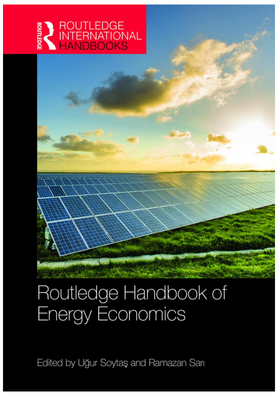

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Energy and economic growth

David I. Stern

1 Introduction

Figure 2.1 shows that energy use per capita increases with GDP per capita, so that richer countries typically use more energy per person than poorer countries. The slope of the logarithmic regression line implies that a 1% increase in income per capita is associated with a 0.7% increase in energy use per capita (Csereklyei et al., 2016). This means that energy intensity is on average lower in higher-income countries (Figure 2.2). These relationships have been very stable over the last several decades (Csereklyei et al., 2016). Energy intensity (energy used per dollar of GDP) in today's middle-income countries is similar to that in today's developed countries when they were at the same income level (van Benthem, 2015).

Mostly as a result of countries' energy intensity decreasing as they get richer, global energy intensity has decreased over time (Figure 2.3). However, global energy use per capita has increased over time, and when we also take population growth into account, total energy use has risen strongly. Between 1971 and 2010, total world energy use increased by about 140% while total GDP increased by 270%, and population by 80%.

Energy intensity has also converged across countries over time, so that countries that were more energy-intensive in the 1970s tended to reduce their energy intensity by more than less energy-intensive countries, and the least energy-intensive countries often increased in energy intensity (Figure 2.4). Though data are limited to fewer and fewer countries as we go back further in time, these relationships also appear to hold over the last two centuries: energy use increased, energy intensity declined globally, and countries converged in energy intensity (Csereklyei et al., 2016).

The next section of this chapter examines the factors that might lead to lower energy intensity with higher GDP and convergence in energy intensity, as seen in Figures 2.2 to 2.4. I then review the literature on the theoretical relationship between energy and economic growth. The penultimate section looks at the empirical evidence on the question of whether changes in energy use cause changes in GDP or vice versa. Concluding remarks point to the main gaps in our knowledge.

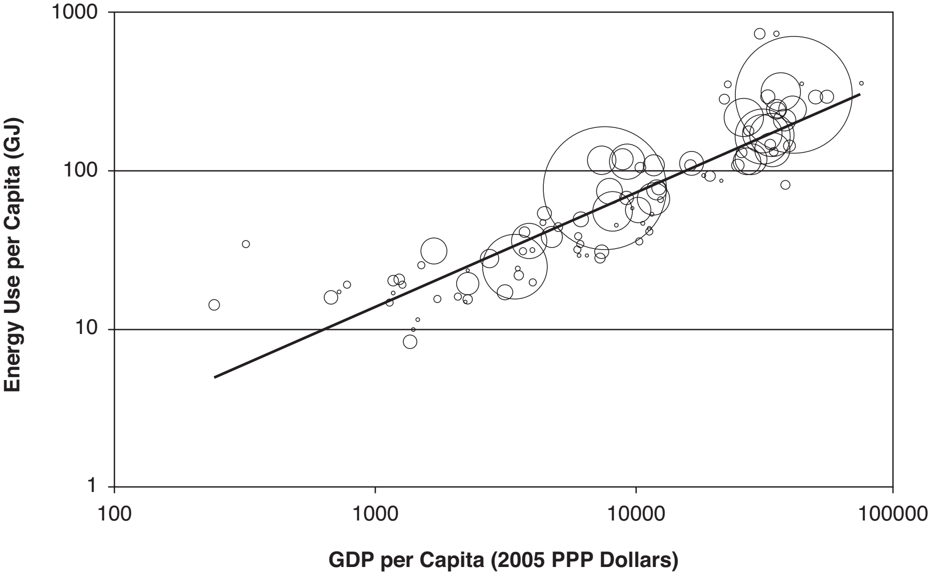

Figure 2.1 Energy consumption per capita and GDP per capita 2010

Note: Bubbles are proportional to total energy use. The two largest circles are the United States at upper right and China in the middle.

Source: International Energy Agency and Penn World Table 7.1.

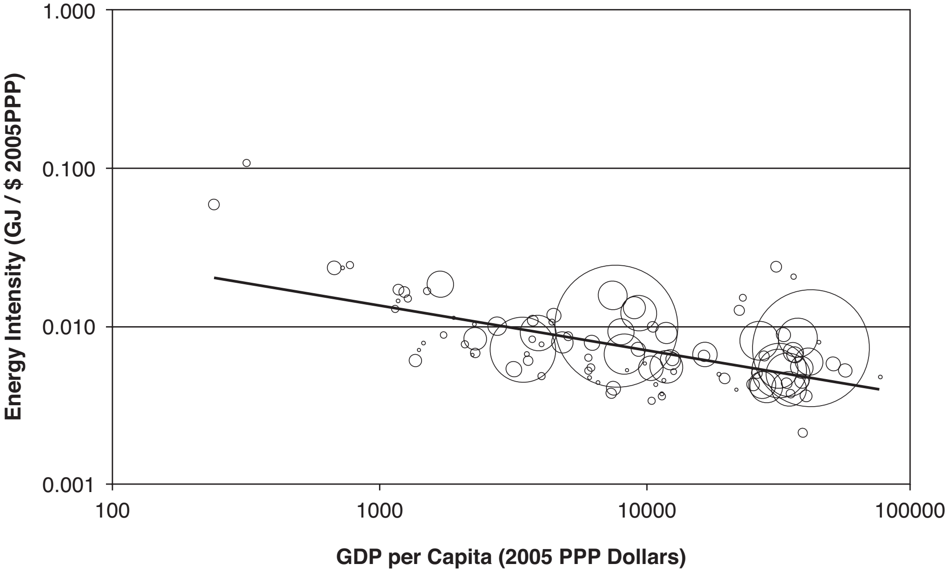

Figure 2.2 Energy intensity and GDP per capita 2010

Note: Bubbles are proportional to total energy use. The two largest circles are the United States at lower right and China in the middle.

