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The Impact of Electricity on Economic Development: A Macroeconomic Perspective

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Abstract

We find that electricity use and access are strongly correlated with economic development, as theory would suggest. Despite large empirical literatures and suggestive case evidence, there are, however, few methodologically strong studies that establish causal effects on an economy-wide basis. There is some evidence that reliability of electricity supply is important for economic growth. We propose that future research focuses on identifying the causal effects of electricity reliability, infrastructure, and access on economic growth; testing the replicability of the literature; and deepening our theoretical understanding of how lack of availability of electricity can be a constraint to growth.

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1. Introduction

Much progress has been made in recent decades in connecting the people of the world to reliable supplies of electricity, but some regions remain particularly under-served. To justify intervention by development agencies and governments to improve electricity access and reliability, it is desirable to know that this intervention would have a causal effect on economic growth, poverty, and other development indicators of interest. In this paper, we review the evidence at the economy-wide or macroeconomic level with a focus on the regions of the world with the lowest levels of electrification and electricity use, in particular Sub-Saharan Africa. We also identify key gaps in knowledge. We structure our review around the following questions:

- How serious do electricity supply problems have to be in order to constitute a serious brake on economic growth?
- To what degree has electrification prolonged or accelerated economic growth?
- What can be learnt from the development experience of countries that have invested successfully in electrification?

In principle, it should be easier to find evidence for causal effects using more disaggregated micro level data as some variables can more easily be considered exogenous, and randomized trials and other field experiments are possible. On the other hand, growth is an economy-wide, dynamic, and long-term process with effects that cannot usually be captured in micro studies. Therefore, macroeconomic analysis is also needed. In this paper, we mainly focus on country-level data but also look at some studies that use state- or region-level data. An accompanying microeconomic paper (Lee, Miguel, and Wolfram, 2016) covers data at both the individual consumer and firm levels as well as aggregate data at the settlement or county-equivalent level.

While there is more research on energy and economic growth in developed countries than in developing countries (van Ruijven et al., 2008), there is reason to think that energy is more important for economic growth in developing countries. This is in part because it is likely that energy was more important as a driver of economic growth in today's developed economies when they were at lower income levels. In the pre-industrial economy, energy scarcity was a constraint on economic growth (Wrigley, 2010). This constraint was relaxed by the development of technologies to exploit fossil fuels and later other modern energy carriers, which were potentially available in far greater flows than traditional renewable energy sources.

Electricity offers numerous advantages over other energy carriers, enabling far more efficient lighting (Fouquet, 2008), information and communication technologies, and more productive organization of manufacturing (Kander, Malanima, and Warde, 2014). Over time and as average incomes increase, there is a tendency to use higher quality – more productive, cleaner, and more flexible – energy carriers, especially electricity (Burke, 2013; Csereklyei, Rubio, and Stern, 2016). However, empirical evidence of the causal effect of electricity on economic growth and development is weak (Payne, 2010; Bruns, Gross, and Stern, 2014).

Most existing research focuses on the economic implications of electricity use and household access to electricity. The quality of electricity supply is also likely to be important. A focus of this paper is thus to marshal evidence on the reliability and cost of electricity including electricity usage prices and fees for new connections. Internationally comparable data on the quality of electricity supply and the cost of usage and connections have recently become available through the efforts of the World Bank (2016a) and World Economic Forum (2015).

Many developing countries have reformed their electricity sectors in the last few decades. These efforts – mostly in the direction of market liberalization and corporatization – have only been partially successful in promoting efficient pricing and greater electricity access (Jamasb, Nepal, and Timilsina, 2017). Studies assessing the economic effects of these reforms are scarce; so far effects on economic growth seem positive, while effects on poverty are mixed (Jamasb, Nepal, and Timilsina, 2017). Our focus is on the effects of actual quantities and prices of electricity and infrastructure rather than of institutional change, which is dealt with in another paper in this project (Eberhard and Godinho, 2016).

The next two sections look at the theoretical relationship between energy and economic growth and development, and the particular characteristics and role of electricity. Section 4 provides a simple graphical and bivariate statistical analysis of key relationships between electricity and development variables. Section 5 reviews empirical evidence from time series analyses of the relationship between electricity consumption and economic growth. Section 6 reviews studies on the effect of infrastructure and electricity quality on economic growth. The penultimate section looks at electrification success stories and whether these have resulted in improved development outcomes. We then conclude and identify priority areas for research.

2. Energy and Economic Growth

Physical laws describe the operating constraints of economic systems (Boulding, 1966; Ayres and Kneese, 1969). Production requires energy to carry out work to convert materials into desired products and to transport raw materials, goods, and people. The second law of thermodynamics (the entropy law) implies that energy cannot be reused and there are limits to how much energy efficiency can be improved. These limits can be approximated by a production function with an elasticity of substitution significantly below one (Stern, 1997). A meta-analysis of the existing empirical literature found that the elasticity of substitution between capital and energy is indeed less than one (Koetse, de Groot, and Florax, 2008).[1] As a result, energy is an essential factor of production and continuous supplies of energy are needed to maintain existing levels of economic activity as well as to grow and develop the economy (Stern, 1997). There may also be macroeconomic limits to substitution of other inputs for energy. The construction, operation, and maintenance of tools, machines, and factories require a flow of materials and energy. Similarly, the humans that direct manufactured capital consume energy and materials. Thus, producing more of the substitutes for energy requires more of the thing that it is supposed to substitute for. This again limits potential substitutability (Cleveland et al., 1984). While there are limits to substituting energy for other inputs, meta-analysis of existing studies suggests inter-fuel substitution possibilities are good (Stern, 2012). Transitions between different energy sources have taken place in the past and can take place in the future.

Before the Industrial Revolution, economies depended on energy from agricultural crops and wood as well as smaller amounts of wind and waterpower, all of which are directly dependent on the sun. This is still largely the case in rural areas of low-income countries. While solar energy is abundant and inexhaustible, it is diffuse compared to fossil fuels, and plants only capture about 1% of the energy in sunlight. Therefore, the maximum energy supply in a biomass-dependent economy is low, as is the “energy return on investment” for the human-directed energy expended to extract energy. This is why the shift to fossil fuels in the Industrial Revolution was so important in releasing constraints on energy supply and, therefore, on production and economic growth (Wrigley 2010).

[1] A meta-analysis is a statistical analysis of the results of a body of individual empirical studies.

In spite of this, core mainstream economic growth models disregard energy or other resources (Aghion and Howitt, 2009), and energy does not feature strongly in research on economic development (Toman and Jemelkova, 2003). For example, a search for "energy" in titles and abstracts of the *Journal of Economic Growth* yields no results. The mainstream empirical literature on the determinants of economic growth also usually ignores the role of energy (e.g. Barro, 2003; Moral-Benito, 2012). There are many models where resources are an input to production in the sub-field of environmental and resource economics (Stern, 2011), but most assume good substitutability between resources and other inputs (i.e. a Cobb Douglas production function where the elasticity of substitution is one) and do not focus on the potential role of energy in enabling growth.

By contrast, a prominent tradition in heterodox ecological economics, known as the biophysical economics approach, is based on thermodynamics (Georgescu-Roegen, 1971; Cleveland et al., 1984; Hall et al., 2001; Ayres and Warr, 2009; Murphy and Hall, 2010). Ecological economists usually argue that substitution between capital and resources, such as energy, can only play a limited role in mitigating the scarcity of resources (Stern, 1997). Furthermore, some ecological economists argue that when we account for the role of energy, there is little role left for technological change in driving economic growth (Hall et al., 2001). These researchers argue for a model where energy use is the main or only driver of economic growth. However, because the quality of resources and technology do affect the amount of energy needed to produce goods and services, and because energy intensity has declined in the long term in leading economies such as the United States (US) and United Kingdom (UK) (Csereklyei, Rubio, and Stern, 2016), we find it difficult to argue for such a model (Stern, 2011).

In order to better integrate the biophysical and mainstream economics approaches, Stern and Kander (2012) modify Solow's neoclassical growth model (Solow, 1956) by adding an energy input that has low substitutability with capital and labour, while allowing the elasticity of substitution between capital and labour to remain one. This is a so-called nested constant elasticity of substitution (CES) production function. The model also breaks down technological change into innovations that directly increase the productivity of energy (energy-augmenting technological change) and those that increase the productivity of labour (labour-augmenting technological change).

