ENERGY ECONOMICS

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CHAPTER 1

HISTORY AND FUTURE OF ENERGY USE

1. Introduction

Energy has been a topic of discussion for centuries. In their time, Malthus (1798) and Ricardo (1817) were already issuing warnings for high population growth. The growth in population would bring about an era of diminishing returns in agriculture and would increase the scarcity of non-renewable resources. Later, Jevons (1865) used detailed estimates of available coal reserves in the UK and combined these estimates with the potential new uses of coal in order to predict the increasing scarcity of coal in the world.

In this chapter, we provide a macroeconomic and long-term view of energy and resources. In the second section, we present what economics as a science sees as the driving forces of energy use. The ultimate driving factors will be population, technological progress, institutions, and availability of resources. These factors determine economic growth, energy use, and energy prices. In the third section, this framework is used to very briefly analyze the historical development of energy use. In the fourth section, we draw some lessons for the future. In the final section, we present an overall scheme for understanding developments on the energy markets.

2. Drivers of energy use and energy prices

The demand for energy (or energy use) is a derived demand. Energy as such has no value, but when combined with – for example – capital, energy services are produced that create value for those who use these services. To understand the long run and short run demand for energy, one therefore needs to understand what drives the demand for these energy services. The next sections present two simple frameworks that help us to better understand the demand for energy services and energy in the production and household sector. Both frameworks take a microeconomic perspective.

2.1 Energy use in the production sector

In order to structure the determinants of energy use and prices, we need a small formal representation of an economy. We do this with the help of a few equations. We have two final goods: a general good Y that serves all purposes and a final energy good E (electricity or coal, gas, oil delivered to firms or households). The first equation is a production function for the general good Y:

$$Y = F(\rho, \theta, K, L, E, A)$$

This equation gives the maximal output of the general good Y that can be generated by combining efficiently four types of input: capital K, labor L, energy E, and land A. The overall output level depends on two more factors: the level of technological progress ρ and the institutional quality θ. It is useful to express the production possibilities per capita (where small letters represent the quantity per capita) and leave out land as production input, as we mainly discuss industrial production:

$$y = F(\rho, \theta, \mathrm{k}, \mathrm{e})$$

The output per capita y depends on the available capital (e.g. machines, buildings, vehicles) and the available quantity of energy. Energy has to be understood in a very broad sense, covering manpower and horse power, energy provided by a combustion engine (power) or an electric engine (electric power) as well as heating oil, diesel and gasoline.

For any given level of inputs (k,e) the ultimate production level will depend on the level of technology (ρ). The level of technology will determine the overall efficiency of the production process including the conversion efficiency of energy. Take for example moving an object in the production process: one can do this manually, using horse power, a small truck, or a robot. The higher the level of technology, the fewer inputs are needed for a given level of output. Technologies can be 'oriented' in the sense of saving more of one input: it can be energy saving, labor saving etc. If one production factor (say energy) becomes more expensive, it pays off to look for new technologies that allow substituting the expensive production factor by cheaper production factors (investment in insulation, fine-tuned heaters).

A second factor that plays a key role to increase the level of output for given inputs are the institutions. Institutions represent all organizational aspects in an economy: the political system, the legal system that includes property rights and company law. But it also includes less formal elements such as social norms. The political and legal systems will be important in understanding under which forms the production process can be organized. If one needs a certain scale of operation, one needs sufficient capital and coordination. A private firm that can call upon the capital market (a corporation in the legal sense) is one of the most important institutions that can increase the productivity of an economy. Another important institution is a patent law that allows an inventor to sell his knowledge to the users. When there is no patent protection, the incentive for inventors to look for better techniques will be much smaller. Acemoglu and Robinson (2012) demonstrate the importance of institutions by comparing areas that have identical geographical conditions but show large differences in economic performance. One of their examples is about two border towns, one located in Mexico and the other one in Texas. Both towns have the same genes and the same climate but the average income is three times higher in Texas due to a different institutional environment. There are many other examples: North and South Korea or the Dominican Republic and Haiti. In both cases, the countries occupy the same island but their productivity is dramatically different because of the differences in institutional structure.