Source: International Energy Agency and Penn World Table 7.1.

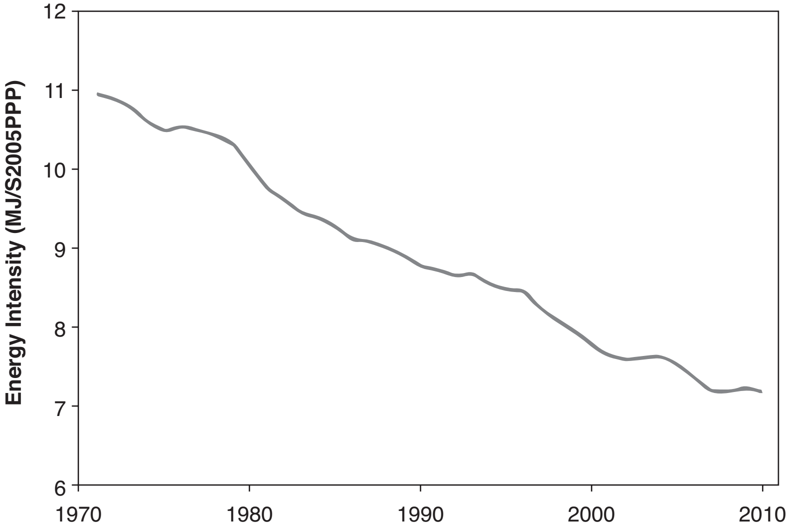

Figure 2.3 Global energy intensity

Source: International Energy Agency and Penn World Table 7.1.

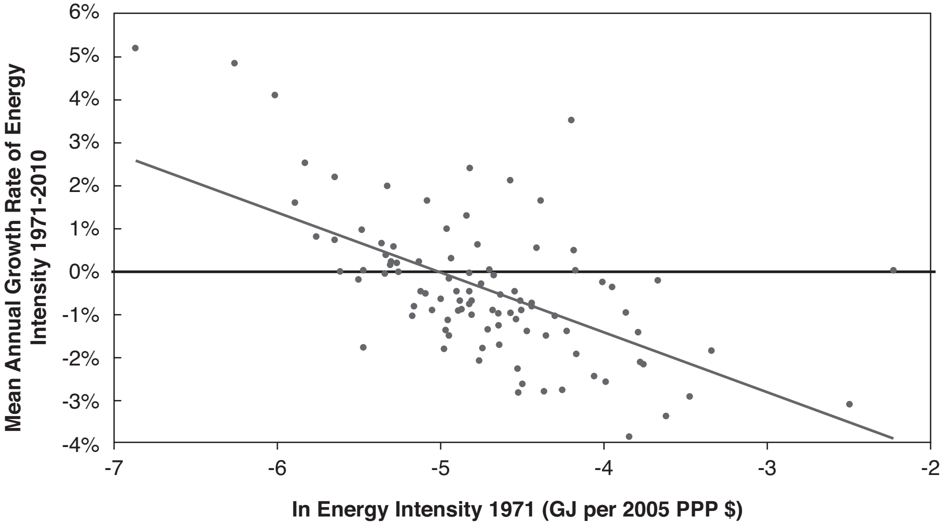

Figure 2.4 Convergence of energy intensity

Source: International Energy Agency and Penn World Table 7.1.

2 Factors affecting the linkage between energy and GDP

2.1 Introduction

Why is energy intensity lower in richer countries and declining globally over time? We can use a production frontier approach to examine the factors that could affect the relationship between energy use and economic activity. Assuming separability between inputs and outputs and factor-augmenting technological change, a production function for multiple outputs can be written as:

$$\left(Q_1, \ldots, Q_M\right)' = f\left(A_{X1}X_1, \ldots, A_{XN}X_N, A_{E1}E_1, \ldots, A_{EP}E_P\right) \tag{2.1}$$

where $Q_1, \ldots, Q_M$ are various outputs, such as manufactured goods and services, $X_1, \ldots, X_N$ are various non-energy inputs such as capital and labor, $E_1, \ldots, E_P$ are energy inputs such as coal and oil, and the A_i are indices of the state of factor-augmenting technology. The relationship between energy and an aggregate of output such as GDP is then affected by:

- Substitution between energy and other inputs
- Shifts in the composition of the energy input
- Shifts in the mix of the other inputs
- Shifts in the composition of output
- Technological change
- Economies of scale.

I discuss each of these in turn, apart from shifts in the mix of other inputs and economies of scale, as these have not been discussed much in the literature. An important factor offsetting the effects of technological change is the rebound effect, which I discuss separately.

2.2 Substitutability of energy and capital

Koetse et al. (2008) conduct a meta-analysis of the (Morishima) elasticity of substitution (MES) between capital and energy for an increase in the price of energy. Their base case finds that the MES between energy and capital is 0.216, so that capital and energy are poor substitutes. The MES estimated using panel or cross-section data is greater – 0.592 and 0.848, respectively. It is likely that these larger values reflect long-run elasticities and the lower values short-run elasticities (Stern, 2012a), so that in the long run substitution of capital for energy could reduce energy intensity substantially. Stern (2012b) found that capital deepening reduced energy intensity by 7% globally from 1971 to 2007. On the other hand, Wang (2011) found that capital accumulation was the main driver of reduced energy intensity in China.

