3 Energy Demand–Theory and Empirical Analysis

In this chapter, we will introduce some theoretical as well as empirical elements of measuring energy demand. Understanding the factors that influence energy demand, and the demand for energy services, is very important, not only for firms but also for policymakers. For instance, information on the price and income elasticities of electricity demand can be used by electric utilities to design a new tariff structure, or by the government to estimate the impact of the introduction of a new energy tax. Furthermore, energy demand analysis is also useful to forecast future demand. Forecasting the energy demand is particularly important in developing countries where we expect a significant increase in the demand for energy services, and therefore, indirectly, also for energy because of increases in population and gross domestic product (GDP).

In this chapter, we propose a discussion based on microeconomic theory to highlight the role of the production process and of technology in determining energy demand. It is essential to understand that the energy demand depends on both consumption behaviour and on investment behaviour in technologies.

3.1 Introduction to Energy Demand Analysis

3.1.1 Energy Demand as a Derived Demand for Energy Services and Industrial Goods

In order to understand the demand for energy, it is important to keep in mind that it depends on the demand for both energy services and on the demand for goods.

Consumers and firms do not consume energy directly but instead use energy in combination with other inputs such as capital and labour to produce goods (e.g., cars, computers, and washing machines) and energy services (e.g., lighting, heating, and cooling, transport, cooking, and washing), that is, services produced by combining capital, labour, and energy, with energy playing an important role.

For instance, in order to wash clothes, a household must combine labour, capital (the washing machine), and electricity to produce washed clothes. As a result, the demand for electricity depends on the demand for washed clothes and on the level of energy efficiency of the washing machine. As another example, a firm that produces washing machines uses a combination of capital (equipment needed to manufacture a washing machine), labour, and energy to produce its product. Accordingly, its energy demand depends on the energy required to produce washing machines, the level of energy efficiency of the machines/capital used in the production process, and on the final demand for washing machines.

In this context, it is important to understand that the technology choice of households and firms (whether they purchase old and energy-inefficient, or new and energy-efficient technologies) can heavily influence energy demand for a long period. In fact, most of the machines, appliances, and general technologies used in the production of goods and energy services have a long lifetime. For instance, the typical lifetime of a washing machine is around 15 years, while that of a car is around 10 years, and the life of a heating system could be up to 20–30 years. This implies:

- The initial choice of technology has a long-term impact on energy consumption as well as on the type of energy used (renewable or non-renewable).
- The transformation of the current energy sector into a more sustainable one based on the use of energy-efficient technologies and renewable energy sources can take time.

3.2 Household Production Theory and Energy Demand

This next section will apply household production theory to the analysis of energy demand. This theory has been also used in several domains such as labour and health economics, and it can also help us to understand energy demand within the residential sector.

3.2.1 Key Functions of Household Production Theory

Household production theory is based on two key functions: the utility function and the production function. Following this theory, households purchase goods on the market, which are then used as inputs in the production process for energy services (ES), a component that appears as an argument in the utility function of the households, along with other goods. The production function, on the other hand, represents the production process for energy services. In the context of household production theory, a household wants to consume a reasonable quantity of energy services and other goods, given a predefined level of income, and wants to produce energy services using a production process that minimises the cost. As a simplification of this framework, a household is assumed to maximise the following utility function that includes two goods – energy services and other goods as described in Equation 3.1:

$$U = u(ES, OG) \tag{3.1}$$

U: Utility
ES: Energy services
OG: Other goods

The energy services (ES) are generally produced by the household using two inputs – energy and the capital stock (such as appliances and heating systems). The production function for the energy services can be described as follow:

$$ES = f(E, CS) \tag{3.2}$$

ES: Energy services
E: Energy
CS: Capital stock

It must be noted that for the production of some energy services such as cooking, labour is also used as an input in the production process. In fact, to produce a meal, a household uses energy, an electric stove (i.e., capital), as well as time. In this case, another production factor (labour) would be added in Equation 3.2.

If we substitute the value of ES from Equation 3.1 into Equation 3.2, we obtain the following expression for the household utility function:

$$U = u(ES(E, CS), OG) \tag{3.3}$$

U: Utility
ES: Energy services
E: Energy
CS: Capital stock
OG: Consumption of other goods

From standard microeconomic theory, we know that households try to maximise their utility function described in Equation 3.3 under an income restriction. Household production theory entails that households do this while minimising the cost of producing energy services. In the next subsection, we will describe this optimisation process that requires making:

1. A decision on the optimal combination of energy services and other goods that maximises utility subject to a given level of income.
2. A decision on the optimal combination of inputs that minimises the production cost in producing the optimal level of energy services.

From a mathematical point of view, these optimisation processes are simultaneous. We present this approach first graphically, and then using mathematical expressions.

3.2.2 Graphical Representation of Household Choices

Households face two optimisation decisions: the decision to optimise consumption (depicted in Figure 3.1) and the decision to minimise costs in the process of producing the energy services (illustrated in Figure 3.2).