For given institutions and technological know-how, the output per capita depends on the available capital and energy. Iso-output lines are called isoquants and they give an idea of the substitution possibilities between inputs. Figure 1.1 represents two extreme cases: a fixed proportion technology (‘Leontief-type’ production function) and the full substitutability case (‘linear’ production function). In the first case, in order to move from a level of output per capita of y° to y^*, one needs to increase the inputs in the same proportion. For example: one tractor always needs a given amount of fuel to work for one hour. Having more tractors or more fuel but not both is useless as they will not generate more output. Very poor substitution possibilities between energy, land, and other inputs were implicit assumptions in Malthus’ and Ricardo’s reasoning. If over time the amount of energy or land per capita is decreasing, once one has passed a critical ratio, the overall level of output per capita has to decrease over time. In Figure 1.1, the bold arrow shows a possible development of the production inputs over time. It is a development with increasing energy scarcity. If there are no substitution possibilities, the total output will go down once one passed point A.

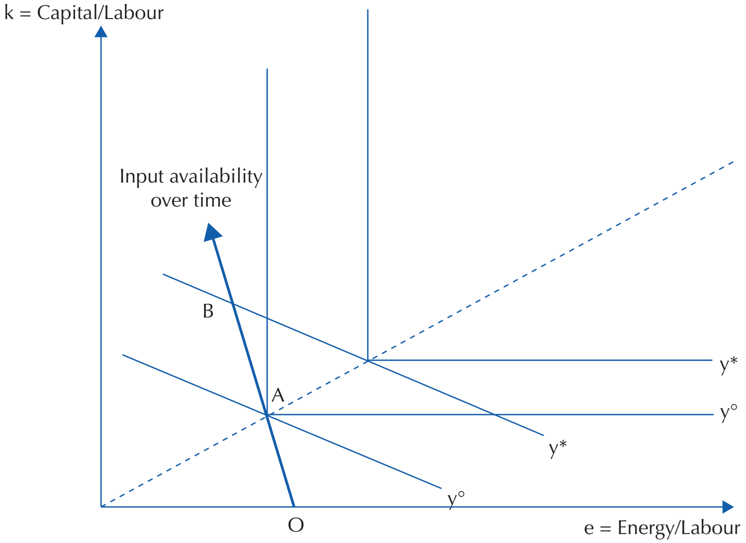


FIGURE 1.1. Substitution possibilities in the production sector.

The other extreme view is represented by the linear isoquants for levels $y°$ and $y*$. When the isoquants are linear, one can always substitute one input by another by substituting 1 unit of energy by a fixed number of units of capital. Take again the example of a tractor: by spending x units more on a tractor, one can always save z units of fuel and continue to have the same agricultural production. If, for one reason or another, the available quantity of energy per capita decreases over time, as suggested by the arrow in Figure 1.1, the production possibilities of the economy could still increase as long as one can compensate for the decrease in energy availability with more capital. The substitution possibilities in the economy will thus be a crucial parameter for the 'sustainability' of economic growth. We return to this issue in chapter 5.

In a market economy, an efficient use of available capital, labor, as well as energy inputs in the production of goods requires that the relative prices of inputs are the same in all production sectors and that all production units minimize their costs. The intuition for these conditions is simple: relative prices of inputs signal the relative scarcity of the inputs in the whole economy. If a particular input is more productive in another sector, one should use it there. Cost minimization means that no inputs are wasted: the economic equilibrium is situated on an isoquant, not below it. In addition cost minimization implies that a minimum of scarce inputs are used.

Once we allow prices to organize the use of resources, we can work on a more partial scale and use demand functions for inputs rather than production functions. A demand function for inputs is a functional relation between the demand for one input and exogenous drivers that are taken as given (prices of the input, other prices, production levels). A demand function represents the input choices of the firm. Demand functions can be aggregated at the level of the sector, at the level of the economy etc. The demand function for energy use in one production sector can be derived by minimizing the production costs TC for given production function F( ) and given output level Y°:

$$\begin{aligned}&\text{Minimize } \mathrm{TC} = \mathrm{p}_E E + \mathrm{p}_K K + \mathrm{p}_L L\\ &\quad \text{w.r.t E,K,L}\\ &\text{subject to } F(\rho, \theta, K, L, E) \geq \mathrm{Y}^\circ\end{aligned}$$

Based on the Lagrange function, we find

$$\mathrm{p}_E = \lambda \frac{\partial F}{\partial E}; \quad \mathrm{p}_K = \lambda \frac{\partial F}{\partial K}; \quad \mathrm{p}_L = \lambda \frac{\partial F}{\partial L}$$

$$\frac{\mathrm{p}_E}{\mathrm{p}_K} = \frac{\frac{\partial F}{\partial E}}{\frac{\partial F}{\partial K}}; \quad \frac{\mathrm{p}_E}{\mathrm{p}_L} = \frac{\frac{\partial F}{\partial E}}{\frac{\partial F}{\partial L}}$$