2.3 Energy quality and shifts in mix of energy inputs

Not all energy sources and fuels are of equal economic productivity. These differences in productivity are termed energy quality. Some fuels can be used for a larger number of activities and/or for more valuable activities. For example, coal cannot be used to directly power a computer, while electricity can. Some fuels, in particular electricity, can transform the workplace entirely and change work processes, thus contributing to productivity gains (Enflo et al., 2009). The productivity of a fuel is determined in part by a complex set of attributes unique to each fuel: physical scarcity, capacity to do useful work, energy density, cleanliness, amenability to storage, safety, flexibility of use, cost of conversion, and so forth. Fuel and energy quality are not necessarily fixed over time, as changes in technology in terms of both new techniques of production and new products and activities change the opportunities for using fuels. However, it is generally believed that electricity is the highest quality energy vector, followed by natural gas and oil, and then coal, wood, and other biomass in descending order of quality. This is supported by the typical prices of these fuels per unit of energy, which is one way of measuring relative energy quality (Stern, 2010).

The evolution of the energy mix over the course of economic development and over history in the technologically leading countries follows a typical pattern moderated by local energy endowments (Csereklyei et al., 2016). In the least developed economies, as in today's developed economies before the industrial revolution, the use of biomass and muscle power dominates. These energy sources decline in share with increasing income and over time. Direct use of coal tends to rise and then fall over time and with income. Increases in the share of oil and then natural gas follow. The share of electricity in total energy use tends to rise. Low-income countries tend to generate electricity from hydropower and oil, while high-income countries have more diverse power sources including nuclear power. Finally, electricity generated from solar and wind power are only now beginning to take off in more developed economies. Figure 2.5 illustrates this pattern for the United States.

Relatively few studies evaluate the role of the change in energy mix on energy intensity. Schurr and Netschert (1960), Berndt (1990), and Kaufmann (2004) argued that the shift in the composition of energy use towards higher quality energy inputs played a key role in reducing energy intensity in the United States. Other studies find, however, a much larger role for technological change than for changes in the composition of energy in the reductions in energy intensity seen around the world. For example, Ma and Stern (2008) find that interfuel substitution had negligible effects on the decline in energy intensity in China between 1994 and 2003. Stern (2012b) finds that between 1971 and 2007, changes in fuel mix within individual countries increased world energy use by 4% while global energy intensity declined by 40%. Shifts in the distribution of economic activity towards countries with lower quality energy mixes such as China and India contributed further to increasing energy intensity globally.

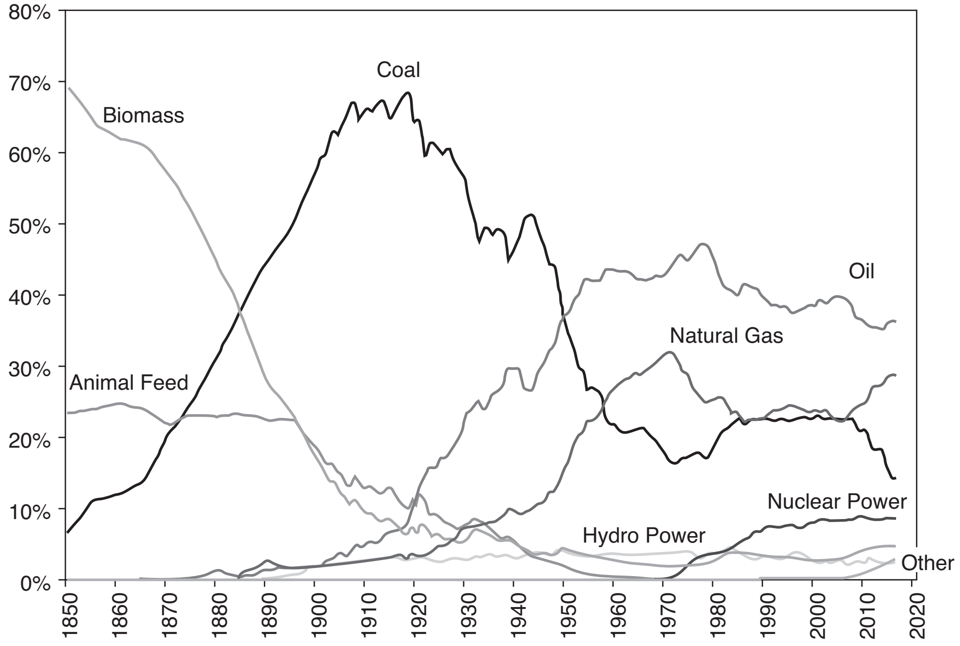

Figure 2.5 Shares of total US primary energy consumption 1850–2016

Source: US Energy Information Administration. Other includes solar, wind, and geothermal energy. Biomass includes wood, waste, and biofuels.

2.4 Shifts in the composition of output

Output mix also typically changes over the course of economic development. In the earlier phases of development, there is a shift away from agriculture towards heavy industry, while in the later stages of development there is a shift from the more resource-intensive extractive and heavy industrial sectors towards services and lighter manufacturing. It is often argued that this will result in an increase in energy used per unit of output in the early stages of economic development and a reduction in energy used per unit output in the later stages of economic development (Panayotou, 1993). However, the energy-saving effects of structural changes may be overstated (Henriques and Kander, 2010). The decline in the share of industry in GDP in developed countries is partly due to the decline in the relative price of industrial goods due to faster productivity increases in industry than in the service sector (Kander, 2005). Furthermore, when the indirect energy use embodied in manufactured products and services is taken into account, the service and household sectors are more energy-intensive than they first appear to be. Evidence also shows that trade does not result in significant reductions in energy use and pollution in developed countries through the offshoring of pollution-intensive industries (Levinson, 2010; Kander and Lindmark, 2006).

