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The role of energy capital in accounting for Africa's recent growth resurgence

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The Role of Energy Capital in Accounting for Africa's Recent Growth Resurgence

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Abstract

After decades of stagnation, Africa began a growth resurgence starting in around 2000. Over the same period, Africa made large investments in its stock of "energy capital," and in particular its stock of electric power plants. We ask how much of Africa's recent growth resurgence can be accounted for by its investments in energy capital. To answer this question we draw on a multi-sector model in which energy complements labor and capital in the production of non-agricultural goods, and new cross-country evidence on the stock of electric power plants. In our main specification, energy capital investments account for around one third of Africa's growth resurgence. This quantitative conclusion is driven by three features of the data: (i) Africa had extremely low energy inputs per worker before 2000, (ii) its stock of energy capital and production of energy increased robustly since then, and (iii) the share of energy in non-agricultural production in Africa is substantial.

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1. Introduction

After decades of stagnation, Sub-Saharan Africa began a period of sustained GDP growth starting in around 2000. According to national accounts data, annualized GDP growth across African countries averaged six percent per year from 2000 to 2013. Over this period, around two-thirds of Africans saw their nation's GDP double. Moreover, most of Africa's GDP growth was associated with per capita income increases, rather than population growth. For example in Africa's two most populous countries, Nigeria and Ethiopia, GDP per capita increased by 99 and 133 percent since 2000. Household surveys confirm Africa's rapid improvements in living standards, and, according to Young (2012), imply even faster rates of growth than do the national accounts.

What are the main factors accounting for Africa's growth? Providing a complete answer is a challenging task, and beyond the scope of this paper.[1] This paper focuses on the role of one promising channel, which is the dramatic increase in energy capital, "energy capital," or capital goods that are used to produce electricity, made by many African countries since 2000. The most conspicuous examples include the numerous large-scale hydropower plants being built in countries like Ethiopia, but much of the investments are more mundane, and involve simply connecting more regions to the electricity grid.

Africa's increases in energy capital have been accompanied by impressive growth in electricity production per capita, bringing Africa up from minuscule levels of electric power usage. In 2000, the average African economy (excluding South Africa) averaged just 70 kilowatt hours of consumption per capita per year. By comparison, the average U.S resident used about this much in just two days. Since 2000, growth in Africa's electricity production has averaged 5.5 percent since 2000, roughly the same magnitude as its GDP growth. Moreover, we show that across African countries, growth rates of manufacturing and service GDP are strongly correlated with electricity growth, showing that the fastest growers are systematically the countries with the largest energy increases.

In this paper, we ask how much of Africa's growth since 2000 can be accounted for by its recent investments in energy capital. A key challenge we face is that growth in energy

[1] One obvious candidate is a rise in commodity prices, which have driven up the value of Africa's natural-resource exports. In the majority of African countries, however, we show that growth in manufacturing and services GDP – excluding natural resources – has been just as dramatic as overall GDP growth. Nigeria and Ethiopia have had manufacturing and services GDP growth averaging over 10 percent per year since 2000, for example, to go along with their overall growth rate of 11 percent per year. Furthermore, some of the fastest growth rates are found in countries (such as Ethiopia) which have negligible exports of natural resources (see Radelet (2010)).

use and growth in GDP suffer from a classic chicken-and-egg problem, where each clearly plays some role in causing the other. Pure econometric techniques to sorting our this two-way causality include, for example, instrumental variables that serve to assign one country to more electricity investment than a second similar country. Finding such instrumental variables at the country level is likely to be a difficult task; in any event, we don't know of any.

Instead, we take a structural approach to disciplining the size of the reverse-causality channel from income to electricity demand. To do so we draw on what is already known about the income elasticity of demand for energy and other expenditure aggregates, using a multi-sectoral model in the spirit of Herrendorf, Rogerson, and Valentinyi (2014), and parameterized to match cross-sectional consumer expenditure patterns. In particular, we match the increasing expenditure share on non-agricultural goods with income, which is standard in the macro literature on structural change, and the increasing energy expenditure share with income (see e.g. Wolfram, Shelef, and Gertler, 2012; Gertler, Shelef, Wolfram, and Fuchs, 2016). The model therefore quantitatively captures the direct effect of income on energy demand and the indirect effect, working through increased demand for (energy-intensive) non-agricultural goods.

On the production side, we follow Hassler, Krusell, and Olovsson (2015) and assume a constant elasticity of substitution (CES) aggregate production function in two inputs: (i) a Cobb-Douglas aggregate of labor and capital, and (ii) energy. Basically all macro models of energy use agree that energy is strongly complementary to other inputs at an annual frequency (Atkeson and Kehoe, 1999; Hassler, Krusell, and Olovsson, 2015; Hassler, Krusell, and Smith, Jr., 2016).[2] Using aggregate time series data from the United States, Hassler, Krusell, and Olovsson (2015) estimate that the elasticity of substitution between energy and the capital-labor composite at the annual level is close to zero. We follow them and choose a low elasticity of substitution, though we show later than higher values also imply a substantial role for energy investments in Africa's growth, so long as the model matches energy's share of non-agricultural value added, which is around ten percent according to African manufacturing censuses.[3]

[2] This high degree of complementarity between sectoral inputs is emphasized by Jones (2011), who cites electricity in particular as an example of a good with limited possibilities for substitution.

[3] The reason Hassler, Krusell, and Olovsson (2015) find a low substitution elasticity for energy is that when energy prices tripled in the 1970s, the energy input share in US production tripled as well, while quantities of energy inputs remained roughly constant. The almost total lack of substitution away from energy in the aggregate economy suggests very a low elasticity of substitution in the production function. Atalay (2015) uses a similar strategy to argue that intermediate inputs in general are likely to have a low degree of substitution with other inputs at business cycle frequencies.

We allow for two types of energy use in the model: grid and non-grid, which are imperfect substitutes in the aggregate energy input. We assume that grid energy investment decisions are made exogenously by the government, and financed by lump-sum taxation on households. Non-grid energy investments are chosen by households privately, and allow households to produce their own energy in the absence of grid energy. Examples could be an electric generator or solar panel purchased by a producer for the own use. The assumption that grid energy investment decisions are made by the government seems a reasonable approximation to reality given that large-scale construction projects, such as hydroelectric dams, are classic public goods, and nearly impossible to coordinate by private individuals. However, the assumption that grid energy investments are financed by private citizens is a less accurate description of reality, given substantial financing from development agencies and foreign nations in practice, but is a convenient simplification and is not important for our quantitative conclusions.

We discipline the importance of the two energy types in aggregate energy production in the model using data on relative quantities and relative prices of grid and non-grid energy constructed from micro evidence on energy capital use (Foster and Steinbuks, 2008). These data show that non-grid energy is about five times as expensive as grid energy, and responsible for a much smaller fraction of total energy than grid energy. This implies that, in our quantitative model, the private sector cannot easily provide their own energy at low cost.

We use the model to ask, counterfactually, how much Africa would have grown had it only increased its (grid) energy investments, but experienced no other changes. In particular, our main exercise is to increase energy investments so as to match the increases in energy consumption since 2000, and to ask how much GDP per capita increases from this change alone. We do this experiment country by country, for Africa's six most populous countries, for which data are readily available.

We find that energy investments account for around one third of Africa's growth in GDP per capita since 2000, on average. This substantial role for energy is due largely to three basic features of the data. First, Africa had very low inputs of energy (that is, electricity, not traditional sources like wood) per capita around 2000. Second, energy inputs increased substantially since 2000, at a rate of around eight percent per year on average. Third, the share of energy in non-agricultural production is substantial, at around ten percent according to several sources of data on manufacturing from Africa and other developing regions of the world. We show that if any of these three features of the data were (counterfactually) not present, the role of energy in accounting for Africa's growth would have been substantially smaller.

One caveat of our analysis is that we focus only on Africa's six largest countries, due to data availability. Other countries' experiences may have been different, and in future work we plan to address a larger set of countries to the extent possible. Perhaps a more important caveat is that, even with the six countries studied at present, there is substantial variation in our model's predictive power across these countries. The model is least successful in the Democratic Republic of Congo, where our model predicts essentially no role of energy investments on growth since 2000. The Congo was mired in a destructive conflict in the 1990s, and grew since then for reasons likely out of the model. On the other end, in the Sudan and in Kenya, more than two-thirds of growth can be explained by energy investments, according to the model. The reason is that both the Sudan and Kenya had large increases in energy production, but with less dramatic GDP growth than the other countries. Among the other countries – Ethiopia, Nigeria and Tanzania – energy investments account for between 23 and 31 percent, near the overall average of one third. Another caveat, which can be made of almost any growth or development accounting paper, is that our findings are really only "accounting" results, and don't provide deeper answers as to why Africa made large energy investments after 2000 and not before. We leave this important question to future research.