On the one hand, households maximise their utility function, under a given budget constraint. In other words, they choose a combination of energy services and other goods that provide the highest level of utility to them, considering the constraints of their budget. Figure 3.1 shows this scenario with energy services (ES) on the horizontal axis and consumption of other goods (OG) on the vertical axis. The straight line gives the budget constraint and the convex curve represents the indifference curve. At point A, where the straight budget line and the convex indifference curve are tangential

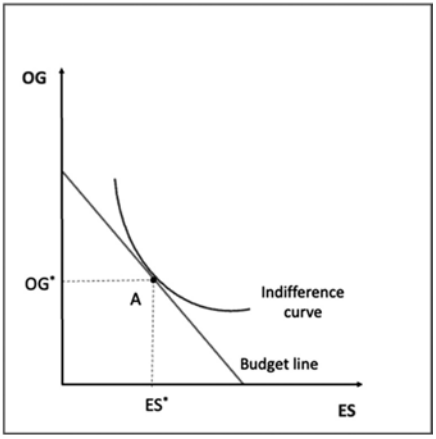

Figure 3.1 Optimisation of consumption

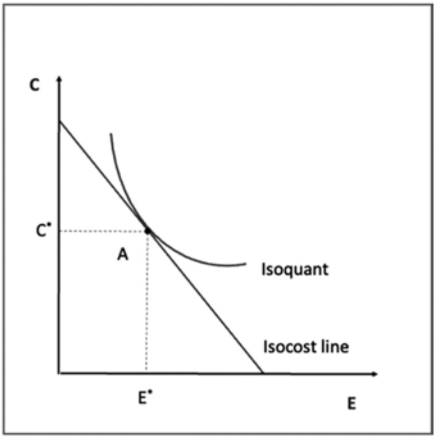

Figure 3.2 Cost minimisation in the production of energy services

to one another, the utility is said to be maximised. The optimal combination of other goods and energy services is thus represented by OG^* and ES^*.

On the other hand, households must also choose the inputs to minimise the cost of producing the chosen level of energy services. In Figure 3.2, capital (C) is shown on the vertical axis, while the level of energy production (E) is indicated on the horizontal axis. At point A, where the straight isocost line and the convex isoquant curve are tangential, the production costs for a predefined level of energy services

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[*] A budget line represents all combinations of quantities of the two goods that can be consumed, given the prices of these goods and income; the indifference curve represents all combinations of the quantities of two goods that give the same level of utility to the consumer.

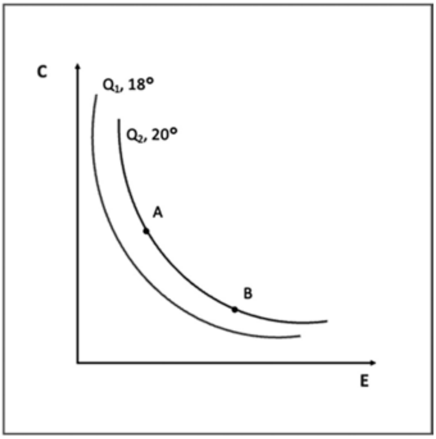

Figure 3.3 Optimisation of energy service production using isoquants

represented by the isoquant are minimised, where the optimal capital and energy production combination is given as $C^*, E^{*\dagger}$.

3.2.2.1 Example: Production of a Heating Service

Let us assume that a household is interested in producing an energy service, for example, the heating of an apartment. We can represent this production decision using isoquants. In Figure 3.3, two isoquant curves are shown, and we plot energy (E) on the horizontal axis and capital (C) on the vertical axis. The Marginal Rate of Technical Substitution (MRTS) is defined as the slope of the isoquant curves and can be computed as -MRTS = $\delta C/\delta E$. The isoquant closer to the origin in the graph (Q_1) represents all possible combinations of capital and energy that result in the heating of the apartment to 18°C, while the isoquant further away (Q_2) denotes all combinations that result in the heating up to 20°C. We must pay attention to the fact that the household can make a choice: it can decide to use a large amount of capital (e.g., to invest in insulation) and consume a low amount of energy in the process to obtain a particular heating level, or it can use a small amount of capital and thereby consume a large amount of energy to reach the same level of heating. Traditional buildings that tend to waste energy can be characterised by the combination of capital and energy represented by point B, whereas energy-saving buildings can be represented by the combination defined by point A. Nevertheless, both combinations of inputs lie on the same isoquant, and therefore give the households the possibility to produce the same level of heating.

In Figure 3.4, an isoquant and two different isocost lines are shown. On the vertical axis, we plot the quantity of capital (C) used in the production process, and on the horizontal axis, we have the amount of energy (E) required. The isoquant represents

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[†] Isocost is a line providing all combination inputs that can be purchased with a given budget; Isoquant is a function illustrating all possible combinations of inputs that can be utilised to produce a given level of output.