Depending on the scarcity of energy, the model displays either neoclassical or energy-constrained behaviour (Stern and Kander, 2012). When energy is superabundant the level of the capital stock and output are determined by the same factors as in the Solow model.[2] But when energy is relatively scarce, the size of the capital stock and the level of output depend on the level of energy supply and the level of energy-augmenting technology. In the pre-industrial era when energy was scarce, the model suggests that increases in energy availability and energy-augmenting technology had much larger effects on economic growth than they do in developed economies today. Until the Industrial Revolution, output per capita was generally low and economic growth was not sustained (Maddison, 2001). After the Industrial Revolution, as energy became more and more abundant, the long-run behaviour of the model economy becomes more like the mainstream Solow growth model.

Stern and Kander (2012) show that this model can simulate the observed features of the Swedish economy in the last two centuries reasonably well, including the fall in the cost share of energy and the decline in energy intensity over time. They find that increases in energy use and energy-augmenting technological change are the main contributors to economic growth in the 19th and early 20th Centuries. In the second half of the 20th Century labour-augmenting technological change becomes the main driver of growth in income per capita as it is in the Solow growth model.

If this model is a reasonable representation of the growth process, mainstream economists are not so wrong to ignore the role of energy in economic growth in developed economies where energy is abundant. Their models may, however, have limited applicability to both earlier historical periods and possibly to today's developing countries. For the lowest-income economies, energy availability is potentially a "binding constraint" to economic growth in the sense of Hausmann, Rodrik, and Velasco (2008). Though energy is internationally traded and so countries are not necessarily limited to their domestic resources, its cost in poor countries is high relative to labour, and importing and using energy requires investment in infrastructure. Reducing the scarcity of energy might thus be expected to provide greater benefits in terms of economic growth in developing economies than in developed economies.

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[2] This applies equally to abundant physical energy or abundant effective energy, where effective energy is the product of the quantity of energy and the state of energy-augmenting technology.

Bacon and Kojima (2016) suggest that researchers could identify a positive effect of energy use on economic growth by testing for a negative link between energy prices and economic growth. However, changes in energy prices do not only change the quantity of energy consumed. If the price elasticity of demand for energy is less than one in absolute value, an increase in the price of energy reduces energy use by a smaller percentage than the increase in energy prices, so expenditure on energy rises. The resulting shift in spending towards energy and away from other goods and services may be more important to economic growth than the effect of reducing the use of energy (Kilian, 2008). We thus need to be careful about what the effect of price shocks on the economy can tell us about the effect of energy use on economic growth.

Reducing energy intensity is an alternative to increasing the supply of energy. In the initially more energy intensive economies such as the United States, the UK, and Sweden, energy intensity has declined for one to two centuries. In less energy intensive economies such as in the Mediterranean and Latin America, energy intensity has been fairly constant or has increased (Csereklyei, Rubio, and Stern, 2016). Energy efficiency, substitution between energy and other inputs, structural change, and changes in energy quality are the main factors that can affect energy intensity (Stern, 2011). Structural change plays a smaller role in changes in energy intensity than is commonly thought (Henriques and Kander, 2010). This is because the share of manufacturing in the value of output falls largely because productivity growth is higher in manufacturing than in services and so the relative price of manufactured goods falls. Improved energy efficiency in manufacturing is more important, therefore, than structural change (Henriques and Kander, 2010).

Improvements in energy efficiency might be expected to reduce energy intensity, but the rebound effect – at the micro-level, the response by energy users to use more energy services when the cost of providing them falls – means both energy use and energy intensity will decline by less than the improvement in efficiency. The micro-level rebound is likely to be larger in developing than in developed countries, as demand can be expected to be more price-elastic (Roy, 2000). Estimates of the macro-level rebound effect are few (e.g. Turner, 2009; Barker et al., 2009; Turner and Hanley, 2011), and vary widely (Saunders, 2013; Turner 2013). At the economy-wide level, “backfire”, where energy use increases as a result of an efficiency improvement, or even “super-conservation”, where the rebound is negative, are both theoretically possible (Saunders, 2008; Turner, 2013; Borenstein, 2015). All existing evidence on the size of the economy-wide rebound effect to date depends on simulation models, which have limited empirical validation.

3. Electricity and Development

Electricity is a high quality energy carrier – more productive and flexible than other energy vectors, with zero pollution at the end use point. Electricity is far more thermodynamically efficient than any alternative technology in applications such as lighting. There are many high-value applications such as computing and telecommunications for which electricity has no substitutes. Where there are alternatives, the high cost of electricity limits its use to quite high-value applications (Kaufmann, 1994) but where electricity is subsidized it will also be used in low-value applications.

In the 19th Century, electric motors proved much more flexible than steam engines and allowed the reorganization of work in factories, providing productivity gains (Kander, Malanima, and Warde, 2014). Other early applications were lighting and telecommunications, first the telegraph and then telephones. Communications, lighting, and industrial power are likely to still be the first applications when electricity is introduced in previously unsupplied regions today.

Traditional fuels are polluting and often require significant inputs of household labour in collection, processing, and use. Development provides market opportunities for employment and the means to avoid the negative effects of traditional fuels. Therefore, as incomes increase, households gradually ascend an "energy ladder" by consuming higher quality fuels such as electricity (Hosier, 2004), although this does not mean giving up traditional fuels altogether (van der Kroon, Brouwer, and van Beukering, 2013) or that incomes are the only factor relevant for household energy transitions (Burke and Dundas, 2015). At the national level, there is also a shift to a higher share of electricity in energy use as income per capita increases (Burke, 2013; Burke and Csereklyei, 2016; Csereklyei, Rubio, and Stern, 2016). The close connection between electricity and economic activity has led some scholars to use night light data to improve the measurement of economic growth (e.g. Henderson, Storeygard, and Weil, 2012). All high-income OECD countries have near-universal access to electricity.

Toman and Jemelkova (2003) outline some of the ways in which increased energy availability could disproportionally affect development outcomes. Several are particularly applicable to electricity: reallocation of household time, especially for women, away from energy provision towards improved education and income generation; enhanced productivity of education investment due to children being able to study at night; the ability to use new technologies including communication technologies; and health benefits resulting from outcomes such as reduced indoor air pollution and the ability to refrigerate.

Providing a reliable supply of electricity requires costly investment as well as skilled control of the electricity network. Electricity supply and demand must be instantaneously balanced at all times in order to prevent network collapse. Meanwhile, electricity demand is volatile, across the course of the day and night, over the weekly cycle, and over seasonal cycles and weather events. Meeting annual peak demand requires network and generation capacity that may only be used for a few hours a year in some cases (Beenstock, 1991). Efficient allocation of resources in electricity infrastructure is a “very challenging task” (Joskow and Tirole, 2007, 83). Due to the complexity and costs of electricity sector management and investment, power supply is often less reliable in developing countries than in developed countries. Electricity theft is also more common (Khanna and Rao, 2009). Reliability issues provide an incentive for industry and other electricity consumers to rely on captive generation (i.e. self-generation) of electricity. We will investigate the importance of reliability for economic growth and development in Sections 4 and 7, below.

There are economies of scale in electricity generation (Christensen and Green, 1976). Methods of providing small-scale electricity, such as diesel generators, are generally costly. Oil-fired generation is the dominant source of electricity in many small countries; particularly island developing countries (World Bank, 2016b). The high price of electricity in these countries is likely to retard development; an issue we investigate in the next section of the paper.

4. Exploring the Data

In this section, we lay out some key facts on the relationship between electricity and economic growth and development. The analysis only establishes correlations or equilibrium relationships and not causal effects. Data on some variables such as the price of electricity are only available for a couple of years. Other variables are available in long time series, but not for all countries. We use the maximum number of countries possible for each analysis.[3] The Appendix details data sources.

Figure 1 presents data on per capita electricity use and GDP per capita for all countries with available data in 2014. Both variables range over orders of magnitude globally and there is a strong linear relationship between their logarithms. There is, though, variation around the main relationship, especially in developing countries: per capita electricity use can vary by an order of magnitude in countries at the same per capita income level. Regression (1) in Table 1 parameterizes this relationship. On average, a 1% increase in GDP per capita is associated with a 1.3% increase in electricity use per capita across countries. Results for only developing countries are similar (2).