Our paper is related to several micro studies that find clear positive impacts of energy investments on development. Lipscomb, Mobarak, and Barham (2013) study the development effects of electrification in Brazil from 1960 to 2000 using a geographic model of hydropower plant placement to instrument for electricity grid expansion. They estimate large effects of electricity on development metrics such as income, employment, housing values and urbanization rates at the region level. Relatedly, Rud (2012) finds large positive effects of electrification on manufacturing activity in particular, using panel data on Indian regions from 1965 to 1984. Looking a shorter time horizon, Dinkelman (2011) uses the land gradient to instrument for electrification at the regional level within South Africa from 1995 to 2001. She estimates increases in employment following electrification, particularly for females, increases in male earnings, and increased migration towards regions getting electrified.[4]

Our paper also contributes to a growing literature on the long-run macroeconomic effects of

[4] Dinkelman and Schulhofer-Wohl (2015) argue that studying the effects of electrification (or other investments) on local areas will be misleading without accounting for the effects of internal migration. Our paper is consistent with their view in that it focuses on the aggregate effects of energy investments, rather than just regional effects.

energy use. Many of these studies focus on the environmental impacts energy use; see e.g. Golosov, Hassler, Krusell, and Tsyvinski (2014) and Hassler, Krusell, and Smith, Jr. (2016) and the references therein. By contrast, our paper ignores environmental issues completely. In Africa, several types of evidence suggest that this may be an innocuous omission. First, most of Africa's energy production (other than in South Africa) comes from hydropower, which leads to minimal air pollution (see e.g. Eberhard, Rosnes, Shkaratan, and Vennemo, 2001). Second, manufacturing activity and automobile use are still at low levels compared to the United States and other developed regions (Gertler, Shelef, Wolfram, and Fuchs, 2016). Our work adds to an extensive literature on growth accounting and development accounting (i.e. accounting for level differences), though to our knowledge no other paper has studied the role of energy capital separately from other capital inputs, or tried to account for Africa's recent growth.[5]

The remainder of this paper is structured as followed. Section 2 summarizes the facts on Africa's growth in GDP and energy inputs since 2000 that motivate this study. Section 3 presents a multi-sector general-equilibrium model that we use in our quantitative analysis. Section 4 calibrates the model to match salient features of Africa's most populous countries around 2000, and Section 5 conducts the quantitative counterfactual experiments used to quantify the role of energy investments in Africa's growth. Finally, Section 6 concludes.

2. Africa's Growth and Electricity Investments Since 2000

In this section we summarize Africa's impressive growth in GDP, in electricity production and consumption, and in electricity capital and since 2000. We then show that GDP growth and electricity growth are strongly positively correlated across African countries.

2.1. Africa's GDP Growth

Table 1 reports Sub-Saharan Africa's average annual growth rate in the 1990s and since 2000. The differences are stark. On average, African countries grew at just 2.5 percent per year in the 1990s, and at 6 percent from 2000 on. Countries growing at 5 percent percent since 2000 (through 2013) have doubled their GDP over this period. Overall, there were just five countries growing at a rate of 5 percent per year in the 1990s, compared to 16 countries since 2000. Thus, since 2000, around two-thirds of Africans live in a country whose GDP

[5]The papers by Klenow and Rodríguez-Clare (1997), Hall and Jones (1999) and Caselli (2005) are prominent examples in the development accounting camp, while Young (1995) s a prominent example in the growth accounting camp.

has doubled. No period in African history has seen such drastic increases in living standards for so many people.

Table 1: Economic Growth in Sub-Saharan Africa

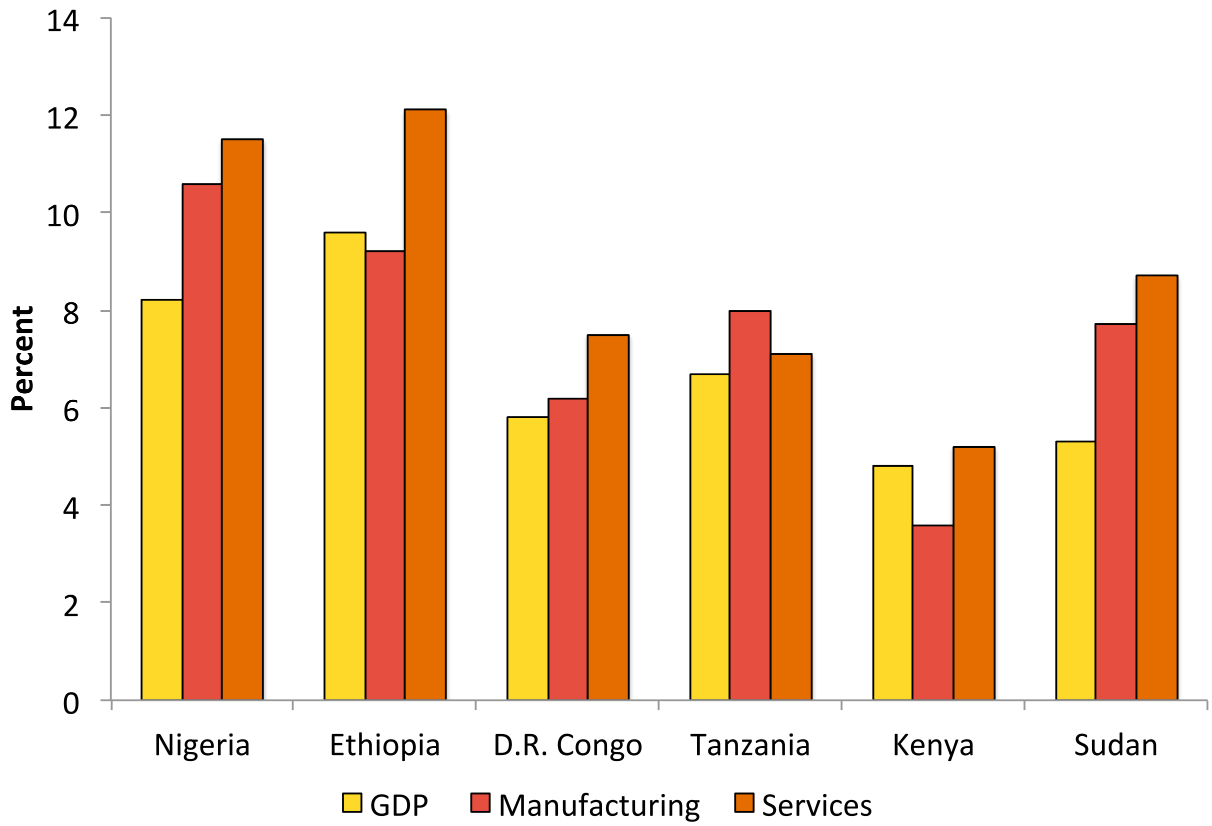
	1990s	Since 2000
Annualized GDP Growth Rate	2.5	6.0
Countries with GDP Growth $\geq 5\%$	5	16
% of Population in Country w/ Growth $\geq 5\%$	14	66

Africa's growth in per-capita terms has been impressive as well. Consider the most populous six countries in Africa (excluding South Africa), on which we will focus in this paper: Nigeria, Ethiopia, the Democratic Republic of Congo, Tanzania, Kenya and Sudan. Since 2000, cumulative growth in GDP per capita averaged an astonishing 68.5 percent across these countries, which amounts to 4.4 percent per year. Leading the pack were Ethiopia at 133 percent cumulative growth in GDP per capita, or 7.1 percent per year, followed by Nigeria, at 99 percent cumulative growth, or 5.7 percent per year.

What accounts for Africa's robust recent growth in GDP? One natural candidate is an increase in the prices of natural resources that Africa tends to export. If this is the case, one calls into question whether Africa's GDP growth is informative about changes in living standards for the average Africans. After all, many natural resources are narrowly held or are controlled by governments, who may or not use natural resource rents productively.