Using the first order conditions of this cost minimum problem, one can derive a demand function for energy use in a firm, in a sector and in the production sector of an economy as a function of the exogenous elements (volume of production and all prices of inputs):

$$D_E = d(p_{E,} p_{\mathrm{K},} p_{L,} Y^\circ)$$

So, the demand function for energy incorporates all substitution possibilities between inputs (the curvature of the isoquants or the functional form of the production function). For given prices of other inputs, one expects the demand for energy from an industrial sector to be a decreasing function of its price, and this reaction will be stronger in the long-term than in the short-term. The reaction in the long term will be stronger because there are more substitution possibilities when one can opt for other technologies and new equipment. This process takes time as running existing installations for some time is usually cheaper. When the demand function is formulated at the level of the country, the composition of the industrial production can change because energy-intensive goods may become more or less expensive. This affects the demand for the different types of output and thus the sectoral composition of the economy. So changes in energy prices work through the whole economy via changes in technology per sector and changes in the sectoral composition of the industrial activity.

2.2 Energy use by final consumers

Energy is used for production purposes but also for heating, lighting, and passenger transport. We formulate the energy demand problem of the consumer in its simplest form as follows. Consumer preferences for energy services x_2 (e.g. heating a house) and other consumption goods x_1 are given by the utility function $U(x_1, x_2)$, which is increasing in both arguments. A utility function is a mathematical expression of the preferences of the consumer and such a function is used to structure the choices of a consumer. As preferences differ among individuals, there are as many utility functions as there are individuals. Structuring the choices with a utility function is useful because it allows setting restrictions on the choice behavior of consumers.

The consumer who maximizes his utility function faces two constraints. The first one is the budget equation, which says that total expenditures on consumer goods and on energy (e) cannot be larger than the income of the consumer:$p_1 x_1 + p_e e \leq I$. The second constraint is the production function of energy services at home, a simple example being $x_2 = ke$, where k is the efficiency of conversion of energy into energy services. If the consumer optimizes consumption under these two constraints, this generates the demand functions:

$$x_1 = F\left(p_1, \frac{p_e}{k}, I\right)$$

$$x_2 = G\left(p_1, \frac{p_e}{k}, I\right)$$

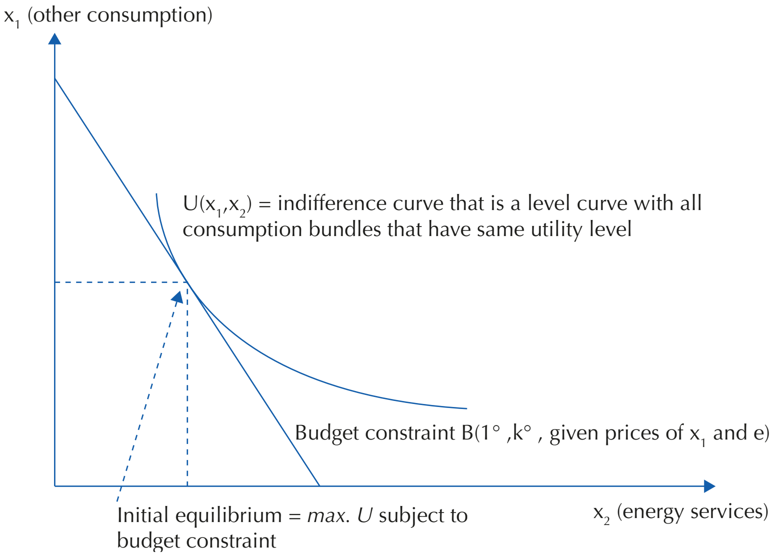


FIGURE 1.2. Initial consumer equilibrium.

This problem is a simplified version of the one where the consumer has to solve a more complex problem: choose the level of efficiency (k) by investing in more efficient equipment (better heater, higher level of insulation) or choose the level of energy services and of other consumption goods. The initial consumer equilibrium is shown in Figure 1.2. The budget constraint defines the border of a set that represents all combinations of x_1 and x_2 that can be bought with a budget $I°$. The utility function is represented by level curves that each represent the combinations of consumption goods that generate the same level of utility. A consumer always prefers a higher level curve. The consumer equilibrium then is that combination of the consumption of the two goods that maximizes his utility and is still feasible given his budget.