To investigate the temporal stability of the relation between per capita electricity use and GDP per capita, we estimated the same cross-sectional regression for 1971. The results (3) are fairly similar to those for 2014 for the full sample (1). However, the slope and R-squared are lower for the developing countries alone (4) than for the full sample (3), though the difference is not statistically significant.[4] In point estimate terms, the cross-sectional electricity-GDP relationship appears to have been less stable over time than the cross-sectional energy-GDP relationship (see Csereklyei, Rubio, and Stern, 2016).

Regressions (5)–(7) use average annual growth rates of per capita energy use and GDP over the 44-year period 1971-2014. Regression (5) starts by examining beta-convergence (Barro and Sala-i-Martin, 1992) for the full sample of countries. Countries starting with low electricity use per capita tended to experience faster growth in this variable over 1971–2014.[5] Regressions (6) and (7) examine the electricity-GDP relationship using regressions of the growth rate of per capita electricity use on the growth rate of per capita GDP. The slope coefficients are smaller than in Regressions (1)–(4), suggesting that the cross-sectional regressions may be upwardly biased.[6] The regression constant suggests that, for the full

[3] We dropped Venezuela from analyses involving prices and costs due to abnormal values. For example, the average price of electricity is reported as $9.54 per kilowatt hour.

[4] Cross-sectional regressions using 2014 data for the samples in columns 3–4 provide slope coefficients of 1.34 (0.070) for all countries and 1.54 (0.181) for developing countries.

[5] Results are similar for the developing country sample. Cross-sectionally, the coefficient of variation – an indicator of sigma convergence (Quah, 1996) – reduces from 1.64 in 1971 to 1.42 in 2014. As Csereklyei, Rubio, and Stern (2016) found for total energy, much of the decline happens in the 1970s.

[6] Burke and Csereklyei (2016) report a final use of electricity-GDP elasticity of 0.88 in an unweighted cross-sectional specification with controls.

sample, the expected annual growth in per capita electricity use in a country with no economic growth is 1.1%. It is 2.3% in the developing country sample. Much of the growth in the use of electricity in developing countries is thus not associated with economic growth.

Next we examine the relationship between several other electricity variables and the level of economic development. For several of these variables we only have data for a few years. We use the observation closest to 2014 and compared it to GDP per capita and electricity consumption in 2014. For electricity access this is usually a slightly earlier year such as 2010 or 2012, while for the cost and reliability measures it is 2015. The economic growth rate is the annual mean for the ten years to 2014. Table 2 provides the correlations between these variables. Some key relationships are presented in the remaining Figures.

Figure 2 presents the relationship between electricity access and GDP per capita for low- and middle-income countries. The poorest country with universal access to electricity is Tajikistan, whereas Equatorial Guinea is a prominent outlier on the right with high income per capita and relatively low access. The remaining Figures also include data for developed countries. Figure 3 shows that it is harder to provide reliable electricity supply than to provide simple access. Figure 4 shows that there is a strong negative correlation between the cost of a new electricity connection (for a standard warehouse, expressed as a share of income per capita) and GDP per capita. There is less of a relationship, however, between the connection cost or electricity prices in US dollars (at market exchange rates) and GDP per capita (Table 2). So, while the relative expense of using electricity is higher in poorer countries, costs are not necessarily higher on an absolute basis. There is a stronger negative correlation between the time it takes to get the new connection and GDP per capita (Table 2).

Figure 5 plots the total value of electricity (price paid per kilowatt hour multiplied by kilowatt hours) as a share of GDP in each country against GDP per capita. The data are suggestive of an inverted-U curve. Electricity use is low in the poorest countries, so expenditure on electricity is also low. Expenditure on electricity is high relative to GDP in middle-income countries. This “cost share” is again low in the highest income countries.

Electricity is subsidized in many countries. Figure 6 presents a measure of the total cost of electricity including both customer payments and subsidies, using the measure of pre-tax electricity subsidies developed by Coady et al. (in press). This scatterplot shows a stronger negative correlation with GDP per capita than Figure 5 did (see Table 2). This is consistent with Csereklyei, Rubio, and Stern’s (2016) finding that the value of energy relative to GDP declined over time in Sweden and Britain as their economies grew.

Looking at Table 2, correlations with the rate of economic growth are low and often the reverse of the correlations with GDP per capita. This is because economic growth is weakly negatively correlated with GDP per capita due to "convergence" effects. There is, though, a moderate positive correlation between electricity access and economic growth.

Interestingly, electricity access is more negatively correlated with the demographic variables than is electricity use, especially with the death rate. We note that electricity may positively affect growth but have limited effects on other dimensions of development when institutions are weak (Laffont, 2005).

5. Time Series Analysis of the Energy Consumption and Economic Growth Relationship

Granger causality tests (Granger, 1969) and cointegration analysis (Engle and Granger, 1987). are two methods for testing for causality among time series variables that have been heavily used in energy economics (Hendry and Juselius, 2000). They have been applied extensively to the relationship between energy, GDP, and other variables from the late 1970s (Kraft and Kraft, 1978; Ozturk, 2010), generating hundreds of journal articles (Bruns, Gross, and Stern, 2014).

Early studies relied on Granger causality tests based on unrestricted vector autoregressions (VARs) in levels. More recent studies often use cointegration methods. A vector autoregression model consists of one regression equation for each variable of interest in a system. Each variable is regressed on lagged values of itself and all other variables in the system. If the coefficients of the lagged values of variable *X* in the equation for dependent variable *Y* are jointly statistically significant, *X* is said to Granger-cause *Y*. Cointegration analysis tests if variables that have stochastic trends – their trend is a random walk – share a common trend. If so, at least one variable must Granger-cause the other (Engle and Granger, 1987).

Early studies also used bivariate models of energy and output. More recent research tends to employ multivariate models. This follows Stern's (1993) argument that ignoring other relevant variables can generate spurious findings. Stern (1993) tested for Granger causality in the United States using a VAR model of GDP, capital and labour inputs, and a Divisia index of quality-adjusted energy use in place of the usual heat equivalent of energy use. The quality-adjusted index gives more weight to electricity than other energy sources. When both the multivariate approach and quality-adjusted energy index were employed, energy use was found to Granger-cause GDP. This suggests that taking into account the higher productivity of electricity is important in finding a causal effect of energy on GDP.

Yu and Jin (1992) conducted the first cointegration study of the energy-GDP relationship using a bivariate approach, while Stern (2000) estimated a dynamic cointegration model for GDP, quality-adjusted energy, labour, and capital for the US. Stern found a cointegrating relation between the four variables and, depending on the version of the model, that energy Granger-causes GDP or that there is mutual causation between energy and GDP. Some subsequent research has appeared to confirm these findings using other measures of energy quality (Warr and Ayres, 2010), data for other countries (Oh and Lee, 2004; Ghali and El-Sakka, 2004), or panels of many countries (Lee and Chang, 2008; Lee et al. 2008).

There have been four meta-analyses (Chen, Chen, and Chen, 2012; Bruns, Gross, and Stern, 2014; Kalimeris, Richardson, and Bithas, 2014; Menegaki, 2014) of primary studies in the energy-GDP literature and at least three recent non-systematic surveys of the electricity-GDP literature (Payne, 2010; Ozturk, 2010; Omri, 2014).[7] Chen, Chen, and Chen (2012) meta-analyse a sample of Granger causality tests between electricity and output while Kalimeris, Richardson, and Bithas (2014) and Bruns, Gross, and Stern (2014) use studies of both total energy and electricity. Based on a rough set analysis, Kalimeris, Richardson, and Bithas (2014) find there are no important differences between the results for electricity and total energy. Chen, Chen, and Chen (2012) and Kalimeris, Richardson, and Bithas (2014) only classify results according to the direction of causality and not the magnitude or significance of the test statistics. These studies find no consensus on the direction of causality.