Kander (2002) and Stern (2012b) find a relatively small role for structural change in reducing energy intensity in Sweden (1800–2000) and the world (1971–2007), respectively. But, using a much finer disaggregation of industries, Sue Wing (2008) finds that structural change explained most of the decline in energy intensity in the United States (1958–2000), especially before 1980.

2.5 Energy efficiency and technological change

There are several ways of measuring changes in aggregate energy efficiency controlling for the other factors discussed above. The distance function approach measures the change in energy efficiency as the change in the minimum energy requirement to produce a given level of output. There are two main ways of measuring energy efficiency using this approach (Shen and Lin, 2017), neither of which obviously identifies a pure energy efficiency component. A second approach is to use an index of energy augmenting technical change. Based on Equation (2.1), the index of energy augmenting technical change can be constructed as:

$$A_E = \sum_{i=1}^{P} S_i A_{Ei} \tag{2.2}$$

where S_i are the shares of each type of energy in the total cost of energy. Change over time in this index can be computed using an index method such as Divisia aggregation. The actual energy augmentation indices need to be estimated econometrically. Bottom-up, engineering-based measurements of energy efficiency represent a third approach.

Estimates of trends in energy efficiency are mixed (Stern, 2011). The direction of change has not been constant and varies across different sectors of the economy. Judson et al. (1999) show that technical innovations tend to introduce more energy using appliances to households and energy saving techniques to industry. Stern (2012b) finds that energy efficiency improved from 1971 to 2007 in most developed economies, former communist countries including China, and India. But there was no improvement or a reduction in energy efficiency in many developing economies. Globally, such technological change resulted in a 40% greater reduction in energy use over the period than would otherwise have been the case and so was the most important driver of reduced energy intensity.

Changes in energy prices may induce endogenous technological changes, though only a fraction of historical improvements in energy efficiency have been due to increases in energy prices (Newell et al., 1999; Popp, 2002; Dechezleprêtre et al., 2011). According to the theory of directed technical change, it is the level of input prices rather than changes in input prices that determine the rate and direction of technical change (Acemoglu, 2008). New energy-using technologies initially diffuse slowly due to high costs of production that are typically lowered radically by a fairly predictable process of learning by doing (Grübler et al., 1999). Diffusion tends to follow a logistic curve with the speed of diffusion depending on among other things how well the innovation fits into the existing infrastructure. Energy-saving innovations such as LED lighting would be expected to diffuse rapidly once their price becomes competitive, while more radical innovations that require new support infrastructures diffuse much more slowly.

Research on the factors that affect the adoption of energy efficiency policies (Matisoff, 2008; Fredriksson et al., 2004) or on the actual adoption of specific technologies (Barreto and Kemp, 2008; Verdolini and Galeotti, 2011) has been limited, though more evidence is available from patent data (e.g. Verdolini and Galeotti, 2011; Dechezleprêtre et al., 2013). Differences in the adoption of energy efficiency technologies across countries and states, over time, and among individuals might be optimal due to differences in endowments, preferences, or the state of technology. But the rate of adoption may also be inefficient due to market failures and behavioral factors. Market failures include environmental externalities, information problems, liquidity constraints in capital markets, failures of innovation markets, and principal-agent problems such as between landlords and tenants (Gillingham et al., 2009; Linares and Labandeira, 2010). There is limited quantitative evidence on what role energy efficiency polices might play in reducing energy consumption compared to business as usual (Bosetti et al., 2011). Fredriksson et al. (2004) find that the greater the corruptibility of policy-makers, the less stringent is energy policy, and that the greater lobby group coordination costs are, the more stringent energy policy is. Matisoff (2008) finds that the most significant variable affecting the adoption of energy efficiency programs by US states is citizen ideology.

2.6 The rebound effect

Energy-saving innovations reduce the cost of providing energy services such as heating, lighting, and industrial power. This reduction in cost encourages consumers and firms to use more of the service in question. As a result, energy consumption usually does not decline by as much as energy efficiency increases. This difference between the improvement in energy efficiency and the reduction in energy consumption is known as the rebound effect. Rebound effects can be defined for energy-saving innovations in consumption and production. In both cases, the increase in energy use due to increased use of the energy service is called the direct rebound effect. For consumer use of energy, estimates of the direct rebound effect in developed countries are usually small – in the range of 10%–30% (Greening et al., 2000; Sorrell et al., 2009) – but are likely larger in developing countries (Roy, 2000). In the case of energy efficiency improvements in industry, the direct rebound effect is likely to be larger for export industries that have more opportunity to expand production than for industries serving the domestic market (Grepperud and Rasmussen, 2004; Allan et al., 2007; Linares and Labandeira, 2010).

Additionally, as a result of the reduction in the cost of the energy service, consumers will demand less of substitute goods and more of complementary goods, including other energy services. Firms will make similar changes in their demands for inputs. There will also be additional repercussions throughout the economy. Goods, whose demand has increased, require more energy for their production and vice versa; the fall in energy demand may lower the price of energy (Gillingham et al., 2013; Borenstein, 2015), increasing energy use, ceteris paribus; and the original energy efficiency improvement is a contribution to an increase in total factor productivity, which tends to increase capital accumulation and economic growth that results again in greater energy usage (Saunders, 1992). All these additional effects are called indirect rebound effects.[1] Direct and indirect rebound effects together sum to the economy-wide rebound effect.