In Figure 1.3, one can observe the consumer's response to a decrease in the income level (ΔI). The budget curve shifts down, and the corresponding indifference curve shows a lower level of utility as the consumption of both goods is now lower. As energy services are a necessity, they tend to be less sensitive to income changes: in the short run, the elasticity with regard to income $(\frac{dx_2}{x_2}\frac{y}{dy})$ will be smaller than 1. In the longer run, this elasticity can increase as the consumer has more time and alternatives to adapt his behavior (insulation, other heating equipment, larger house etc.) to changes in income.

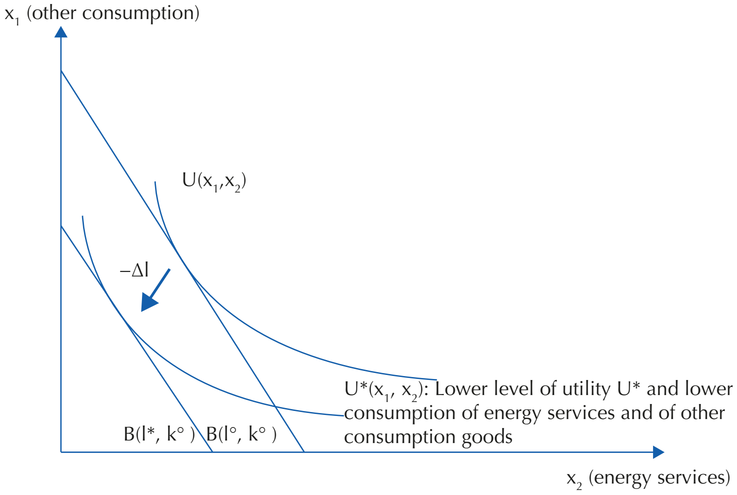


FIGURE 1.3. Consumer response to decrease in income.

In Figure 1.4, the consumer response to an increase in energy efficiency is graphically displayed. In this example, an improvement of conversion efficiency allows us to enjoy the same level of energy services at a lower cost. This saving can be used either to buy more other consumer goods and/or to increase the consumption of energy services. This depends on the preferences of the consumer. The increase in energy service use when a more energy efficient technology is used, is called the "rebound effect". The rebound effect can be small (about 5%) but also large (about 50%), depending on the type of energy services. It is important to realize that a gain in energy efficiency does not lead to a proportional reduction in energy consumed. One can define a price elasticity of energy services:

$$\frac{\partial x_2}{\partial p}\frac{p}{x_2} < 0$$

In the long run, when conversion technology can be adapted, the price elasticity will be larger.

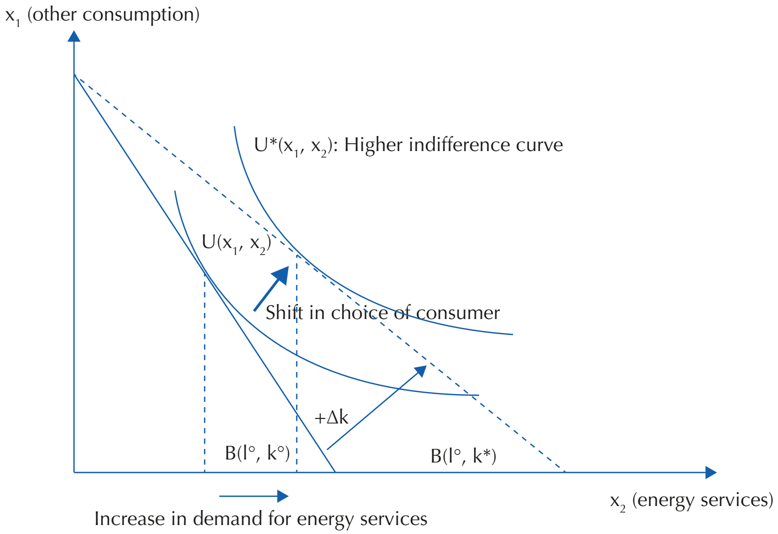


FIGURE 1.4. Consumer response to increase in conversion efficiency.

2.3 Main drivers of energy use

There are two main drivers of energy use. The first one is the price of energy services, which equals the price of energy divided by efficiency (where efficiency is technology driven). The second driver is income (per capita) and economic activity.