Bruns, Gross, and Stern (2014) test if there is a “genuine effect” in this literature rather than just the effects of publication bias and misspecification. Publication bias is the tendency for statistically significant studies to be preferentially published over studies that cannot reject the null hypothesis. This means that a naïve averaging of published results is likely to overstate the effect size or the typical significance level. If there is a genuine effect, studies with larger samples are more likely to yield statistically significant results, *ceteris paribus* (Stanley, 2005). This can be tested by relating a measure of statistical significance, e.g. test statistics, to the sample size or degrees of freedom in a regression analysis of the primary

[7] We refer to prior empirical studies as primary studies, although we note that they analyze secondary data.

studies. Bruns, Gross, and Stern (2014) also control for the tendency to over-fit vector autoregression models in small samples. This “overfitting bias” exaggerates the level of significance of Granger causality tests. They report that 40% of studies find causality in at least one of the two directions. However, they do not find a genuine causal effect of energy on GDP, or *vice versa*, in the literature as a whole. They conclude that the large number of seemingly statistically significant results is probably the result of overfitting and publication bias. They do, however, find a robust effect from output to energy use when energy prices are controlled for.

Bruns, Gross, and Stern’s study covers many primary studies that use electricity rather than total energy, but they do not test whether these studies specifically differ from others. Furthermore, they determined that there had been too few Granger causality studies using quality-adjusted energy – a measure that reflects the higher productivity of electricity – to test for a genuine relationship between quality-adjusted energy and economic growth.

There would seem to be scope, therefore, to conduct a new meta-analysis of studies looking at the effect of electricity on economic growth and testing for the presence of a genuine effect. But even a well-conducted meta-analysis would probably not provide much clarity. As most primary studies omit other energy sources, omitted-variable bias is likely to be more prevalent in studies that focus on the effect of electricity on economic growth than in the more general energy-GDP literature. Bruns and Gross (2013) demonstrate that studies that test the effect of electricity on GDP and omit other energy sources may simply pick up the effect of all energy on economic growth.

Even in well-implemented Granger causality studies, detecting a significant effect of electricity on GDP is likely to be difficult. One reason is that the effect size is likely to be much smaller than that of GDP on electricity. In the data presented in Figure 5, the average ratio of the value of electricity to GDP is 0.046 and so the output elasticity of electricity is likely to be of this order.[8] On the other hand, the income elasticity of electricity is around 1.[9]

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[8] If we assume that firms use electricity so that the value of its marginal product is equal to its price and we assume constant returns to scale, then the elasticity of gross output with respect to electricity would be equal to its share in the total costs of primary and intermediate inputs.

[9] Using the growth rates method, we estimated the regression slope of electricity on GDP as around 1.176 (Table 1). Due to reverse causality and omitted variables bias this may be a biased estimate of the true effect of GDP on energy use, but the bias is not likely to be that large (Csereklyei and Stern, 2015).

Given these magnitudes it will likely be hard to accurately detect the effect of electricity on economic growth using short and noisy time series, for which statistical power is low.

Electricity use may change for various reasons, each of which has different implications for GDP. Energy efficiency improvements should reduce electricity use and increase GDP, while reductions in electricity use due to price increases should reduce GDP. Changes in prices also affect GDP through more than one channel, as discussed above. Disentangling these effects seems to require structural models rather than the reduced-form approaches that have characterised this literature to date.

6. Effects of Infrastructure and Supply Quality on Economic Growth and Development

There is a large empirical literature analysing the effect of various types of infrastructure on macroeconomic performance. Identifying macroeconomic effects is challenging because provision of electricity infrastructure is likely to be correlated with other variables, including water, transport, and telecommunications infrastructure; electricity infrastructure is typically built in the expectation that there will be demand for it, meaning that a reverse causality challenge is likely to exist; and there are likely to be lags of varying length between improved electricity infrastructure and any economic dividends. Here, we focus on studies that adhere to a relatively high methodological standard that can address these issues.

We collected all papers cited in the reviews by Bacon and Kojima (2016), Attigah and Mayer-Tasch (2013), and Straub (2011), as well as all articles that cite these reviews according to *Google Scholar*. We further used the combination of keywords “growth” or “development” with either “electricity”, “infrastructure”, “outages”, or “blackouts” in *Google Scholar*. We then excluded studies that were not relevant; that we judged did not adequately address key issues such as considering other types of infrastructure; that were not published in refereed journals; or that used monetary rather than physical measures of infrastructure, as these may be less accurate due to valuation challenges. Table 3 provides an overview of these studies. We highlight the most relevant results in each.

Our search selected three country-level studies, two of which use panel data and one that uses cross-sectional data. The most recent is that of Calderón, Moral-Benito, and Servén (2015), who find a positive and significant long-run effect of infrastructure on GDP. They measure infrastructure using an index, one component of which is electricity generation capacity. Multiplying their elasticity of output with respect to infrastructure with the index weight given to log electricity generation capacity results in an elasticity of GDP with respect to electricity generation capacity of around 0.03. They cannot reject the null that infrastructure is weakly exogenous, which helps to assuage reverse causality concerns.

An earlier study by Calderón and Servén (2010) included an index of infrastructure quality in addition to the quantity index. They found positive and significant effects on economic growth for both variables. The implied elasticity of GDP with respect to electricity generation capacity is around 0.07. The implied elasticity of GDP with respect to the percentage of transmission and distribution losses in the production of electricity is –0.050.[10] They also found negative effects of electricity infrastructure quantity and quality on income inequality.

Andersen and Dalgaard (2013) analyse the effect of electricity quality on economic growth in Sub-Saharan Africa. Using lightning strikes to instrument outages, they conclude that a 1% increase in outages per month leads to a 0.018 percentage point reduction in the rate of annual economic growth. Given that the standard deviation of log outages per month is 0.85, this implies very large changes in the economic growth rate due to outages: a one standard deviation increase in outages is associated with a reduction in the rate of annual economic growth of 1.5 percentage points.

We identified two high quality studies that analyse the effect of electricity infrastructure on economic performance at a highly aggregated level within a country. Urrunaga and Aparicio (2012) find an output elasticity with respect to installed electric power of about 0.1 for a panel of regions in Peru. Using data for a panel of 15 Indian states over 1965–1984, Rud (2012) found that one additional agricultural electricity connection per thousand people is associated with an increase in manufacturing output per capita of around 2–3%. Rud used groundwater availability as an instrument for electrification, arguing that demand for electricity to power groundwater pumps explains differences in the rate of electrification across states, and in a way that is relatively exogenous to the manufacturing sector.

[10] To compute the first elasticity, we multiply the coefficient of infrastructure quantity (2.193) with the weight of electricity generation capacity used in constructing the index (0.613). As the dependent variable is the average annual growth of GDP per capita of a 5-year period expressed in percent, we divide by 100 and multiply by 5 to obtain the elasticity. As this is a dynamic model, the long-run elasticity will be higher. The elasticity for electricity quality is calculated analogously, though we added a negative sign, as the percentage of transmission and distribution losses in the production of electricity was rescaled with higher values indicating better quality.

These five studies suggest that electricity infrastructure facilitates economic growth. However, methodological challenges remain. The two studies by Calderon and colleagues do not measure the effect of electricity infrastructure itself, instead using an infrastructure index, of which electricity infrastructure is just one component. Additionally, some of the studies use difference and system GMM, techniques that may suffer from problems caused by weak instruments (Bun and Windmeijer, 2010; Bazzi and Clemens, 2013).

7. Case Studies of Electrification Success Stories

7.1 Countries with Relatively Low GDP per Capita in 1971

One way to learn about the role of electricity in economic growth is to study historical success stories. We focus on countries that, from a low economic base in 1971, have since achieved near-universal electricity access, noting that the majority of electricity generation capacity in developing countries has been installed since 1971 (US Energy Information Administration [EIA], 2016). We selected countries satisfying each of the following:

(a) GDP per capita was less than $2,500 in 1971 (in year-2011 US$, PPP);

(b) electricity access rate as reported by the International Energy Agency (IEA, 2016a) exceeded 95% in 2014;

(c) electricity use exceeded 1 megawatt hour (MWh) per capita in 2014; and

(d) population exceeded 1 million people in 2014.

Six countries meet these criteria, and are listed in Table 4. Four are in East Asia. Our list excludes some countries that have achieved impressive electricity access outcomes, such as Brazil, because we are focusing on those that worked off a particularly low income base as of 1971.

Common characteristics of the success stories are that universal access to electricity has been a key national objective, that national governments have played central roles in electricity sector investment and planning, and that there has been strong participation from local governments and communities (Niez, 2010; Bhattacharyya, 2012; van Gevelt, 2014). Each of the success stories experienced relatively rapid growth in real GDP per capita over 1971–2014. South Korea is now a high-income economy, and China is the world's largest economy in PPP terms. We next briefly describe the experiences of the electrification success stories and review evidence of development dividends resulting from this success.