Figure 1 plots average annualized growth of GDP by broad sector in Africa's six most populous countries (excluding South Africa). In each of these countries, growth in manufacturing GDP and services GDP in quite similar to the overall GDP growth. In Nigeria, an oil exporter, manufacturing and service GDP growth even exceed aggregate growth, at over ten percent per year in both sectors. In Ethiopia, which has virtually no natural resource exports, the service sector has had growth of over twelve percent per year, while manufacturing has had growth of around nine percent per year, in the ballpark of the aggregate. These data show plainly that African economic growth has been broad based, and is not a simple artifact of rising prices of natural resources. See also Radelet (2010).

Figure 1: Average Annualized GDP Growth in Africa's Largest Economies Since 2000



2.2. Africa's Electricity Production and Investments

One of the most impressive features of Africa's growth has been its rapid increases in uses of "modern" energy sources, in particular electricity. Most of Africa's energy use currently comes from "traditional" sources, such as burning wood or other biomass (International Energy Agency, 2016). In 2000, modern energy use was at astonishingly low levels in most African countries. Across Africa's six largest countries, for example, electricity usage was just 70 kWh per capita per year. Ethiopia had the lowest electricity inputs, at just 21 kWh per capita per year. The average U.S. resident, as a comparison, used around 13,000 kWh per year, or almost 200 times higher.

Since 2000, African economies have made substantial investments in modern energy capital. Figure 2 plots the annualized growth rate of energy capital and energy capital per capita in the 1990s and in the 2000s, averaged across all Sub-Saharan Africa countries for which data are available (excluding South Africa). To measure energy capital, we use megawatts of electricity production capacity. The source for this data is the UDI World Electric Power Plants Database, which is a global inventory of electric power generating units from 1970-2014.[6] Energy capital per capita actually decreased on average in the 1990s, with an annualized growth rate of -0.61 percent. In contrast, during the 2000s, energy capital per capita increased on average at an annualized rate of 2.58 percent per year, implying that the average African economy saw its level of energy capital per capita grow by more than fifty percent between 2000 and 2013.

Figure 2: Average Annualized Growth Rate of Energy Capital in Sub-Saharan Africa

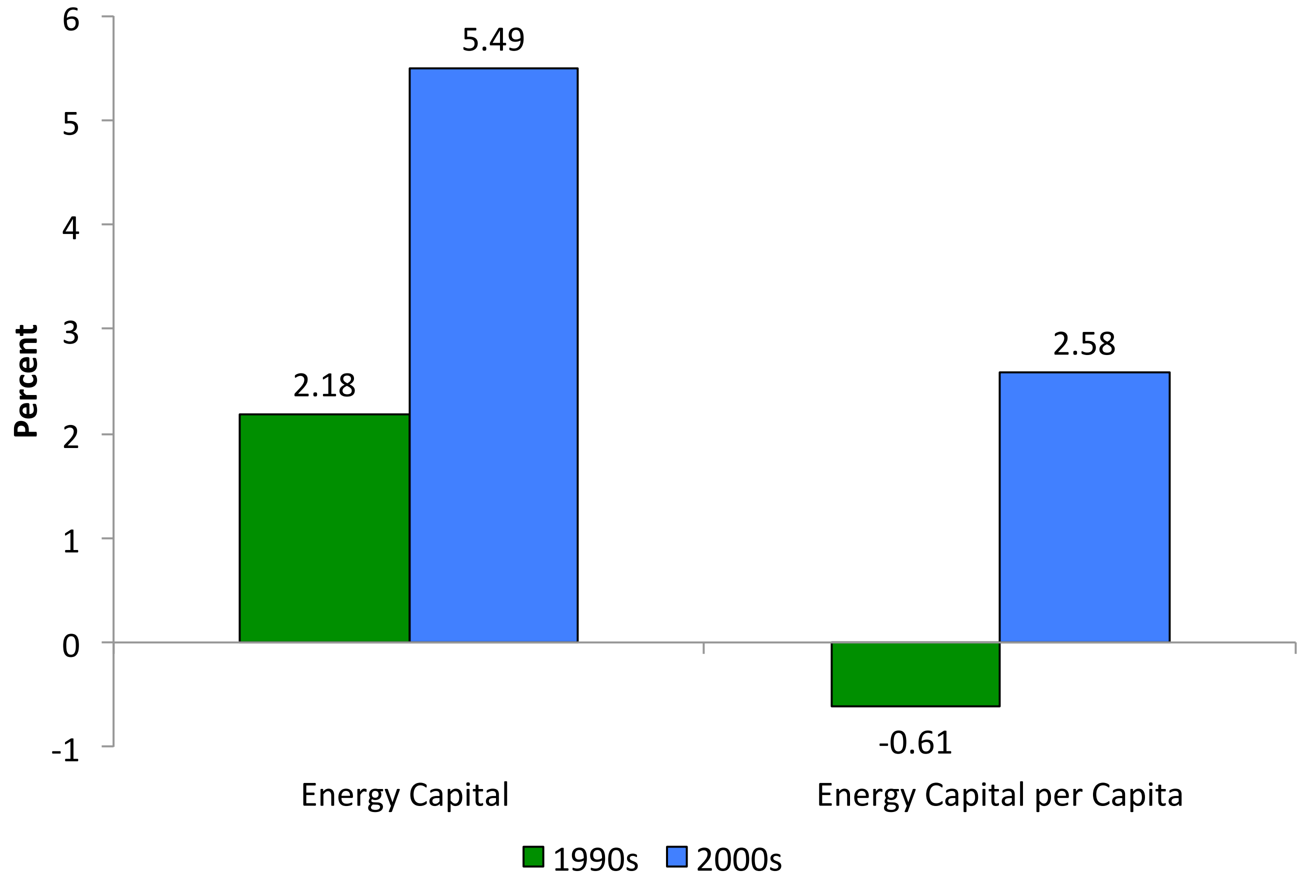
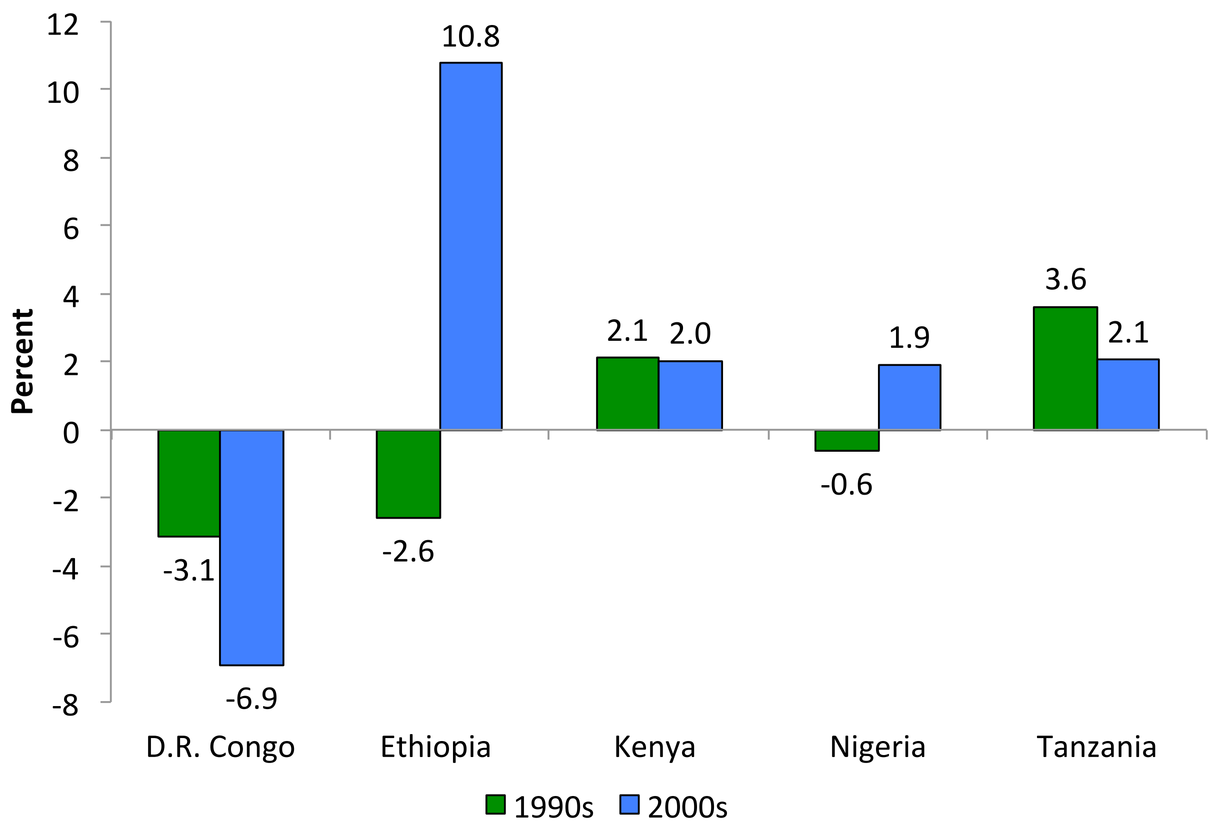


Figure 3 plots the growth rate of energy capital per capita for the Democratic Republic of

[6]Energy capital data are not available over the relevant time horizons for the following Sub-Saharan African Countries: Benin, Botswana, Burkina Faso, Cote d'Ivoire, The Gambia, Guinea-Bissau, Equatorial Guinea, Lesotho, Mauritania and Sudan.

