variables								
Water reserves (thousand cubic meters per capita)	**0.695*****	-0.151	-0.155	-0.266*	-0.087	-0.007	-0.016**	-0.011
	(0.223)	(0.118)	(0.110)	(0.147)	(0.054)	(0.012)	(0.008)	(0.007)
Oil reserves (ttoe per capita)	-3.253*	**6.267**	-2.253*	3.033	-2.743***	-0.148	-0.611***	-0.258**
	(1.798)	**(3.890)**	(1.184)	(4.511)	(0.958)	(0.118)	(0.167)	(0.125)
Coal reserves (ttoe per capita)	-30.197***	11.509*	**46.411*****	-14.268	-11.399**	0.040	-1.449***	-0.611
	(6.857)	(6.793)	**(10.817)**	(9.179)	(4.466)	(0.357)	(0.460)	(0.411)
Natural gas reserves (ttoe per capita)	-0.113	-3.225***	-0.484	**4.606*****	-0.587**	-0.022	-0.114***	-0.054*
	(0.420)	(0.762)	(0.383)	**(1.297)**	(0.271)	(0.043)	(0.041)	(0.031)
Uranium reserves (thousand tons per capita)	0.514**	-0.213*	-0.031	-0.230	**-0.016**	0.001	-0.021**	-0.002
	(0.226)	(0.117)	(0.211)	(0.157)	**(0.055)**	(0.011)	(0.010)	(0.006)
Volcanoes per capita (*1,000,000)	-3.305***	0.648	0.758	1.180	0.381	**0.214*****	0.064	0.048
	(1.199)	(0.607)	(0.501)	(0.742)	(0.263)	**(0.069)**	(0.041)	(0.032)
Second-stage R^2	0.314	0.225	0.266	0.150	0.253	0.222	0.211	0.117
Second-stage F statistic	67.00***	5.62***	7.11***	7.39***	2.45***	9.50***	2.86***	0.63

Countries: 129

Instrument: 1950 log GDP per capita

F statistic on excluded instrument in instrumental variables regressions: Panel A: 118.59; Panel B: 77.46

Stock-Yogo 5 percent significance level critical value (10 percent maximal IV size): 16.38

Partial R^2 on excluded instrument in instrumental variables regressions: Panel A: 0.509; Panel B: 0.418

Notes: ***, **, and * indicate statistical significance at the 1, 5, and 10 percent levels respectively. The bold diagonal is the set of own-resource coefficients. Robust standard errors are in parentheses. Coefficients on constants not reported.

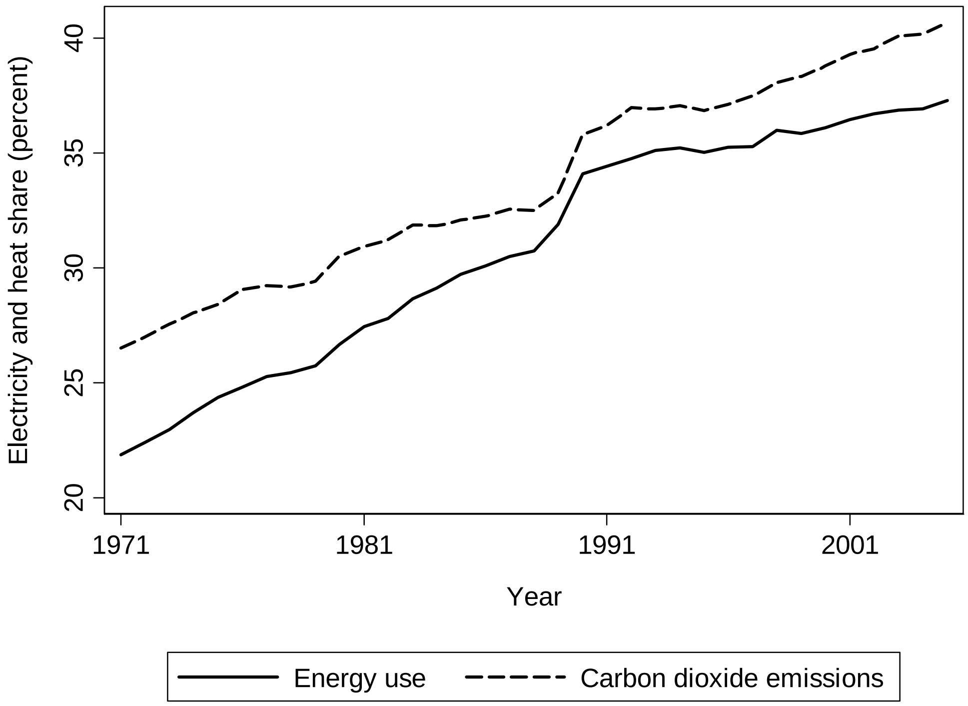

Fig. 1. World share of electricity and heat generation in total energy use and in emissions of carbon dioxide, 1971-2005. Uses IEA (2007a, 2007c).