South Korea: In 1965, only 12% of rural households had access. A concerted electrification program saw this increase to 98% by 1979 (van Gevelt, 2014). van Gevelt (2014) reports that large improvements in the quality of life were seen, with rural household incomes increasing at a real annual average rate of 27% in the 1970s. Electricity has underpinned the development of modern manufacturing and services sectors.

China: Rural electricity access is reported to have reached 61% by 1978, although the quality and quantity of supply was limited (Bhattacharyya and Ohiare, 2012). A large-scale investment program brought rural electricity access to 97% by 1997 (Bhattacharyya, 2012). Improvements in the reliability of supply were also achieved (Peng and Pan, 2006). Yang (2003) found that provinces with greater investment in rural electricity infrastructure experienced faster poverty reduction and higher incomes.

Thailand: In the early 1970s, only around 10% of households outside the Bangkok Metropolitan Region had access to electricity (Global Network on Energy for Sustainable Development, 2016). In 1973, Thailand launched a National Plan for Accelerated Rural Electrification with the aim of extending electricity access to all villages. Thailand has since achieved near universal electricity access. Thailand's economy has also undergone a major transformation, with extreme poverty falling to close to 0% as measured using the 2011 PPP $1.90 a day poverty line (World Bank, 2016b). Now an upper-middle income economy, the World Bank (2016c) refers to Thailand as "one of the great development success stories". We did not find any research specifically linking development outcomes in Thailand to electrification.

Egypt: Egypt experienced impressive progress in electricity access in the second half of the 20th Century, reaching an access rate of around 96% by 1995 (World Bank, 2016b) and 99% by 2014. Loayza and Odawara (2010, p. 2) concluded Egypt's electricity infrastructure has "undoubtedly supported the relatively strong economic growth performance of the country". Egypt scores poorly in terms of the quality of electricity supply, however. The International Monetary Fund (IMF, 2015, p. 5) has brought attention to a growing "infrastructure deficit" in Egypt's electricity sector.

Paraguay: Paraguay shares the large Itaipú and Yacyret hydroelectric facilities with Brazil and Argentina, allowing it to become the world’s fourth-largest exporter of electricity (US EIA, 2016). Electricity access reached 93% by 2000 (World Bank, 2016b) and 99% by 2014. Paraguay underperforms in terms of the quality of electricity supply. Paraguay’s economic growth has been relatively impressive in recent years, with an average annual real GDP per capita growth rate of 3.9% over 2001–2014.[11]

Vietnam: In one of the world’s most successful electrification programs, Vietnam increased access from below 5% in the mid-1970s (IEA, 2011) to 98% by 2014. Vietnam has also made remarkable development progress, reducing extreme poverty from around half of the population in the early 1990s to 3% in 2014 (World Bank, 2016b). Benefits of rural electrification have included higher incomes, boosted school enrolment, and timesavings from the use of appliances such as rice cookers (Khandker, Barnes, and Samad, 2013).

7.2 Sub-Saharan Africa

None of the success stories in Table 4 are in Sub-Saharan Africa, where it is estimated that only 35% of households had electricity access in 2014, far below other regions (IEA, 2016a). The region also performs poorly in terms of electricity quality. The IEA (2014, p. 13) concluded that “a severe shortage of essential electricity infrastructure is undermining efforts to achieve more rapid social and economic development”, while Foster and Briceño-Garmendia (2010, p. 5) describe electricity as “Africa’s largest infrastructure challenge”. Andersen and Dalgaard (2013) conclude that electricity outages have slowed economic growth in the region and Moyo (2013) finds they reduce the productivity of manufacturers. Table 5 lists the top three Sub-Saharan African countries in terms of electricity access, restricting our focus to countries with a 2014 population exceeding one million.

Gabon: The top-ranking country is Gabon, which had an access rate of 89% in 2014, although coverage outside urban areas is limited, and the quality of supply is poor. Gabon is an oil-rich upper-middle income country.

South Africa: Electricity access has increased to 86%, from only 30% in 1993 (Bhattacharyya, 2013). While respondents to a 2009 survey indicated that electricity had benefited their

[11] This and subsequent GDP growth rates use national accounts data from Feenstra, Inklaar, and Timmer (2015). As in the case of Thailand, we did not find any sources that specifically link development outcomes in Paraguay to electrification.

communities through channels such as the ability to start a small business (65% of households) and improved security (42%), Niez (2010) concludes that electricity has not been sufficient to generate economic growth in rural areas. Other infrastructure is also important, as is the quality of electricity supply. South Africa has recently experienced electricity shortages and blackouts, with the World Bank (2016d, p. 154) concluding these “weighed heavily” on economic growth. The IMF (2016) estimates that electricity constraints reduced South Africa’s economic growth by 0.5 percentage points in 2015.

Ghana: Electricity access was 72% in 2014, up from 28% in 1988 (Kemausuor et al., 2011). However, unreliability of electricity supply is frequently cited as a constraint to economic growth (US Government and Government of Ghana, 2011; World Bank, 2013, 2016d; IMF, 2014). 52% of enterprises were reported to own or share a generator in 2013 (World Bank, 2016e). In 2014 only 42% of households could be classed as having reliable grid access (Oyuke, Penar, and Howard, 2016).

There are some low-income Sub-Saharan African countries where a positive association between electricity availability and GDP is observable. Ethiopia, for example, had electricity access of only 13% in 2000 (World Bank, 2016b). Access increased to 25% by 2014 and per capita electricity use tripled (IEA, 2016a, 2016b), though was still only 70 kWh per capita per year. This progress coincided with a decade-long boom during which Ethiopia maintained average annual growth in real GDP per capita of 8.0% (data for 2004–2014). The World Bank (2016f, p. 29) concludes that investment in infrastructure in the electricity, transport, communications, and other sectors has been the “key structural driver” of Ethiopia’s boom. Ethiopia is currently building the largest hydroelectricity facility in Africa, the Grand Ethiopian Renaissance Dam.

There are countries that have recorded strong economic growth despite little progress in electricity access. This is particularly likely when economic output is concentrated in enclave activities such as fossil fuel extraction. Chad provides an example. Only 4% of Chad’s population had access to electricity in 2014 (IEA, 2016a). Per capita electricity use was reported to be a tiny 14 kWh in 2014, only slightly up on the 9 kWh recorded in 1980 (US EIA, 2016). Nevertheless, Chad has maintained an average per capita GDP growth rate of 6.0% per annum over 2000–2014. Chad’s economic growth has been quite narrowly focused on oil extraction. Extraction commenced in 2003, and oil rents equalled one-fifth of Chad’s GDP in 2014 (World Bank, 2016b). The development dividends of Chad’s oil boom have been limited; the country ranked 185th out of 188 in the United Nations Development Programme's (2015) Human Development Index.

Country case studies from Sub-Saharan Africa thus provide some evidence of inadequate electricity access and quality hindering economic growth. Countries with better access to electricity tend to have higher incomes, in line with the general pattern observed in Figure 2. Ethiopia provides an example of a low-income African country where improvements in electricity access have coincided with rapid economic growth. The case of Chad demonstrates that electricity is not strictly necessary for GDP growth when growth is from a concentrated source. *Broad-based* economic growth is more likely to rely on widespread access to electricity.

8. Conclusions and Future Research Priorities

While electricity access is likely not sufficient for economic growth, the data show that electricity use and GDP tend to go hand-in-hand. Theory also suggests that electricity access is likely to be an important enabler of economic growth. However, our review found limited empirical research of a high methodological quality, especially in terms of establishing causal effects. We found that the time series literature on electricity use and economic growth, though large, is mostly inconclusive, and also that further meta-analyses or time series studies of the existing type would probably not be productive. Instead, estimation of structural models that can isolate and identify different channels of influence would be helpful. We found few methodologically strong studies on electricity infrastructure and economic growth, with key studies not specifically identifying the effect of electricity infrastructure. While case studies of success stories are suggestive, firm conclusions on the role of electricity in economic development would benefit from more rigorous statistical evidence.