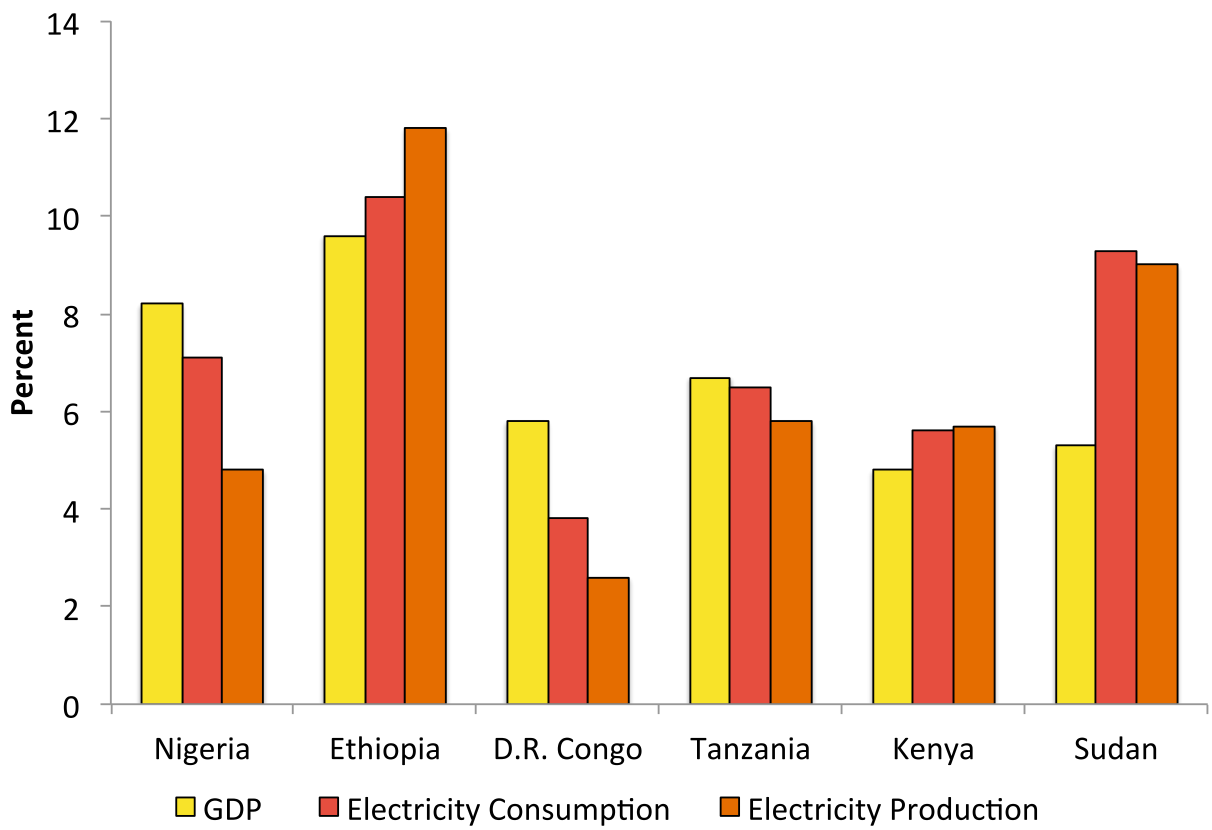
the Congo, Ethiopia, Kenya, Nigeria, and Tanzania, five of the six African countries on which we focus this paper (data on energy capital for Sudan are not available). Looking across these five countries, Ethiopia clearly stands out with an average annualized growth rate of energy capital per capita of 10.8 percent since 2000. Kenya and Nigeria also experienced considerable increases in the growth rate of energy capital per capita since 2000. In contrast, both the Democratic Republic of the Congo and Tanzania saw lower rates of growth in energy capital per capita in the 2000s than in the 1990s.

Figure 3: Average Annualized Growth Rate of Energy Capital Per Capita By Country



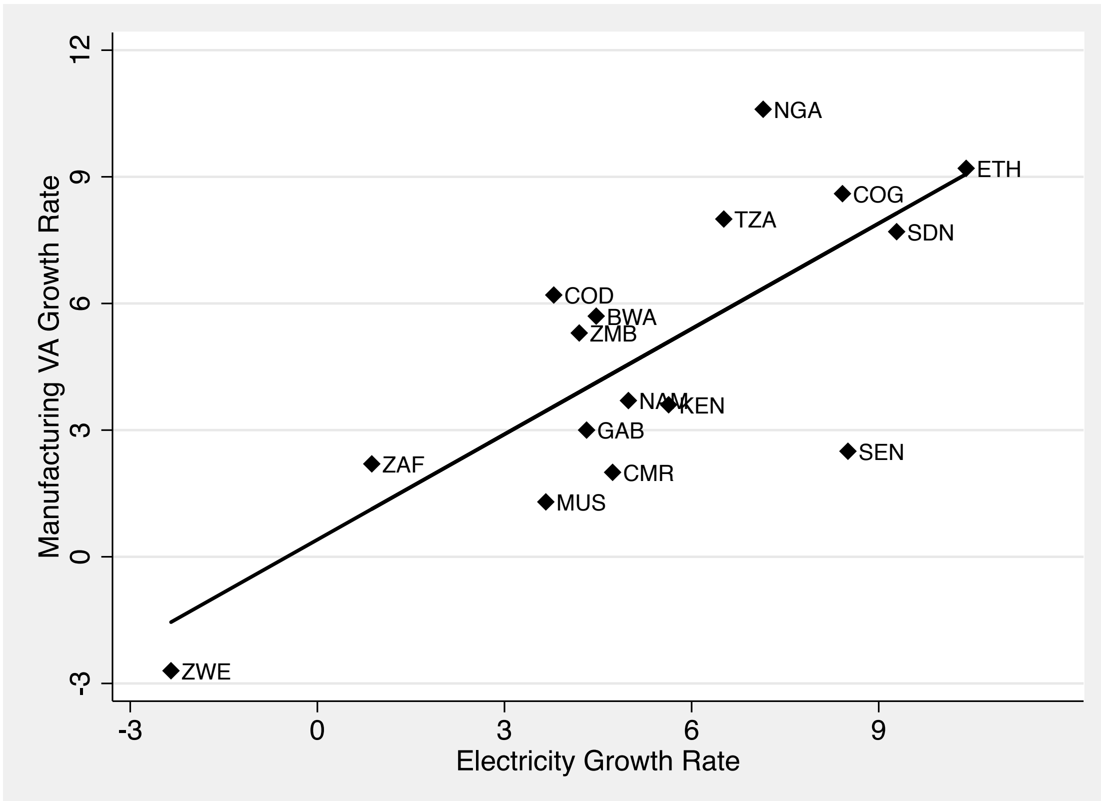
The large increases in energy capital were accompanied by similarly large increases in energy production and consumption. Figure 4 plots the average annualized growth in electricity production and consumption since 2000. The y-axis is the same is for GDP in Figure 1 for comparison's sake. As the figure shows, growth rates of electricity consumption are similar in magnitude to those of GDP. In each of these countries, electricity consumption exceeded GDP growth over this period. In Ethiopia, Sudan, Kenya and Tanzania, electricity production increased by roughly as much or more than GDP per capita, as new power plants and distribution lines were constructed. In Nigeria and the Congo, the story seems to be more about reducing waste: net imports did not increase in Nigeria or the Congo since 2000, thus, the increase in electricity consumption without such a large increase in production must reflect lower fraction lost to theft or loss. In any case, each of these countries had impressive increases in electric energy usage since 2000.