It is usually assumed that the indirect rebound is positive, and so the economy-wide rebound is greater than the direct rebound effect and greater in the long run than in the short run (Saunders, 2008), but this might not be the case (Turner, 2013; Borenstein, 2015). At the economy-wide level, "backfire", where energy use increases as a result of an efficiency improvement, or "super-conservation" where the rebound is negative, are both theoretically possible (Saunders, 2008; Turner, 2009). Lemoine (2017) conducts a general equilibrium analysis of the rebound effect. Assuming that all sectors share the same technology, general equilibrium effects amplify the partial equilibrium rebound, as investigated by Saunders (1992). With heterogeneous technologies, general equilibrium effects amplify the rebound for low elasticities of substitution and reduce it for high elasticities of substitution between energy and non-energy inputs in production. Backfire is possible even for elasticities of substitution less than unity, especially for innovations in those sectors that are relatively energy inefficient or energy-intensive. In general, this analysis shows that the economy-wide rebound effect is likely to be large and backfire is likely.

There are few estimates of the economy-wide rebound effect, and these vary widely (Saunders, 2013; Turner, 2013). Evidence to date depends on computable general equilibrium models that have limited empirical validation or partial equilibrium econometric models that do not encompass all effects and mostly do not credibly identify the rebound effect. Turner (2009) finds that, depending on the assumed values of the parameters in a simulation model, the rebound effect for the UK can range from negative to more than 100%. Adetutu et al. (2016) use a stochastic frontier model to estimate energy efficiency and then use a dynamic panel model for 55 countries to estimate the effect of efficiency on energy use. This is the most credible empirical method proposed to date, however, as Adetutu et al. control for energy prices and output, it is a partial equilibrium approach. They find that in the short run rebound is 90%, while in the long run rebound is –36%.

3 The theory of the role of energy in economic growth

3.1 The ecological economics approach

Interdisciplinary ecological economists base their approach on the physical laws that describe the operating constraints of economic systems (Ayres and Kneese, 1969). In particular, 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. As a result, energy is always an essential factor of production (Stern, 1997), and continuous supplies of energy are needed to maintain existing levels of economic activity as well as to grow and develop the economy. Before being used in the production of goods and services, energy and matter must be captured from the environment, and energy must be invested in order to extract useful energy (Hall et al., 1986).

Ecological economists usually argue that substitution between capital and resources can only play a limited role in mitigating the scarcity of resources (Stern, 1997). Furthermore, some ecological economists downplay the role of technological change in productivity growth, arguing that growth is a result of either increased energy use or innovations allowing increased use of energy (Hall et al., 1986; Cleveland et al., 1984; Hall et al., 2003; Ayres and Warr, 2009). Therefore, in this view, increased energy use is the main or only cause of economic growth, and value is derived from the action of energy that is directed by capital and labor. Energy flows into the economy from fossil fuels and the sun. Capital and labor are considered intermediate inputs that are created and maintained by the primary input of energy and flows of matter. The level of these flows can be computed in terms of the embodied energy use associated with them.

However, because the quality of resources and the level of technology do affect the amount of energy needed to produce goods and services, this argument that energy is the sole factor of production is not so convincing. For example, the quality of resources such as oil reservoirs is critical in determining the energy required to extract and process fuels. As an oil reservoir is depleted, the energy needed to extract oil increases. On the positive side, improved geophysical knowledge and techniques can increase the extent to which oil can be extracted for a given energy cost. Odum's energy approach (Brown and Herendeen, 1996), which includes the solar and geological energy embodied in natural resource inputs in indicators of total embodied energy, is one attempt to address this issue. An alternative approach is to measure material and energy inputs on the common basis of their exergy (Ayres et al., 1998; Ukidwe and Bakshi, 2007). A third response is to measure energy inputs in terms of useful work (Ayres and Warr, 2009). However, Georgescu-Roegen (1971), Perrings (1987), and O'Connor (1993), among others, developed models that allow for a number of different factors of production while complying with the physical laws of the conservation of mass and thermodynamics to varying degrees. The ecological economics approach does not have to reduce to an energy-only model of the economy.

The effect of resource quality on the economy can be expressed using the concept of energy return on investment (EROI) – the ratio of useful energy produced by an energy supply system to the amount of energy invested in extracting that energy. Lower quality energy resources have lower EROIs. Ecological economists argue that the more energy that is required to extract energy, the less energy is available for other uses and the poorer an economy will be. In this view, the increase in EROI allowed by the switch from biomass to fossil fuels enabled the industrial revolution and the period of modern economic growth that followed it (Hall et al., 1986). Murphy and Hall (2010) document EROI for many energy sources, arguing that it has declined over time despite extensive innovation in the energy industry. Wind and direct solar energy have more favorable EROIs than biomass fuels, but worse than most fossil fuels. However, unlike fossil fuels, the EROI of these energy sources tends to improve over time due to innovation (Kubiszewski et al., 2010).

Substituting other inputs for energy or improving the efficiency with which energy is used could reduce the energy required in production. However, ecological economists argue that both these processes have limits. Technological change only allows us to get closer to the ultimate thermodynamic limits of energy efficiency; it cannot circumvent them. Substitution too is constrained by these thermodynamic limits.

Substitution can occur *within* a category of similar production inputs (e.g. between different fuels) and *between* different categories of inputs (e.g. between energy and machines) (Costanza and Daly, 1992). There is also a distinction to be made between substitution at the micro level (within a single engineering process or at a single firm) and at the macro level (in the economy as a whole) (Stern, 1997).

As shown in Figure 2.5, the long-run pattern of energy use in industrial economies, such as the United States, has been dominated by substitutions from biomass and animal power to coal, oil, natural gas, and primary electricity. Meta-analysis of existing studies of interfuel substitution suggests that the long-run substitution possibilities at the level of the industrial sector as a whole are good. But there seems to be less substitutability at the macro-economic level (Stern, 2012a).