The main challenge for empirical work in this field is finding exogenous variation in the variable of interest in order to identify causal effects. Leading approaches for identifying causal effects from observational data include instrumental variable techniques, difference in differences methods including the synthetic control approach (Abadie, Diamond and Hainmueller, 2010), and some time series techniques such as structural vector autoregressions. We do not wish to be overly prescriptive on techniques, but instead sketch the key questions for which more evidence is needed. The specific priority questions that we have identified are:

1. *What is the effect of electricity supply disruptions on economic growth?* The potentially large role for electricity reliability found by Andersen and Dalgaard (2013) and suggested by several of the case studies warrants further investigation. The key challenge is to identify the causal effect of reliability on economic growth. Major one-time exogenous failures would quite likely have different effects on economic growth than routine problems.

2. *Does electricity sector success boost economic success?* There is scope for the roles of electricity access in generating economic growth and development to be further examined using systematic econometric analsyis of cross-country comparative datasets. Emphasis should be placed on distinguishing between short- and long-run effects. Impacts on a variety of development outcomes could be explored.

3. *How robust is the effect of electricity infrastructure on economic growth?* Recent studies use infrastructure indices that make it difficult to identify the specific contribution of electricity infrastructure to economic growth (e.g. Calderón, Moral-Benito, and Servén, 2015). The effect of electricity infrastructure could be tested directly, while an index of other types of infrastructure is used as a control. It is of interest to assess the relative effects of different types of infrastructure in order to help policy makers and donors prioritize. Robustness could be assessed by systematic sensitivity analysis with respect to the variables that are used to measure infrastructure (Bacon and Kojima, 2016).

4. *Are the key findings in the electricity-growth literature replicable*? Recent studies show a rather low rate of replicability for experimental research in economics (Camerer et al., 2016) and psychology (Open Science Collaboration, 2015; Klein et al., 2014). Ensuring the replicability of key studies would strengthen the basis for evidence-based policy making. Replication studies could include sensitivity analyses with respect to alternative estimation procedures. Key studies that could be considered for replication analyses include Calderón, Moral-Benito, and Servén (2015) and Rud (2012).

5. *How can electricity be a "binding constraint" on economic growth*? The goal would be to build a theoretical (and simulation) model of the potential role of electricity access challenges in constraining economic growth. Is it necessary to assume that institutional deficiencies limit the development of electricity infrastructure development as in the "barriers to riches" (Parente and Prescott, 2000) approach to underdevelopment? Or can

the low short-run profitability of electricity infrastructure result in an equilibrium of little investment and little resulting economic growth?

6. *Can a new generation of time series models better identify the role of energy in economic growth?* Existing time series models are unlikely to provide robust conclusions, but a new generation of structural vector autoregression time series models that identify different factors that drive changes in energy use might. These could be used to identify the effect of increased energy use on economic growth in the face of technological change that both reduces energy requirements and boosts economic growth.

Appendix: Data Sources

URLs for the various data sources are given in the reference list. See the notes to Table 4 for additional information.

Penn World Table 9.0

Per capita GDP data are from Penn World Table version 9.0, measured in constant 2011 international dollars. As recommended by Feenstra, Inklaar, and Timmer (2015), our analysis in Section 4 uses the $CGDP^{O}$ variable for cross-sectional comparisons and the $RGDP^{NA}$ variable for growth rates. The growth rate of $RGDP^{NA}$ is based on the growth rate of GDP in each country's national accounts.

World Bank: Doing Business

We obtain data on electricity prices, reliability, and connection costs from World Bank (2016a). The 2016 report gives data for the price of electricity supplied to a standard warehouse in 2015 and 2016 in specific cities in each country included in the survey as well as a set of indicators on the cost of an electricity connection to a standard warehouse and electricity reliability. The 2010–14 reports give data on costs of a connection but do not provide the other variables. Where more than one city in a country is reported, we have used the average of the electricity prices of the named cities. The cost of connection is given as a share of income per capita. We convert to USD at market exchange rates by multiplying by nominal GDP per capita in USD at market exchange rates. Electricity prices often vary considerably across consumer groups. Our use of the electricity price paid by a standard warehouse means that our measures of the value of electricity (i.e. price*quantity) and the cost of electricity (which also includes subsidy spending) are proxies.

The denominator of the electricity "cost share" is nominal GDP in U.S. Dollars at market exchange rates from the *World Development Indicators*. The numerator is the 2015 price per kWh multiplied by the quantity of electricity consumed in 2014. For the subsidy-adjusted version we add the value of subsidies in billions of US dollars to the numerator. We used 2014 GDP for Iran and Mozambique.

World Economic Forum

World Economic Forum (2015) provides data on the quality of electricity supply on a scale of 1–7 (extremely unreliable to extremely reliable) from surveys of executive opinion.

IEA World Indicators

Electricity use data in TWh are taken from IEA (2016b). These data exclude transmission losses but include electricity used by the energy sector. The data often underestimate off-grid generation.[12]

UN Energy Statistics Database

We take installed generating capacity in MW for 1990–2013 from UN (2016).

US EIA International Energy Statistics

Installed generating capacity 1980–2012 are from US EIA (2016).

IMF Energy Subsidies Template

We use pre-tax subsidies for 2015 in calculating the electricity cost share variable. The data are available in a spreadsheet from:
www.imf.org/external/np/fad/subsidies/data/subsidiestemplate.xlsx

and described by Coady et al. (in press).

World Development Indicators

We sourced the following variables from World Bank (2016b):

- Electricity access (% of households). We only use data points from surveys, excluding estimated or assumed data points.

[12] Personal communication with Nikolaos Kordevas, IEA.

- Power outages in a typical month, based on data from the World Bank Enterprise Surveys.
- Birth rate, crude (per 1,000 people).
- Fertility rate, total (births per woman).
- Population growth (annual %).
- Death rate, crude (per 1,000 people).
- Poverty headcount ratio at $3.10 a day (2011 PPP) (% of population).
- Poverty headcount ratio at $1.90 a day (2011 PPP) (% of population).
- Poverty headcount ratio at national poverty lines (% of population).
- Gini index (World Bank estimate).
- Low-, (lower/upper) middle-, high-income groupings. These are the current designations used by the World Bank (2016b). We use “developing countries” to refer to low and middle income countries.

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Table 1. Regression Analysis

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable	ln electricity use per capita				Growth rate of electricity use per capita (annual average)		
Country group	All	Developing	All	Developing	All	All	Developing
Countries	136	86	105	63	105	105	63
Year/period	2014	2014	1971	1971	1971–2014	1971–2014	1971–2014
ln GDP per capita	1.345	1.305	1.419	0.969			
	(0.066)	(0.085)	(0.121)	(0.268)			
Growth rate of GDP per capita (annual average)						1.176	0.950
						(0.099)	(0.077)
ln Electricity use per capita, 1971					-0.011		
					(0.001)		
Constant	-5.004	-4.719	-5.705	-2.442	0.108	0.011	0.023
	(0.604)	(0.793)	(1.087)	(2.077)	(0.013)	(0.005)	(0.004)
Buse R^2	0.839	0.754	0.785	0.323	0.610	0.694	0.781

Note: Developing countries include all low and middle income countries according to the World Bank Development Indicators in 2016. Robust standard errors in parentheses. Regressions are estimated using weighted least squares with weights equal to the square root of population so that the error variance is assumed to be proportional to the inverse of population. We use Buse's (1973) goodness of fit statistic.

Table 2. Correlation Analysis

	ln GDP per capita, 2014	GDP per capita growth rate, 2004–2014 (annual average)	ln electricity use per capita, 2014	Electricity access (% of population), 2010 or 12
GDP per capita growth rate, 2004–2014 (annual %)	-0.05			
ln Electricity use per capita, 2014	0.93	-0.33		
Electricity access (% of population), 2010 or 2012	0.84	0.34	0.82	
Generating capacity per capita (watts), 2013	0.71	-0.22	0.77	0.63
Connection cost (% of income per capita), 2015	-0.67	-0.11	-0.61	-0.68
Connection cost (US$), 2015*	-0.21	-0.09	-0.26	-0.31
Price of electricity (US cents per kWh), 2015	-0.17	-0.31	-0.17	-0.22
Value of electricity/GDP, 2014/2015	-0.08	0.00	0.15	0.34
Subsidy adjusted cost of electricity/GDP, 2014/2015	-0.26	0.04	-0.01	0.08
WEF Quality of electricity supply, 2015	0.84	-0.21	0.80	0.58
Time for a connection (days), 2015	-0.32	0.04	-0.18	-0.19
Gini index (World Bank estimate)**	-0.34	-0.17	-0.35	-0.20
Poverty headcount ratio at $3.10 a day (2011 PPP) (% of population)**	-0.84	-0.22	-0.80	-0.83
Birth rate, crude (per 1,000 people), 2013	-0.80	0.05	-0.78	-0.81
Death rate, crude (per 1,000 people), 2013	-0.27	0.00	-0.10	-0.42
Fertility rate, total (births per woman), 2013	-0.76	0.00	-0.74	-0.81
Population growth (annual %), 2013	-0.30	-0.03	-0.28	-0.53

* Multiplies World Bank 2015 connection cost as share of income per capita data by 2014 GDP per capita data in US Dollars at market exchange rates.