Figure 4: Avg. Annualized Electricity Growth in Africa's Largest Countries Since 2000



Looking across countries, the data show that countries with the largest increases in electricity were also the ones that grew the most. Figure 5 plots manufacturing GDP growth and electricity consumption growth since 2000 across all Sub-Saharan African countries for which data are available. The 45-degree line is also plotted for expositional purposes. As the figure shows, the correlation between the two variables is quite strong. The Spearman correlation coefficient is 0.76, with a p-value of 0.001. When looking at overall GDP growth or services GDP growth, the correlation coefficients are also quite high, at 0.63 and 0.64, with p-values of 0.007 and 0.008. Of course, this correlation does not help separate the role of electricity in driving growth from the increase in demand for electricity as GDP increases. For this we turn to a model.

Figure 5: Manufacturing GDP Growth and Electricity Growth in Africa Since 2000



3. Model

In this section, we build a model to help us quantify the role of energy investments in Africa's robust growth in GDP per capita since 2000. Our basic approach is to discipline the income elasticity of demand for energy directly in the model, in order to capture the channel leading from income growth to energy demand. We then use the model to divide up growth in GDP per capita into two parts: (i) that coming from energy investments, and (ii) that coming from other exogenous factors.

3.1. Households and preferences

The economy is inhabited by a continuum of households of measure one. Each household is endowed with one unit of labor which they supply inelastically to the labor market. Households can use their income to consume or to save.

Households divide their consumption among an agricultural good (e.g., food), C_a, a non-agricultural good, C_n, and energy, C_e. The non-agricultural good is the numeraire and can be used to finance all three types of consumption. Empirically, the share of household expenditures on agricultural falls as the income per capita rises and the economy undergoes structural change (see e.g. Herrendorf, Rogerson, and Valentinyi, 2014). To ensure that our model captures Engel's Law, i.e. the negative relationship between income and agricultural expenditure shares, we follow the structural change literature (e.g. Kongsamut, Rebelo, and Xie, 2001) and assume that all households must consume a minimum "subsistence" level of the agricultural good, $\bar{a}$.[7]

Lifetime utility is logarithmic over the three consumption goods,

$$\sum_{t=0}^{\infty}\beta^t\left(\omega_a\log(C_{a,t}-\bar{a})+\omega_n\log(C_{n,t})+\omega_e\log(C_{e,t})\right). \tag{1}$$

Parameters ω_a, ω_n and ω_e denote the long-run expenditure shares of agriculture, non-agriculture, and energy, respectively.[8] We require that these shares sum to unity: $1=\omega_a+\omega_n+\omega_e$. As $\bar{a}$ approaches zero, the logarithmic preferences imply that the elasticity of substitution between each pair of consumption goods approaches unity.

Household save in physical capital. Following Greenwood, Hercowitz, and Krusell (1997), we allow for separate levels of productivity for consumption goods and investment goods. In particular, we assume that one unit of physical capital can be purchased from $\frac{1}{q}$ units of the non-agricultural good. Capital accumulates according to

$$K_{t+1}=(1-\delta)K_t+qI_t, \tag{2}$$

[7] Other specifications of non-homothetic preferences, such an additive utility term in non-agriculture (Laitner, 2000; Alvarez-Cuadrado and Poschke, 2011), or thresholds below which only agriculture is consumed (Gollin, Parente, and Rogerson, 2002, 2007) would yield similar qualitative predictions. In future work we plan to explore the model's quantitative predictions under two recent specifications that allow for even more flexibility in matching expenditure patterns (Boppart, 2014; Comin, Lashkari, and Mestieri, 2014).

[8] We use the term long-run expenditure shares to refer to the expenditure shares in a country for which $\bar{a}$ represents a trivial amount of total consumption, such as the United States.

where parameter δ denotes the constant depreciation rate and I_t is investment in terms of non-agricultural goods. Households rent the capital to firms at rate R_t.

3.2. Production technologies

Perfectly competitive firms produce the agricultural good, Y_a, the non-agricultural good, Y_n, and energy, E. We describe each production process in turn.

3.2.1. Agricultural good

The production technology for the agricultural good is Cobb-Douglas between capital, K_a, and labor, N_a,

$$Y_{a,t} = A_t K_{a,t}^{\theta} N_{a,t}^{1-\theta}, \tag{3}$$

where θ denotes capital's share and A is exogenous total factor productivity (TFP) in non-energy production.

3.2.2. Non-agricultural good

Following the macro-energy literature (e.g., Hassler, Krusell, and Olovsson (2015)), the production technology for the non-agricultural good features a constant elasticity of substitution, ϵ, between a capital-labor composite, $K_n^{\theta} N_n^{1-\theta}$, and energy,

$$Y_{n,t} = A_t \Big[(1-\mu)(K_{n,t}^{\theta} N_{n,t}^{1-\theta})^{\frac{\epsilon-1}{\epsilon}} + \mu E_{n,t}^{\frac{\epsilon-1}{\epsilon}} \Big]^{\frac{\epsilon}{\epsilon-1}}, \tag{4}$$

where μ is the distribution parameter between energy and the capital-labor composite.

3.2.3. Energy

Firms and households purchase an aggregate energy input, E_t, from the final energy producer. The aggregate energy input is itself a Cobb-Douglas aggregate of two types of energy: grid energy, E_{gt}, and off-grid energy, E_{ot}. Formally,

$$E_t = E_{ot}^{\rho} E_{gt}^{1-\rho}, \tag{5}$$

where parameter ρ denotes the share of off-grid energy in the energy aggregate.

In reality, these two inputs are meant to capture the fact that households and firms generally have two sources for their electricity, and that the two sources are not perfect substitutes. For example, while an off-grid solar system can easily power a light bulb or mobile phone, it does not provide sufficient energy for a television, iron, or refrigerator, which are three highly desirable appliances (see e.g. Lee, Miguel, and Wolfram, 2016). Similarly, an off-grid generator can power a small number of sewing machines, but not an entire textile plant (see e.g. Eberhard, Rosnes, Shkaratan, and Vennemo, 2001).

We model the production of grid and off-grid energy by two representative firms; one which produces grid energy and one which produces off-grid energy. Each representative firm is responsible for the generation of the electricity and for any required resource extraction (such as coal mining). The main difference between the production of grid and off-grid energy is that grid production uses public capital, K_g, while off-grid production uses private capital, K_o. Examples of this public capital include transmission lines, hydropower dams, power stations and so forth.[9] The respective production technologies for grid and off-grid energy are

$$E_{gt} = A_{gt} K_{gt}^{\phi} N_{gt}^{1-\phi} \quad \text{and} \quad E_{ot} = A_{ot} K_{ot}^{\phi} N_{ot}^{1-\phi}. \tag{6}$$

Parameter ϕ is capital's share and A_g and A_o denote exogenous TFP in grid and off-grid energy production, respectively.

Since the grid capital is publicly provided, firms in the grid energy sector earn positive profits, Π_g, from energy production,

$$\Pi_g = p_g E_g - w N_g, \tag{7}$$

where p_g is the relative price of grid energy. The profits are returned to the household through lump-sum transfers.

Our paper makes the strong assumption of perfect competition in electricity markets. Ryan (2014) shows that in India, electricity prices and supply are governed by imperfect competition among electricity providers. To the extent that prices of electricity do not reflect market value, this will affect our quantitative conclusions in several ways. We return to this issue later.

[9] Note that we are calling energy capital as something different from what Caselli (2015) calls natural capital, and includes stocks of natural resources like diamonds, oil or land that is valuable for tourism.

3.3. Government

The government's only role is to finance investment in grid capital. Like privately provided capital, grid capital can be purchased from $\frac{1}{q}$ units of the non-agricultural good and it depreciates at constant rate δ. The law of motion for grid capital is

$$K_{g,t+1} = (1-\delta)K_{g,t} + qI_{g,t}, \tag{8}$$

where I_g denotes government investment in grid capital. The government finances investment in grid capital through lump-sum taxes on the households, T_t.