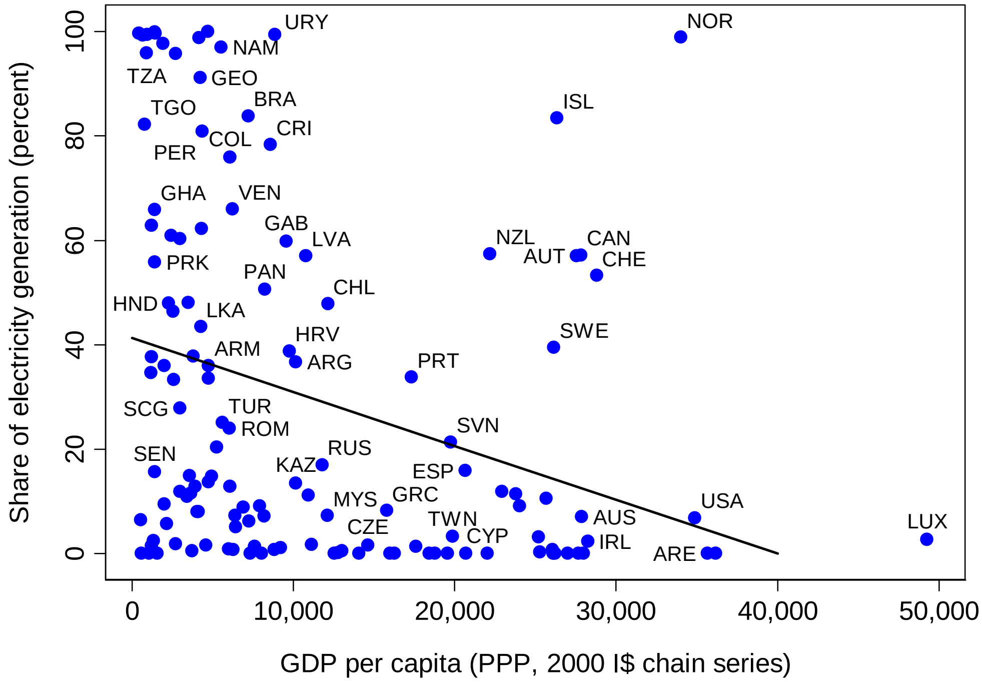

Fig. 2. Income and the hydro share of electricity generation, 2003. 131 countries included. Uses IEA (2007a, 2007b), Heston et al. (2006).

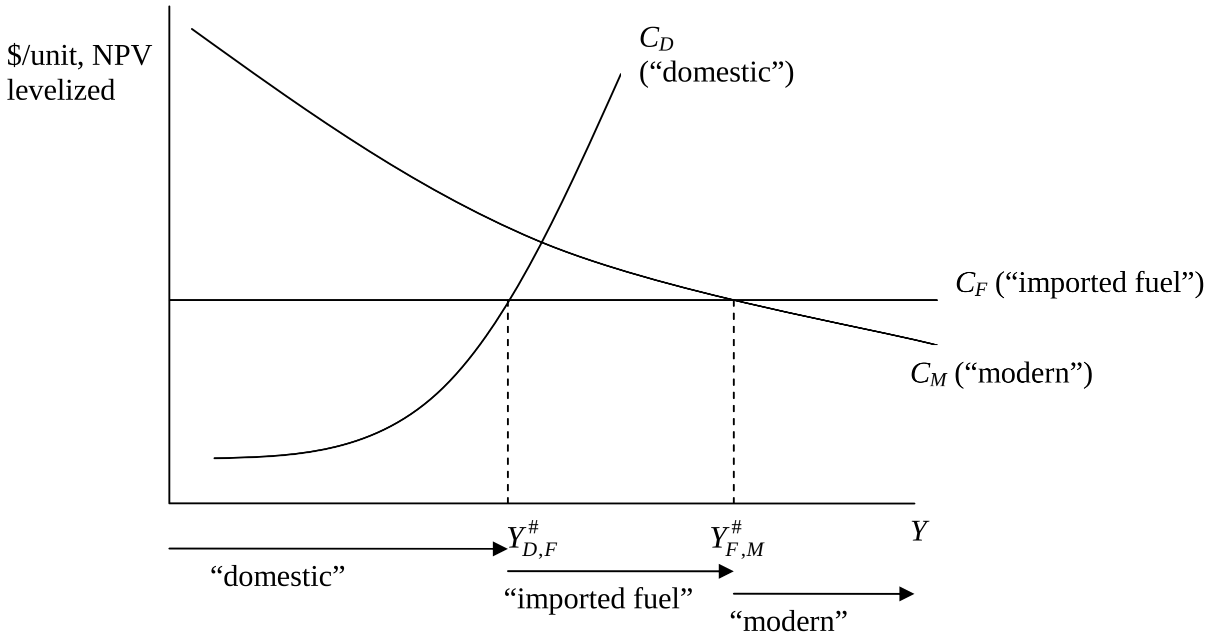

Fig. 3. A model of the unit cost of electricity from a new plant, by income.