** Data for various years from 1995 to 2013, with an average date of 2010.

*** Approximate critical values (these values and above are significant at the stated level) for a one-tailed test: 10% significance level: ±0.13; 5%: ±0.15; 1%: ±0.2; 0.5%: 0.21. Double the probabilities for a two sided test.

Table 3. Electricity Infrastructure and Macroeconomic Performance: Overview of studies

Authors	Data	Empirical strategy	Dependent variable	Key explanatory variable	Key finding
Andersen and Dalgaard (2013)	Cross section of 39 countries in Sub-Saharan Africa over 1995–2007	Lightning density is used to instrument outages	Average annual growth rate of GDP over the period 1995–2007	Number of outages in a typical month	Increase of outages by 2.3 per month leads to a reduction in annual economic growth of about 1.5 percentage points
Calderón, Moral-Benito, and Servén (2015)	Panel of 88 countries over 1960–2000; annual data	Estimation of production function; identification by finding one cointegrating vector and weak exogeneity of inputs	GDP per worker	Index of infrastructure quantity (first principal component of electricity generation capacity, number of main telephone lines, and total length of the road network)	Output elasticity of electricity generation capacity of around 0.03

Calderón and Servén (2010)	Unbalanced panel of 97 countries over 1960–2005; non-overlapping 5-year averages	Estimation of growth regressions with various control variables; identification by using system GMM-IV with both internal instruments and external instruments (urban population, labour force, and population density)	Growth of GDP per capita (annual average percent over 5 years)	Index of infrastructure quantity (first principal component of electric power-generating capacity, total telephone lines, and length of the road network) and index of infrastructure quality (first principal component of waiting time for the installation of main telephone line, percentage of transmission and distribution losses in the production of electricity, and share of paved roads in total roads)	Implied output elasticity of power-generating capacity and percentage of transmission and distribution losses of around 0.07 and –0.05, respectively
Urrunga and Aparicio (2012)	Panel of 24 regions of Peru over 1980–2009	Estimation of production function; identification by internal instruments using difference and system GMM	Growth of GDP per capita	Installed electric power	Output elasticity of installed electric power of around 0.1
Rud (2012)	Panel of 15 Indian states over 1965–1984; annual data	Effect of electrification on manufacturing output is identified by using groundwater as an instrument	Manufacturing output	Agricultural units connected to the electricity network per 1,000 people	Positive and significant coefficient for electrification variable

Table 4. Electricity Access Success Stories Among Countries with Relatively Low Incomes in 1971

Country	Electricity use per capita (kWh)			GDP per capita (PPP, 2011 US$)			Electricity access (% of population)	Quality of electricity supply
	1971	2014	Average annual growth rate (%)	1971	2014	Average annual growth rate (%)	2014	2014
South Korea	296	10,564	8.7	2,396	35,104	6.4	100	5.7
China	152	3,927	7.9	1,342	12,473	5.3	100	5.3
Thailand	120	2,566	7.4	2,276	13,967	4.3	99	5.2
Egypt	203	1,699	5.1	1,046	9,909	5.4	99	3.5
Paraguay	82	1,563	7.1	2,083	8,284	3.3	99	3.3
Vietnam	41	1,439	8.6	803	5,353	4.5	98	4.1

Note: Electricity use data are from the IEA (2016b). GDP is $RGDP^e$ from Feenstra, Inklaar, and Timmer (2015). Electricity access data are as collected and/or estimated by the International Energy Agency (IEA, 2016a) or, for South Korea, by the World Bank (2016b). The quality of electricity supply scores are the 2014–2015 weighted averages from a survey of business executives that asks: "*In your country, how would you assess the reliability of the electricity supply (lack of interruptions and lack of voltage fluctuations)? (1 = not reliable at all; 7 = extremely reliable)*" (World Economic Forum, 2015). 1971 data are not available for electricity access or quality of electricity supply. Countries are ordered by electricity access rate in 2014, then electricity use per capita in 2014. Our scope is limited to the 105 developing countries for which electricity access data are available from the IEA (2016a), plus South Korea. There are data uncertainties for each series. kWh = kilowatt hour.

Table 5. Sub-Saharan Africa's Electricity Access Success Stories

Country	Electricity use per capita (kWh)			GDP per capita (PPP, 2011 US$)			Electricity access (% of population)	Quality of electricity supply
	1971	2014	Average annual growth rate (%)	1971	2014	Average annual growth rate (%)	2014	2014
Gabon	186	1,303	4.6	6,042	14,161	2.0	89	2.5
South Africa	2,246	4,240	1.5	7,807	12,128	1.0	86	2.9
Ghana	313	357	0.3	2,812	3,570	0.6	72	2.2

Note: Shows the three countries with the highest electricity access rates and populations exceeding 1 million in 2014. See Table 4 for details.

Figure 1. Per Capita Electricity Use and GDP (2014)

Figure 2. Electricity Access (c. 2012) and GDP per Capita (2014) for Developing Countries

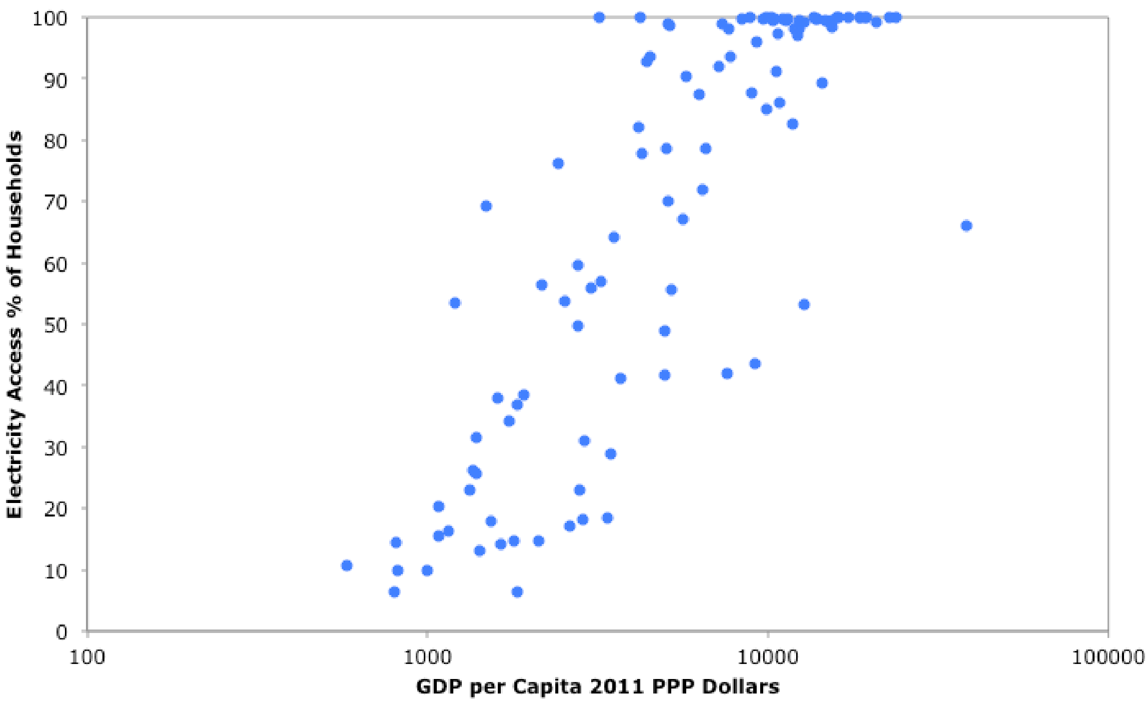

Figure 3. Reliability of Electricity Supply (2015) and GDP per Capita (2014)