There are two main types of consumers: households and the industry (in a broad sense). Demand for energy services for households could increase when the price decreases, which happens when either efficiency increases or energy prices decrease. Demand for energy services can also increase because of changes in preferences for comfort at the consumer end (for example more rooms heated, higher room temperature, more air conditioning, more transport) or other exogenous changes in the living circumstances (other climate, better roads leading to more driving). We also know that demand for energy reacts to changes in energy conversion technology and that this reaction is not necessarily proportional (see section 2.2).

Demand for household energy services can also increase when income increases. There is a direct effect on the consumption of energy by households from heating, transport, etc. because of the higher demand for comfort. An income increase also implies higher demand for (non-energy) consumption goods that also require energy to be produced, which also positively affects demand for energy by industry and service sectors.

Energy use by the production sector (industry, services, agriculture) has two main drivers: demand for outputs by the production sector and energy intensity of production. Demand for outputs depends on the relative prices of goods and on income levels of local households and foreign consumers. The energy intensity of a production sector depends on the relative prices of energy and other inputs as well as on the technology.

Clearly, decisions at the micro level will also influence evolutions at the aggregate level. But, in the long run, technological progress, population growth, institutional changes and changes in the economic structure, will also impact the evolution of energy use over time. One typical measure to describe a country's evolution of energy use over time is 'energy intensity', which is defined as the amount of energy used (measured in some common unit) to produce one unit of output (measured by GDP). In combination with population size and income per capita, energy intensity explains energy use. The following expression (actually an identity) makes this clear:

$$E_t = Population_t \times \frac{GDP_t}{Population_t} \times \frac{E_t}{GDP_t}$$

This expression will help us to discuss the evolution of energy use both from an historical and forward looking perspective.

3. Energy in historical perspective

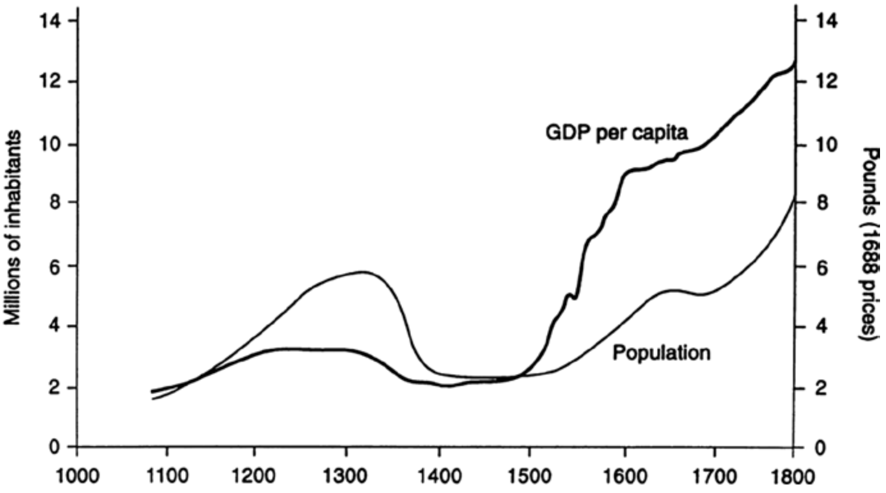
A detailed study of energy in a historical perspective would take us too long. In this course we will mainly study recent developments (after 1950), but it is useful to briefly look back in time.

Our early ancestors were hunters and tended to eat their kill raw. Before they knew fire they lived on an energy budget of 8 MJ/day. Fire use increased energy consumption to 17 MJ/day and domestication of animals raised it to 40 MJ/day. Once coal was used more intensively, consumption in the US rose to 400 MJ/day in the early 20th century and it continued to grow to 1000 MJ/day in 2000 (Aubrecht, 2006).

To discuss the main drivers of energy use throughout history, we rely on the work of Fouquet and Pearson (1998) and Fouquet (2009, 2011). Most of this work is related to the UK for which good historical data is available. The analysis focuses on the period after the 13th century.

3.1 Income and population growth

Figures 1.5 and 1.6 show how population and GDP per capita evolved over the last 700 years. In the second half of 14th century there was a very strong decrease of the population due to the Black Death. This created a scarcity of labor and allowed some countries, such as the UK, to get rid of the feudal system. The poor people in this feudal system virtually had no rights but because they were in high demand, they could now start to claim more rights.



Source: Fouquet and Pearson (1998).

FIGURE 1.5. Estimates of population and real GDP per capita (1086-1800).