Appendix – Variable descriptions

Variable name	Variable description	Source	Notes
Hydro share of electricity generation	Electricity from hydroelectric power plants as a percent of total electricity generation	IEA (2007a, 2007b)	
Oil share of electricity generation	Electricity fuelled by crude oil and petroleum products as a percent of total electricity generation	IEA (2007a, 2007b)	
Coal share of electricity generation	Electricity fuelled by coal, coal-derived fuels, and peat as a percent of total electricity generation	IEA (2007a, 2007b)	
Natural gas share of electricity generation	Electricity fuelled by natural gas (excluding natural gas liquids) as a percent of total electricity generation	IEA (2007a, 2007b)	
Nuclear share of electricity generation	Electricity produced by nuclear power plants as a percent of total electricity generation	IEA (2007a, 2007b)	
Geothermal share of electricity generation	Electricity produced by geothermal sources as a percent of total electricity generation	IEA (2007a, 2007b)	
Biomass and waste share of electricity generation	Electricity produced by biomass, biofuels, and waste as a percent of total electricity generation	IEA (2007a, 2007b)	
Wind share of electricity generation	Electricity produced by wind as a percent of total electricity generation	IEA (2007a, 2007b)	
Log GDP per capita	Natural logarithm of GDP per capita in 2000 international $ (chain series)	Heston et al. (2006)	
1950 log GDP per capita	Natural logarithm of 1950 GDP per capita in 1990 international Geary-Khamis $	Maddison (2009)	Countries that were not independent in 1950 and for which data are not available: data for the former jurisdiction of which they were a part were used. For several countries, data in 1990 international Geary-Khamis $ were constructed, e.g. Luxembourg's GDP per capita in 1950 was set equal to 1.74*Belgium's GDP per capita in 1950, using the 1950 GDP per capita ratio from Heston et al. (2006)
Log population	Natural logarithm of population (in thousands)	Heston et al. (2006)	
Log land	Natural logarithm of land area in squared kilometers	World Bank	

		(2009)	
Transition economy dummy	Equals 1 for countries classified as transition economies, 0 otherwise	Development Research Institute (2008)	26 of the 129 countries in the cross-sectional regressions are classified as transition economies
Security council dummy	Equals 1 if the country is a permanent member of the United Nations Security Council, 0 otherwise		
Nuclear weapon dummy	Equals 1 if the country is known to have nuclear weapons, 0 otherwise	Allison (2004)	Equals 1 for India, Israel, Pakistan, and the five permanent members of the United Nations Security Council
Water reserves (thousand cubic meters per capita)	Renewable internal freshwater resources (internal river flows and groundwater from rainfall) in thousand cubic meters per capita, 2002	World Bank (2009)	Data for Kuwait and Taiwan are from the World Resources Institute (2009)
Oil reserves (ttoe per capita)	Proved reserves of crude oil, in thousand tons, 2003	EIA (2009b)	Converted to tons using BP (2009) conversion factors. Population data from Heston et al. (2006)
Coal reserves (ttoe per capita)	Total recoverable coal, in thousand tons of oil equivalent, 2005	EIA (2009b)	Converted to ttoe using BP (2009) conversion factors. Population data from Heston et al. (2006)
Natural gas reserves (ttoe per capita)	Proved reserves of natural gas, in thousand tons of oil equivalent, 2003	EIA (2009b)	Converted to ttoe using BP (2009) conversion factors. Population data from Heston et al. (2006)
Uranium reserves (thousand tons per capita)	Reasonably assured resources recoverable at a cost of less than $130 per kilogram of uranium as of 1 January 2003, in thousand tons	OECD Nuclear Energy Agency and the International Atomic Energy Agency (2004)	Population data from Heston et al. (2006)
Volcanoes per capita (*1,000,000)	Number of holocene volcanoes *1,000,000, divided by 2003 population	Siebert and Simkin (2002)	Volcanoes straddling national borders are included in the list of volcanoes of all border countries. Population data from Heston et al. (2006)