3.4. Equilibrium

We define a stationary competitive equilibrium. Labor and private capital are perfectly mobile across the sectors. The aggregate state variables are the level of private capital, $K = K_a + K_n + K_o$, and the level of public capital, K_g.

Given a level of grid energy investment, I_g and levels of technological progress A_n, A_a, A_o and A_g, a competitive equilibrium consists of households' decision rules, $\{C_a, C_n, C_e, K'\}$ firms' production plans, $\{K_a, K_n, K_o, N_a, N_n, N_o, N_g, E_n\}$, and prices $\{r, w, p_a, p_e, p_g, p_o\}$, such that the following holds:

1. Given prices, taxes, and grid-energy profits, households choose C_a, C_n, C_e and K' to optimize equation (1) subject to the intertemporal budget constraint,

$$p_a C_a + C_n + p_e C_e + \frac{K'}{q} \leq w + RK + (1-\delta)\frac{K}{q} + \Pi_g - T \tag{9}$$

   and the non-negativity constraints,

$$C_a \geq 0, \quad C_n \geq 0, \quad C_e \geq 0 \quad \text{and} \quad K' \geq 0. \tag{10}$$

2. Firm demands for capital, labor, and energy satisfy:

$$r = \frac{\partial (p_a Y_a)}{\partial K_a} = \frac{\partial Y_n}{\partial K_n} = \frac{\partial (p_o E_o)}{\partial K_o} \tag{11}$$

$$w = \frac{\partial (p_a Y_a)}{\partial N_a} = \frac{\partial Y_n}{\partial N_n} = \frac{\partial (p_o E_o)}{\partial N_o} = \frac{\partial (p_g E_g)}{\partial N_g} \tag{12}$$

$$p_e = \frac{\partial Y_n}{\partial E_n} \tag{13}$$

3. The government budget balances:

$$I_g = T \tag{14}$$

4. Markets clear:

$$E = E_n + C_e \tag{15}$$

$$K = K_n + K_o + K_a \tag{16}$$

$$N = N_n + N_o + N_a + N_g \tag{17}$$

$$p_a Y_a + Y_n + p_e(E - E_n) + (1-\delta)\left(\frac{K}{q} + \frac{K_g}{q}\right) = p_a C_a + C_n + p_e C_e + \frac{K'}{q} + \frac{K'_g}{q} \tag{18}$$

4. Calibration

We analyze the effects of increases in grid electricity on economic growth in six of the most populous countries in Sub-Saharan Africa: The Democratic Republic of the Congo, Ethiopia, Kenya, Nigeria, Sudan, and Tanzania. We calibrate the model to match the average characteristics of these countries in the pre-growth steady state, years 1986-2000.

We normalize non-energy TFP, A and grid-energy TFP, A_g to unity: $A = A_g = 1$. This amounts to a choice of units. We take the values for six parameters, $\{\epsilon, \theta, \phi, \delta, \omega_a, \omega_n\}$, directly from the data. We then calibrate the remaining parameters so that certain moments in the model match their empirical values. Table 2 reports the calibrated parameter values and their source. Subsections 4.1 and 4.2 describe direct calibration and method of moments procedures, respectively.

Table 2: Parameter Values

Parameter	Model Value	Source
Production		
Elasticity of substitution: ϵ	0.05	Hassler, Krusell, Olovsson (2015)
Distribution parameter: μ	1.46e-14	Method of moments
Capital share: θ	0.33	Capital's share of income
Capital share in energy: ϕ	0.90	Capital's share of energy production
Off-grid energy share: ρ	0.01	Method of moments
Depreciation rate: δ	0.04	Penn World Tables
TFP in non-energy: A	1	Normalization
TFP in grid energy: A_g	1	Normalization
TFP in off-grid energy: A_o	0.05	Method of moments
Investment technology: q	0.52	Method of moments
Preferences		
Discount rate: β	0.96	Assumption
Weight on agriculture: ω_a	0.02	Herrendorf, Rogerson, and Valentinyi (2014)
Weight on energy: ω_e	0.04	U.S. expenditure share on energy
Weight on non-agriculture: ω_n	0.94	$1-\omega_a-\omega_e$
Subsistence consumption: $\bar{a}$	0.83	Method of moments
Number of workers: N	1	Normalization
Government		
Electricity investment: I_g	0.01	Method of moments

4.1. Direct calibration

We calibrate the values for parameters, $\{\epsilon, \theta, \phi, \delta, \omega_a, \omega_n\}$, directly from the data. Parameter ϕ corresponds to capital's share in the production of grid-energy. Producing grid-energy requires both extracting the raw materials, such as coal or oil, and generating and transmitting electricity. Our model bundles these two components into a single, energy producing firm. The empirical analog of our model's grid-energy sector is thus, a combined sector comprised of both resource extraction and power generation.[10] The U.S. labor share in this combined sector is 0.1, yielding a value of capital share for the production of grid energy equal to 0.9.

[10]The combined sector corresponds to NAICS codes 2211, 211, 2121, and 213 (power generation and supply, oil and gas extraction, coal mining, and support activities for mining). Data on labor compensation are from the BLS. Data on value-added are from the NIPA GDP-by-Industry accounts

The elasticity of substitution between the capital-labor composite and energy is a particularly prominent parameter in the macro-energy literature. Hassler, Krusell, and Olovsson (2015) argue that this elasticity must be close to zero to replicate the historical movements in energy share and energy prices in the US. Based on their evidence, we choose $\epsilon = 0.05$, the largest value that matches the historical data reasonably well.

The utility function weights, ω_a, ω_n, and ω_e represent the respective consumption expenditure shares of agriculture, non-agriculture, and energy, in the special case when $\bar{a} = 0$. Or, alternatively, when income is sufficiently high such that $p_a \bar{a}$ is small relative to total consumption expenditures. Following the estimation used by Herrendorf, Rogerson, and Valentinyi (2014), we set $\omega_a = 0.02$. We choose $\omega_e = 0.038$, the relative importance weight on household energy consumption in 2015 U.S. Consumer Price Index (U.S. Bureau of Labor Statistics, 2015). These two choices imply that $\omega_n = 1 - \omega_a - \omega_e = 0.942$.

We set the depreciation rate, δ, equal to 0.04, the average value from 1986-2000 across the six Sub-Saharan Africa economies in our study (Feenstra, Inklaar, and Timmer, 2015). For capital's share in agriculture and in the capital-labor composite in the production of non-agriculture, we use the standard value of one third, $\theta = 0.33$. For the discount factor, we use the standard value of $\beta = 0.96$.

4.2. A method of moments

Given the directly calibrated parameter values, we choose the remaining six parameters, $\{A_o, \mu, \rho, \bar{a}, I_g, q\}$ to ensure that certain moments in the model match their values in the data. While all six parameters are jointly determined, some moments are more important for pinning down some parameters than others. We describe each parameter and its primary moment in turn.

Parameter q determines the effectiveness with which agents can transform the non-agricultural consumption good into capital. All else constant, economies that are better at creating capital goods (higher q) will have higher capital-output ratios. We choose q to target the average capital-output ratio across the Sub-Saharan African economies in our study from 1986-2000 (Feenstra, Inklaar, and Timmer, 2015).

The value of off-grid TFP, A_o, determines determines the effectiveness with which capital and labor can be used to produce off-grid energy relative to grid-energy. As A_o increases, the marginal cost of producing off-grid energy falls, which, in turn, reduces the relative price of off-grid energy. Estimates from Foster and Steinbuks (2008) suggest that off-grid energy is approximately five times as expensive as grid energy in Sub-Saharan Africa (see Eberhard, Rosnes, Shkaratan, and Vennemo, 2001, Figure 1.10 and Table A1.8.). We choose A_o to target this relative price difference. Finally, I_g determines the initial level of grid-energy in the 2000 steady state. We choose this value to match the average ratio of (externally financed) energy investment relative to GDP in the 1990s (Gutman et. al 2015).