Ecological economists emphasize the importance of limits to inter-category substitution; in particular, the substitution of manufactured capital for resources including energy (Costanza and Daly, 1992). Thermodynamic limits on substitution can be approximated by a production function with an elasticity of substitution significantly below 1 (Stern, 1997). As discussed earlier, a meta-analysis of the existing empirical literature finds that the elasticity of substitution between capital and energy is less than 1 but much greater than 0 (Koetse et al., 2008).

In addition to this micro-economic limit to substitution, there may also be macroeconomic limits to substitution. 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 "substitute" for energy – manufactured capital – requires more of the thing that it is supposed to substitute for. This again limits potential substitutability (Stern, 1997).

3.2 Neoclassical approaches

Despite the fact that energy must be an essential factor of production, the core mainstream economic growth models disregard energy or other resources. Aghion and Howitt's (2009) textbook on economic growth only discusses growth and the environment in a chapter near the end of the book. Acemoglu's (2008) textbook does not cover the topic at all. There has been some analysis of the potential for resources to constrain growth in the journal literature, but it has mostly been contained within the sub-field of environmental and resource economics, and the main focus has been on the implications of non-renewable resources for economic growth. Solow (1974) introduced non-renewable resources – which could represent fossil or nuclear fuels – into neoclassical growth models and showed that sustainability (or the ability of a nation to support a constant level of economic production indefinitely) is achievable under certain institutional and technical conditions. Stiglitz (1974) showed that if instead the economy is a free market economy with perfect competition but has the same technology as Solow's (1974) model, the resources are exhausted and consumption and social welfare eventually fall to zero. A large literature has developed in the wake of these and other classic papers (Stern, 2011). Recent examples of papers in this literature are André and Smulders (2014) and Peretto and Valente (2015). These models do not, however, usually specify whether the resources in question are energy or non-energy resources; André and Smulders (2014) is an exception in this regard. Neither do they mostly attempt to model a realistic historical economic development path (Tahvonen and Salo, 2001; Stern and Kander, 2012). Given the existence of renewable energy, it is not clear how relevant such an approach will be to the future, either. Shanker and Stern (2018) use a model with endogenous directed technical change and a constant price of energy – the price of energy usually rises in models with non-renewable resources – which does reproduce the stylized facts laid out in the first section of this chapter. Energy intensity falls due to energy-augmenting technical change but rebound means that energy use rises over time.

Economic historians have debated the importance of energy in the acceleration of economic growth known as the industrial revolution. Many researchers (e.g. Wilkinson, 1973; Wrigley, 2010; Pomeranz, 2001; Allen, 2009; Gutberlet, 2012; Kander et al., 2014; Fernihough and O'Rourke, 2014; Gars and Olovsson, 2015) argue that innovations in the use, and growth in the quantity consumed, of coal played a crucial role in driving the industrial revolution. But some economic historians and economists either argue that it was not necessary to expand the use of modern energy carriers such as coal (e.g. Clark and Jacks, 2007; Kunnas and Myllyntaus, 2009; Madsen et al., 2010) or do not give coal a central role (e.g. Harley and Crafts, 2000; Clark, 2014).

Before the industrial revolution, most energy was in the form of wood and animal and human muscle power – wind and water power contributed relatively little energy (Kander et al., 2014). The supply of this renewable energy was constrained by the availability of land, and so energy was scarce (Wrigley, 2010). Wrigley (2010) stresses that the shift from an economy that relied on land resources to one based on fossil fuels is the essence of the industrial revolution and can explain the differential development of the Dutch and British economies. Both countries had the necessary institutions for the industrial revolution to occur, but capital accumulation in the Netherlands faced a renewable energy resource constraint, while in Britain coal provided a way out of that constraint. This explanation emphasizes the low substitutability between the essential inputs of capital and energy. Allen (2009) focuses on innovations in the use of energy in his explanation of why the industrial revolution occurred in Britain. Many technological innovations were required in order to use coal effectively in new applications ranging from domestic heating and cooking to iron smelting. Like Wrigley, he compares Britain to other economies in Europe, but also to China. England stands out as an exception in two ways: coal was relatively cheap there and labor costs were higher than elsewhere. Therefore, it was profitable to substitute coal-fueled machines for labor in Britain, even when these machines were inefficient and consumed large amounts of coal, but not elsewhere. Continued innovation that improved energy efficiency and reductions in the cost of transporting coal eventually made coal-using technologies profitable in other countries too.

On the other hand, Clark and Jacks (2007) argue that an industrial revolution could still have happened in a coal-less Britain with only "modest costs to the productivity growth of the economy" (p. 68), because the value of coal was only a modest share of British GDP. They argue further that Britain's energy supply could have been greatly expanded, albeit at about twice the cost of coal, by importing wood from the Baltic. But Fernihough and O'Rourke (2014) and Gutberlet (2012) use geographical analysis to show the importance of access to local coal in driving industrialization and urban population growth in Europe, though Kelly et al. (2015) provide contradictory evidence from Britain on this point.

A number of researchers have attempted to model the role of energy in the acceleration of growth using mainstream economic growth models. Hansen and Prescott (2002) have two sectors, with a land input in the agricultural "Malthus" sector, no natural resource input to the industrial "Solow" sector, semi-endogenous population growth, and exogenous technical progress that is assumed, a priori, to be much faster in the Solow than in the Malthus sector. Once production using the Solow technology becomes more profitable, that sector quickly comes to dominate the economy and the growth rate accelerates. Though Hansen and Prescott (2002) do not explicitly model energy use in the Solow sector, they do mention that the reduction in the role of land in output can be seen as a transition to fossil fuels, which require less land area for production.