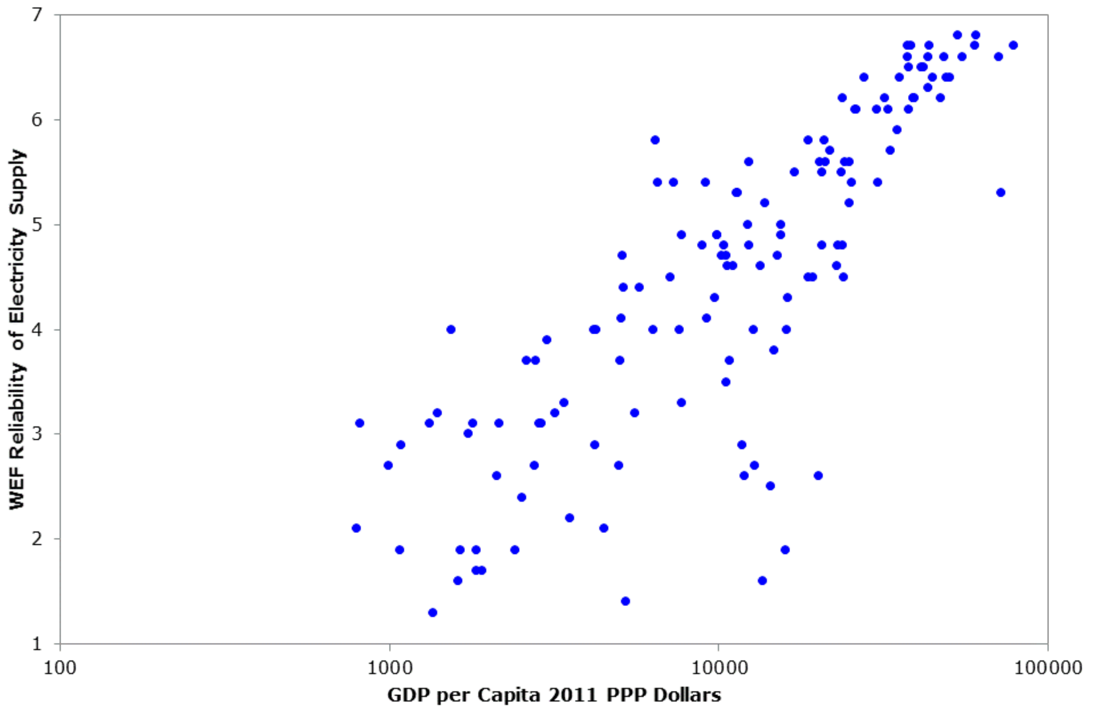

Figure 4. Connection Cost (2014) and GDP per Capita (2014)

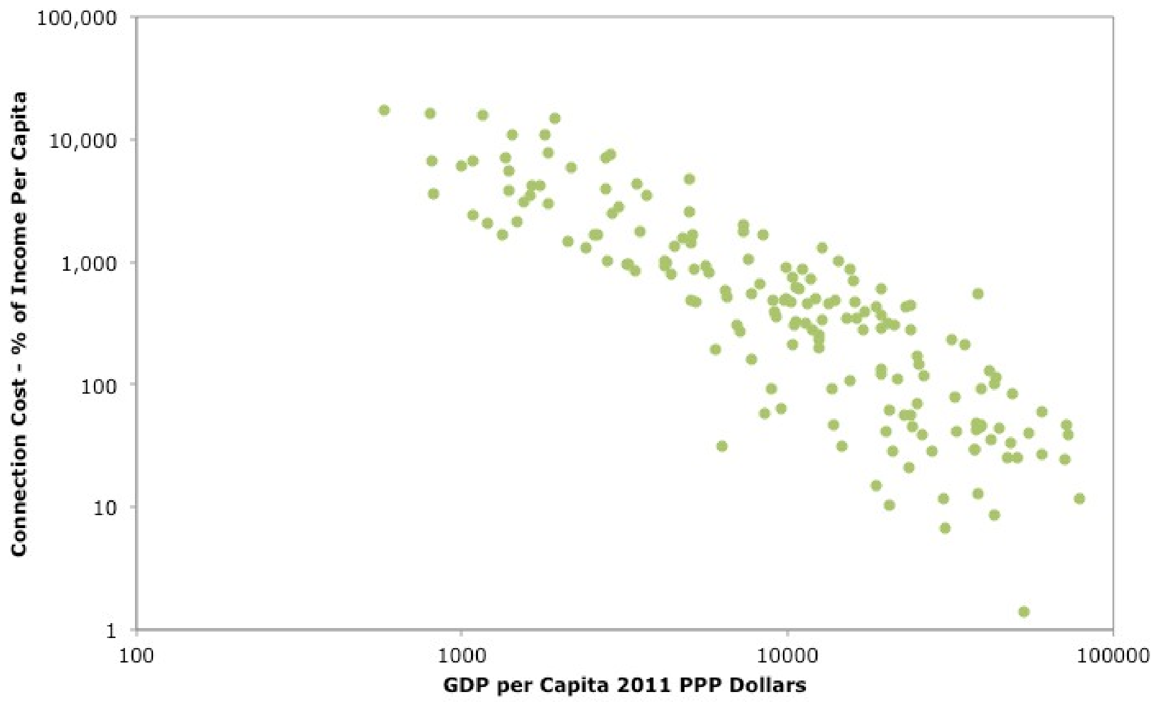

Figure 5. Value of Electricity Divided by GDP (2014)

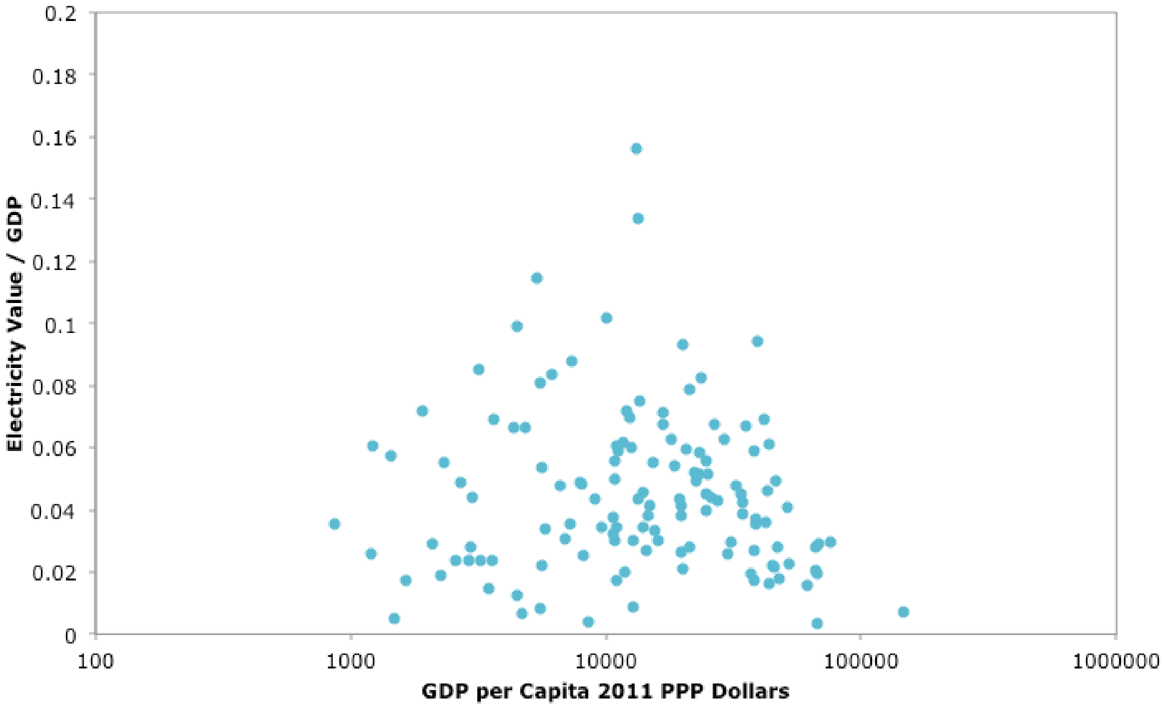

Figure 6. Cost of Electricity Including Pre-Tax Subsidies Divided by GDP (2014)