Parameter μ primarily governs energy's share of non-agricultural output. Estimating the model analog of energy share in developing countries is particularly challenging because, in many cases, the observed energy price does not reflect its true shadow value. Shortages of electricity infrastructure combined with highly regulated pricing likely create substantial excess demand for energy. Our model does not incorporate these market imperfections. Therefore, the value of energy share we observe in the data is a lower bound on the value that energy share would obtain, if the economy behaved according to our model with no market imperfections. With this caveat in mind, we target the average energy share in the manufacturing sector in Ethiopia. The average value of this share over years 1996-2000 (the years in the pre-growth period for which data is available) is 10 percent.[11] Similar to our value in Ethiopia, Allcott, Collard-Wexler, and O'Connell (2016) find that the average energy share in Indian manufacturing is 11 percent.

The value of ρ, off-grid energy share in the production of the energy aggregate is pinned down by the fraction of off-grid capital relative to total capital. Six percent of Sub-Saharan Africa's total generating capacity was from off-grid sources in 2006 (Foster and Steinbuks, 2008). Therefore, we choose ρ to target $\frac{K_o}{K_g+K_o} = 0.06$. Parameter $\bar{a}$ determines the relative size of the agricultural sector. We choose $\bar{a}$ such that the employment share in agriculture is 0.67, the average value across Ethiopia, Nigeria, Sudan, and Tanzania, the four countries for which data is available.

We use the Nelder-Meade simplex algorithm (Nelder and Mead, 1965) to minimize the squared distance between the model and empirical values of the moments. The model fits the moments quite closely; the minimized squared distance is 1.02×10^{-15}. Table 3 reports the values of the moments we target in the model and their corresponding values in the data. All moments match their targets to two decimal places or more.

How well does the model perform in matching moments not targeted directly? We first compared the model's predictions for the energy shares of expenditure in the model and data from Africa. Eberhard, Rosnes, Shkaratan, and Vennemo (2001) report that Ethiopia's average budget share on energy in 2000 was 2 percent. The model predicts a value of 1 percent, which is not far off. Herrendorf, Rogerson, and Valentinyi (2014) report that the

[11] Data from the Report on Large and Medium Scale Electricity and Manufacturing Survey, Table 3.7.

Table 3: Model Fit

Moment	Data	Model
Capital-output ratio $\frac{K}{Y}$	1.9	1.90
Grid-electricity-investment-output ratio: $\frac{I_g}{Y}$	0.008	0.008
Share of Employment in Agriculture: $\frac{N_a}{N}$	0.67	0.67
Electricity share of GDP: $\frac{p_e E}{Y}$	0.10	0.10
Fraction of off-grid capital: $\frac{K_o}{K_o+K_g}$	0.06	0.06
Price of off-grid to grid electricity: $\frac{p_o}{p_g}$	5.00	5.00

agriculture consumption share of GDP (Figure 6.9) is about 60 percent in African countries. Our model predicts 72 percent. So this is reasonably comparable as well.

van Benthem (2015) report income elasticities of demand for energy (LDC category, Table 6). The average elasticity is 0.83. In the model, the elasticity is 1.96. Thus, the model's elasticity is too large relative to the data. We note that this will render the model's predictions an under-estimate, since the model over-predicts the magnitude of the effect of income on electricity demand, which in turn leads the model to under-predict the effect of energy on income growth. In future work we plan to return to this issue.

Finally, we assess whether the model's subsistence requirement is comparable with existing evidence. In the model, the subsistence requirement is about 61 percent of GDP per capita in Ethiopia in 2000. This corresponds to about $1.82 per day at PPP. This value is in the same ballpark as the $1 per day and $2 per day thresholds for extreme poverty commonly reported by the World Bank. We conclude that our subsistence term is reasonable given these values.

5. Quantitative Counterfactual Exercises

Our goal is to estimate the contribution of expansions in grid energy infrastructure to growth since 2000 in each of the six Sub-Saharan African economies in our study. We describe the computational experiment for Ethiopia. The experiments for the other countries are analogous.

5.1. Baseline Experiment

We begin the Ethiopian economy in its pre-growth steady state, calibrated according to Section 4. We then calibrate a post-growth steady state which corresponds to year 2013, the last year for which data on GDP and electricity consumption are available. Specifically, we choose the values for non-energy TFP (A) and grid-energy investment (I_g) such that the percent increase in GDP per capita and electricity per capita (measured in kilo watt hours per capita) in the pre- and post-growth steady states match their observed increases in Ethiopia between 2000 and 2013. By design, this post-growth steady state matches all of the Ethiopian growth in output and grid-energy over the 2000-2013 period.

We also calculate a third, hypothetical, steady state in which only grid-energy infrastructure grows; non-energy TFP remains at its pre-growth level. The three steady states are summarized in Table 4. We use the superscripts pre and $post$ to denote the pre- and post-growth steady state values of A and I_g. The pre-growth values of A and I_g are the values reported in Table 2 in Section 4.

Table 4: Computational Experiment

Steady State	Non-Energy TFP	Grid-Energy Investment
Pre-growth (year 2000)	$A = A^{pre}$	$I_g = I_g^{pre}$
Post-growth (year 2013)	$A = A^{post}$	$I_g = I_g^{post}$
Hypothetical	$A = A^{pre}$	$I_g = I_g^{post}$

To evaluate the importance of grid-energy infrastructure for Ethiopia's growth, we compare the increase in GDP per capita between the pre-growth and hypothetical steady state with the increase in GDP per capita between the pre- and post-growth steady states. We perform this same exercise for each economy in our study. Figure 6 plots the percent increase in per capita GDP over this period and the increase that would have occurred from electricity investments alone. Table 5 reports the percent of the observed increase in GDP per capita explained by the expansions of grid-energy infrastructure.

Figure 6: GDP per Growth 2000-2013: Data and Model Counterfactual

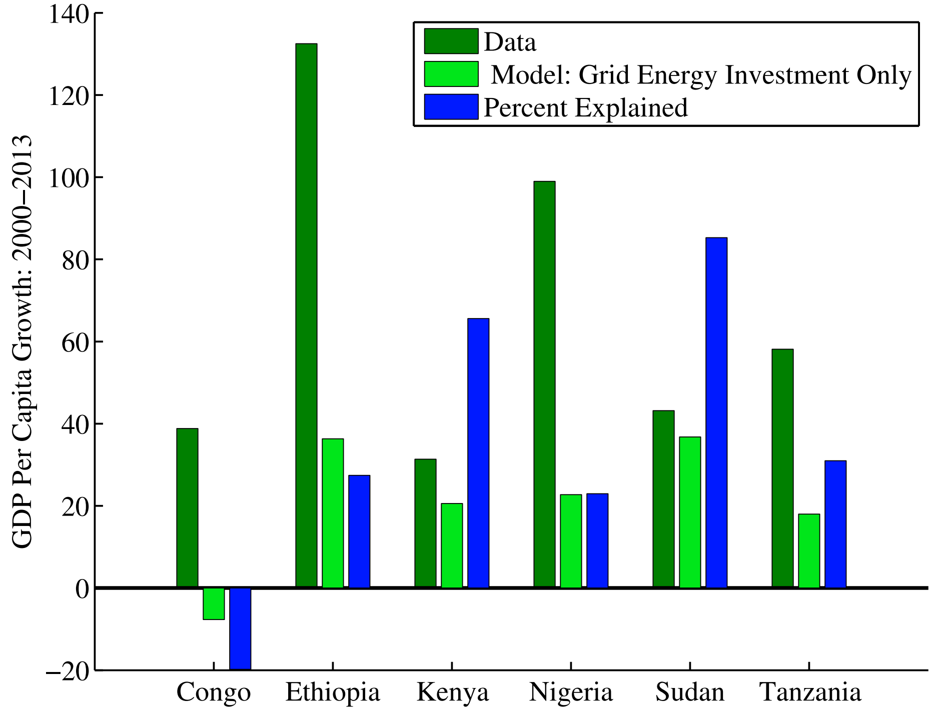


Table 5: Percent of Growth Explained By Grid Energy Investment

Congo	Ethiopia	Kenya	Nigeria	Sudan	Tanzania	**AVERAGE**
-19.8	27.4	65.6	23.0	85.3	31.0	**35.4**

Expansions in grid-energy infrastructure explain approximately one third (35.4 percent) of growth on average. Energy infrastructure plays a particularly important role in growth in Sudan, explaining 85.3 percent of total growth. The model finds such a large role for energy in Sudanese growth because the observed increase in electricity per capita between the pre- and post-growth periods was very large, exceeding the growth rate of per capita GDP by almost a factor of four. Sudan's story is mirrored in Kenya; large growth in Kenyan per capita electricity consumption relative to growth in per capita GDP imply that expansions in grid-energy infrastructure also explain over half (65.6 percent) of Kenyan growth.