Tahvonen and Salo (2001), Fröling (2011), and Gars and Olovsson (2015) model fossil fuel use explicitly. However, like Hansen and Prescott (2002), these researchers all assume that productivity in the use of fossil fuels is higher or can increase faster than that in the use of renewable energy. Pezzey et al. (2017) instead assume that there is no a priori difference in the ease of developing new "machines" that use either biomass or coal. Instead, the supply of energy in the biomass-using sector is fixed while the supply of coal is infinitely elastic. Allen (2009) shows that the real price of coal was fairly constant over several centuries, which supports the latter assumption. Clark and Jacks (2007) explain that throughout the period of the industrial revolution innovation overcame the effects of depletion, resulting in the long-run supply of coal being highly elastic.

In Pezzey et al.'s (2017) model, each of the two intermediate goods sectors uses labor, an energy input (wood in one sector and coal in the other) and sector-specific machines. The output of these two sectors is combined into final output via a high-elasticity constant elasticity of substitution (CES) production function. Pezzey et al. show how the rising relative price of wood can cause the direction of technical change to shift increasingly towards the development of coal-using machines. As coal use can be expanded without limit, the rate of economic growth accelerates. However, they also show that with a high enough elasticity of substitution between the outputs of the two sectors in producing final output, an industrial revolution is not inevitable. Greater initial scarcity of wood relative to coal, greater initial knowledge of technologies for using coal relative to technologies for using wood, and/or higher population growth puts the economy on a path to an industrial revolution. The converse slows industrialization or even prevents it forever. The greater the elasticity of substitution and/or the smaller the output elasticity of energy, the more extensive is the set of initial conditions that lead to stagnation. Empirical calibration for Britain in the period 1560–1900 produces historically plausible results.

However, this study makes the simplifying assumption that the elasticity of substitution between machines and energy is unity. As discussed above, we should expect it to be less than 1 on both theoretical and empirical grounds. Stern and Kander (2012) add an energy input that has low substitutability with capital and labor to Solow's (1956) growth model. Otherwise, they make the same assumptions as Solow, including that technological change is exogenous. Using 200 years of Swedish data Stern and Kander estimate that the elasticity of substitution between energy and the other two inputs is 0.65.

When the elasticity of substitution is unity, cost shares in a single sector model must be constant. Assuming that the elasticity of substitution between energy and capital is less than 1 allows the share of energy in production costs to fall over time. The cost share of energy has fallen in the long run in both Britain and Sweden, countries for which we have data from 1800 till the present (Figure 2.6). An elasticity of substitution of less than unity also allows us to distinguish between labor-augmenting innovations and energy-augmenting innovations, which again is not possible using a Cobb-Douglas production function.

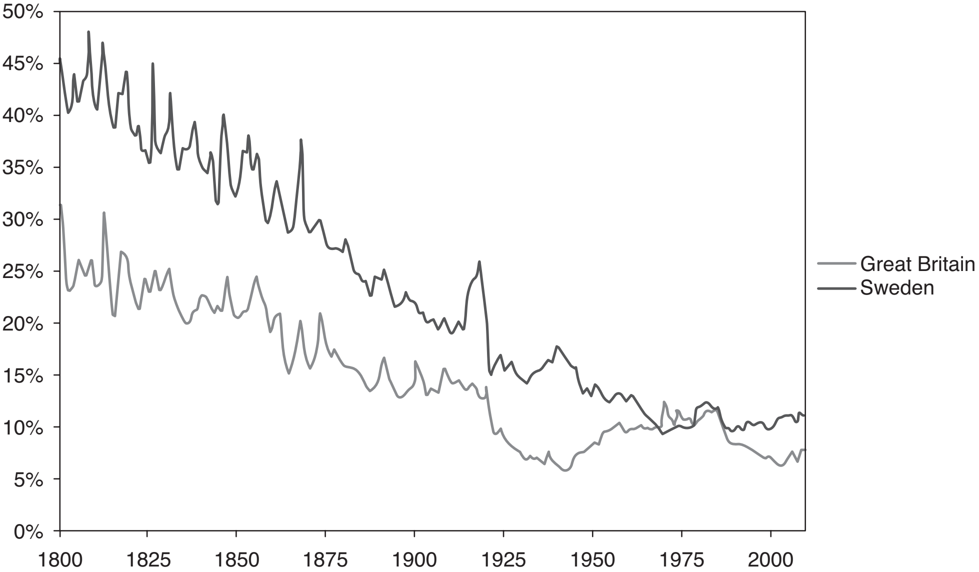

Figure 2.6 Share of energy in total production costs: Britain and Sweden 1800–2009

Source: Gentvilaite et al. (2015).

Stern and Kander's (2012) production function is given by:

$$Y = \left[(1-\gamma)\left(A_L^{\beta} L^{\beta} K^{1-\beta}\right)^{\phi} + \gamma\left(A_E E\right)^{\phi} \right]^{\frac{1}{\phi}} \tag{2.3}$$

Equation (2.3) embeds a Cobb-Douglas function of capital, K, and labor, L, $L^{\beta}K^{1-\beta}$, in a constant elasticity of substitution production function of this combined input and energy, E, to produce gross output, Y. $\phi = \frac{\sigma - 1}{\sigma}$, where σ is the elasticity of substitution between energy and the capital-labor aggregate. A_L and A_E are the augmentation indices of labor and energy, respectively, which can be interpreted as reflecting both changes in technology that augment the effective supply of the factor in question and changes in the quality of the respective factors. $A_E E$ and $A_L L$ are called effective energy and effective labor, respectively.