Ethiopia has the largest observed percentage increases in both per capita GDP and electricity consumption between the pre- and post-growth periods; per capita electricity consumption increased by 205 percent and per capita GDP increased by 132 percent. The increase in energy infrastructure explains 27.4 percent of Ethiopia's growth over this period. While this impact is substantial, it is considerably smaller then the model's findings for Sudan and

Kenya. The main reason for this difference is that the growth of electricity per capita relative to per capita GDP is much higher in Sudan and Kenya than in Ethiopia.

Nigeria and Tanzania experienced lower growth in per capita electricity consumption than Ethiopia which was accompanied by lower growth in per capita GDP. These two effects are partially offsetting and the overall contribution of grid-energy infrastructure investment to growth in both these countries is similar to its contribution in Ethiopia. Grid-energy infrastructure expansions explain 23 percent of growth in Nigeria and 31 percent in Tanzania.

In contrast to the other economies in our study, the expansion of grid energy infrastructure fails to explain any of the growth in the Congo. While the Congo did experience a modest (12 percent) increase in electricity per capita between the pre- and post-growth periods, our model predicts that all of this increase was driven by higher demand for energy instead of by lower prices from more grid-energy infrastructure. In fact, matching Congolese growth in per capita GDP and electricity consumption requires grid-energy infrastructure to decrease by 15 percent. The lower infrastructure combined with the higher demand imply that the price of energy in the post-growth steady state is 7.5 times higher than in the pre-growth steady state.

Three basic channels drive our quantitative conclusions, and in particular the large importance of energy investments in Africa's growth. First, grid-energy infrastructure in the initial period was very low, with grid-energy investment less than one percent of GDP. The low existing levels of infrastructure combined with diminishing returns to other factors imply that the marginal returns to grid-energy investment are very high. Second, there were large increases in per capita electricity consumption between the pre- and post-growth periods, ranging from 12 percent in the Congo to 205 percent in Ethiopia. Third, energy plays a substantial role in non-agricultural production in Africa, accounting for approximately 10 percent of manufacturing GDP.

To assess the relative importance of each of these channels, we recalculate the percent of growth explained by grid-energy investment when we (counterfactually) reduce each channel, one at a time, by fifty percent. Table 6 reports the results from these counterfactual exercises. To evaluate the impact of the first channel, low existing levels of infrastructure combined with diminishing returns, we double the level of grid-energy investment in the initial steady state. The results, reported in the third column of Table 6, indicate that the low initial levels of infrastructure are a crucial part of the story; with twice as much infrastructure in the pre-growth steady state, on average grid-energy investment only explains 10 percent of growth as opposed to 35.4 percent in the baseline.

Table 6: Counterfactuals: Percent of Growth Explained by Grid Energy Investment

Country	Baseline Exp.	Counterfactuals		
		Double pre-growth I_g	Halve I_g growth	Halve pre-growth $\frac{p_e E}{Y}$
Congo	-19.8	-8.3	-9.5	-21.9
Ethiopia	27.4	7.2	17.0	11.5
Kenya	65.6	20.3	38.7	29.2
Nigeria	23.0	7.4	13.9	10.1
Sudan	85.3	21.9	71.2	35.5
Tanzania	31.0	11.2	17.7	14.2
AVERAGE	**35.4**	**10.0**	**24.8**	**13.1**

To evaluate the impact of the second channel, the large increases in grid-energy infrastructure, we suppose that the growth rate of grid-energy infrastructure is half of the value we calculated in the baseline experiment. We adjust the growth rate of non-energy TFP, A, to ensure that the model still matches GDP per capita in the long-run steady state. The results, reported in the fourth column of Table 6, indicate that in this counterfactual, grid-energy investment is less important than in the baseline experiment, explaining 24.8 percent of growth, on average.

Finally, to evaluate the importance of the third channel, the energy share, we recalibrate the model to match an economy with an energy share of 0.05, half the value of the energy share target we match in Section 4. The results, reported in the fifth column of Table 6, imply when energy is half as important in production, the contribution of grid-energy investment to growth is considerably smaller than in the baseline experiment, only 13.1 percent on average.

Reducing the impact of each channel by fifty percent substantially reduces grid-energy investment's contribution to Africa's growth, implying that all three of the channels are important determinants of the role of grid-energy investment in overall growth. However, increasing the level of grid-energy investment in the initial steady state has the largest impact on the results. This finding suggests grid-energy investment was so important to growth in Sub-Saharan Africa over this period largely because existing levels of grid-energy infrastructure were extremely low.

5.2. Sensitivity Analysis

We evaluate the sensitivity of our results with respect to two key energy-related parameters, the elasticity of substitution, ϵ and the distribution parameter, μ, in the CES production function for the non-agricultural good (equation (4)). In the calibration (described in Section 4) we first choose a set of parameters, which includes ϵ directly from the data and the empirical literature. Given these directly calibrated parameters, we choose a second set of parameters, which includes μ, to ensure that certain moments in the model match their values in the data. We repeat this procedure in the sensitivity analysis for ϵ; we recalibrate the model for the higher value of ϵ to ensure that the moments in the model still match their observed values in the data.

Table 7: Sensitivity Analysis: Percent of Growth Explained by Grid Energy Investment

	Congo	Ethiopia	Kenya	Nigeria	Sudan	Tanzania	**AVERAGE**
Baseline experiment	-19.8	27.4	65.6	23.0	85.3	31.0	**35.4**
$\epsilon = 0.1$, recalibrate	-17.3	28.2	61.0	22.9	87.9	31.2	**35.6**
$\mu = 10 \times \mu$	-20.5	33.2	66.1	25.8	104.6	33.0	**40.4**

Table 7 reports the effects of doubling ϵ and recalibrating the model and of increasing μ by one order of magnitude. Neither of these parameter changes substantially change the results; doubling ϵ implies that grid-energy investment explains approximately one percentage point more growth than in the baseline experiment while increasing μ by one order of magnitude implies that grid energy investment explains approximately five percentage points more of growth. We conclude that our choice of ϵ per se doesn't drive our quantitative conclusions. As long as the model is calibrated to match energy's share of non-agricultural employment (of ten percent), the choice of ϵ, perhaps surprisingly, is not central to our quantitative results.

6. Conclusions and Future Work

After decades of low or non-existent growth, Sub-Saharan Africa experienced a dramatic increase in GDP growth starting around 2000. The economics literature does not yet agree on why. This paper explores the role of energy investments, such as new power plants and an expansion of the electricity grid, which also increased fairly dramatically since 2000. These energy investments led to robust increases in electric power consumption in Africa, and particularly in the countries that experienced the most rapid growth in GDP.

To help quantify the importance of energy investments on Africa's recent growth, we build a multi-sector model with energy inputs in production and non-homothetic preferences. We use the model to help separate the role of increases in energy production on GDP per capita from the reverse channel, running from GDP increases to greater energy demand. To do so, we discipline the model's preferences using data on non-agricultural, agricultural and energy expenditures as a function of income. We then feed in the observed increases in Africa's energy production, and ask how much of Africa's growth can be accounted for by the energy increases alone.

In our main specification, around one-third of Africa's growth in GDP per capita since 2000 can be attributed to its energy investments. The large quantitative importance of energy investments is due in large part to three basic features of the data. First, Africa had extremely low levels of electricity consumption in 2000, at far less than one-percent of the U.S. level. Second, electricity consumption increased dramatically since 2000, averaging around eight percent growth per year on average. Third, energy plays an important role in non-agricultural production in the developing world, with a share around ten percent.

In future work, we plan to incorporate richer preferences, like those of Boppart (2014) or Comin, Lashkari, and Mestieri (2014), which allow for greater flexibility in matching the cross-section of expenditure patterns than the restrictive Stone-Geary preferences used currently. One limitation of our model so far is that it over-predicts the income elasticities of energy (and non-agricultural goods). This may lead us to under-estimate the role of electricity in driving Africa's growth. We also plan to incorporate more direct data on energy investments, and on energy capital more generally. These data can hopefully provide more evidence with which to refine our quantitative conclusions.

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