In Solow's (1956) model, as long as there is technological change, the economy can grow in the long run. In Stern and Kander's model, depending on the availability of energy and the nature of technological change, energy can be either a constraint on growth or an enabler of growth. When effective energy, $A_E E$, is very abundant, the model behaves very similarly to Solow's original model and energy neither constrains nor drives growth. The more energy there is, the less important energy appears to be. But when effective energy is relatively scarce, the level of output depends on the level of energy supply and the level of energy-augmenting technology, and labor-augmenting technological change alone no longer results in economic growth. Stern and Kander (2012) find that increases in energy use and energy-augmenting technological change were the main contributors to economic growth in the 19th and early 20th centuries but in the second half of the 20th century labor-augmenting technological change became the main driver of growth in income per capita as it is in the Solow growth model.

4 Testing for Granger causality between energy and GDP

Two methods for testing for causality among time series variables are Granger causality tests (Granger, 1969) and cointegration analysis (Engle and Granger, 1987). These methods have been applied extensively to test for causality and cointegration between energy, GDP, and other variables from the late 1970s on (Kraft and Kraft, 1978; Ozturk, 2010). There are now hundreds of journal articles on this topic (Bruns et al., 2014).

Early studies relied on Granger causality tests on unrestricted vector autoregressions (VARs) in levels of the variables, while 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, then X is said to Granger cause Y. Cointegration analysis tests whether variables that have stochastic trends – their trend is a random walk – share a common trend. If so, then at least one variable must Granger cause the other.[2]

Early studies also used bivariate models of energy and output while more recent research tends to employ multivariate models. Ignoring other relevant variables can generate spurious causality findings. The most common additional variables used are capital and labor or energy prices. A third way to differentiate among models is whether energy is measured in standard heat units or whether a method is used to account for differences in quality among fuels.

The results of early studies that tested for Granger causality using bivariate models were generally inconclusive (Stern, 1993). Using a multivariate vector autoregression (VAR) model of GDP, capital and labor inputs, and a Divisia index of quality-adjusted energy use for the United States, Stern (1993) found that energy use Granger caused GDP. Yu and Jin (1992) conducted the first cointegration study of the energy GDP relationship using the bivariate approach. Stern (2000) estimated a dynamic cointegration model for GDP, quality-weighted energy, labor, and capital. The analysis showed that there is a cointegrating relation between the four variables and, depending on the version of the model used, found that energy Granger causes GDP or that there is mutual causation between energy and GDP. Some subsequent research appeared to confirm these findings (Warr and Ayres, 2010; Oh and Lee, 2004; Ghali and El-Sakka, 2004; Lee and Chang, 2008; Lee et al., 2008).

Bruns et al. (2014) carry out a meta-analysis of 75 single-country Granger causality and cointegration studies comprising more than 500 tests of causality in each direction. They find that most seemingly statistically significant results in the literature are probably the result of statistical biases that occur in models that use short time series of data ("overfitting bias") or the result of the selection for publication of statistically significant results ("publication bias"). The most robust findings in the literature are that growth causes energy use when energy prices are controlled for in the underlying studies. However, Bruns et al. (2014) find that studies that control for capital do not find a genuine effect of energy on growth or vice versa. But they had too small a number of studies that used quality-adjusted energy to test whether there was a genuine relationship between energy and growth when this measure of energy use was employed. So, their findings do not necessarily contradict the previous research by Stern and others reviewed above.

5 Gaps in knowledge and policy implications

As this chapter has shown, the relationship between energy and GDP is one where there is remarkably little consensus and large gaps in knowledge remain. The field of energy economics has expanded rapidly in the last decade, but much research is repetitive and adds little to existing knowledge (Smyth and Narayan, 2015). In particular, there is a very large literature using reduced form time series models to test for causality and cointegration between energy and output. But this literature appears inconclusive with equal numbers of studies finding causation in each direction (Bruns et al., 2014), though Bruns et al. (2014) find that studies that control for the price of energy find a genuine effect of output on energy use but not vice versa. This could be because the effect of energy use on output is much smaller than that of output on energy use. Additionally, holding energy prices constant should measure the effect of an improvement in energy efficiency on output, which may be even smaller.

There is also a lack of consensus in research on the drivers of changes in energy intensity. In particular, energy intensity has risen in many developing countries. The reasons for this are little researched. There is also a lack of consensus on the size of the economy-wide rebound effect. Existing estimates derived from simulation models range from negative rebound to backfire, where energy efficiency improvements actually increase rather than reduce energy use. Empirical estimates are all partial equilibrium approaches that mostly do not credibly identify the economy-wide rebound effect. Therefore, there is little guidance on the potential for energy efficiency policies to actually conserve energy. However, historical evidence and theory suggest that rebound could be large.

Research is also hampered by inadequate data. With the exception of traditional biomass, energy use data are normally of good quality. But data on prices is much more fragmentary.[3] Most economic research is based on understanding the linkages between prices and quantities. So, this is an important area where comprehensive international datasets could be very useful.

Despite the lack of empirical clarity, we can draw some implications for policy from theory and the available evidence. Most countries need to plan on energy use continuing to increase. Increasing the availability of energy and improving energy efficiency is likely to be of more importance to development in developing than in developed countries. Policies that encourage innovation in energy efficiency will probably save much less energy than an engineering analysis or micro-level behavioral analysis would suggest. Climate mitigation policies need to mostly focus on switching to low or zero carbon energy sources rather than expecting gains from energy conservation or efficiency. On the other hand, if such policies to discourage energy use are implemented in developed economies, the effects on economic growth probably will not be that large.

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Notes

1 Some researchers (e.g. Azevedo, 2014; Gillingham et al., 2015) define changes in prices and growth effects as macro effects that they distinguish from indirect rebound effects.

2 The reverse is not the case. Variables may be causally related but not cointegrate because of relevant omitted variables. One of the most important of these may be the unobserved state of technology.

3 The International Energy Agency provides data on the prices of some fuels for a group of mostly developed economies. The World Bank provides data on the price of gasoline and, recently, electricity for a large number of countries.

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