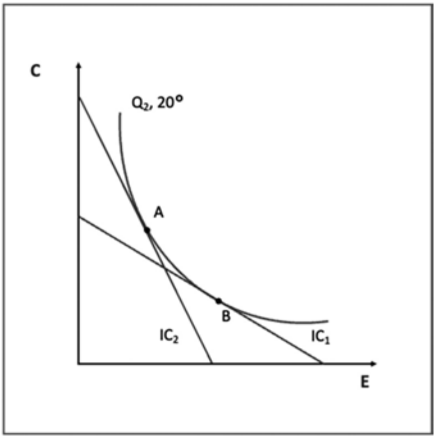

Figure 3.4 Energy service optimisation using isoquants and isocosts

the level of the energy service (Q_2) used in heating to 20°C. The isocost line 1 (IC_1) and the isocost line 2 (IC_2) have different slopes, that is, different values of the ratio of the two prices (that of energy and capital). IC_1 has a flatter slope than IC_2. In relative terms, IC_1 indicates that energy is cheaper than capital, in comparison to the situation represented by IC_2. Note that the different ratios of the energy price to that of capital can lead to varying optimal household decisions. The optimal combination of inputs is represented by the points where the relevant isocost curves are tangential to the isoquants. If the ratio of the two prices is represented by IC_1, a household would minimise the cost of producing the level of energy service (Q_2) with the combination of inputs represented by point B. In case the ratio of the two prices is represented by IC_2, the household would minimise the cost of producing the level of energy service (Q_2) with the combination of inputs represented by point A. This point A could represent either the construction of a new energy-saving building or the energy-saving renovation of an existing building. In moving from B to A, the households reduce energy expenditures.

When modelling energy demand, it is vital to distinguish between short-run and long-run scenarios. So far, we have looked at a scenario in which a household can freely choose and change inputs for the production of energy services. However, this flexibility is only available in the long run. Now, we will discuss a model of production in the short run, where the capital stock is fixed and cannot be changed. Once more, Figure 3.5 shows two isoquant curves with energy on the horizontal axis and capital on the vertical axis. In this scenario, the capital stock is fixed at C^*. In this case, a household can only decrease its energy consumption by decreasing the level of energy services produced. This could manifest in a reduction of room heating from 20°C to 18°C.

Of course, the question of which combination is the best for the household, that is, which combination minimises the cost to produce the energy service Q_2, arises from this optimisation exercise. Naturally, the optimal choice depends on the capital and

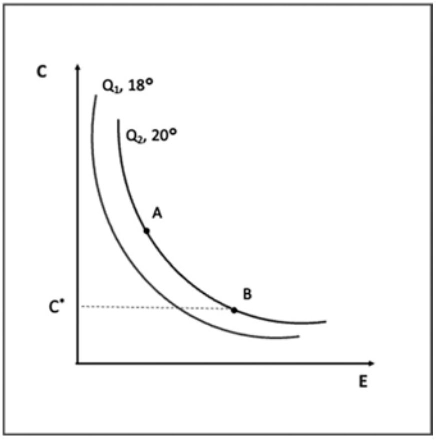

Figure 3.5 Optimisation of energy service production with fixed capital stock using isoquants

energy prices that determine the slope of the isocost lines at different points. If the isocost curve is tangential to the isoquant at point B, then the household is minimising the heating expenditures and the fixed capital stock is no longer a constraint. However, if the isocost curve is tangential to the isoquant at A, then the capital stock at C^* is binding, and the household has higher heating costs than it would in the long run at point A.

3.2.3 Analytical Representation of Household Choices

From a mathematical point of view, the optimisation problem of households involves the maximisation of the utility function subject to an income restriction, as well as the restriction related to the minimisation of production costs. The optimisation process in the long run (when all production factors and inputs are flexible or can be adjusted) can be represented as follows:

$$\begin{aligned} &max\ U(ES(E,CS),OG) \\ &s.t.\ C(P_E,P_{CS},ES) + P_{OG}OG \leq Y \end{aligned} \tag{3.4}$$

U: Utility
ES: Energy services
E: Energy
CS: Capital stock
OG: Consumption of other goods
P_E: Price of energy
P_{CS}: Price of capital stock
P_{OG}: Price of other goods
Y: Household income

In the constraint in Equation 3.4, we substitute the expenditure for energy services (given by its price multiplied by its quantity) with a cost function to underline the fact that these services are produced by households. This optimisation exercise assumes that there are constant returns to scale so that the cost of producing energy services can be simplified as the price of energy services multiplied by the level of energy services produced given by the formula:

$$C(P_E,P_{CS},ES) = P_{ES} \cdot ES \tag{3.5}$$

Upon the maximisation of the utility function under the constraints presented in Equation 3.4, four equations are obtained. These describe the demand for: energy services (ES), other goods (OG), energy (E), and capital stock (CS).

$$ES = f(P_{ES},P_{OG},Y) \tag{3.6}$$

$$OG = g(P_{ES},P_{OG},Y) \tag{3.7}$$

$$E = h(P_E,P_{CS},ES,P_{OG},Y) \tag{3.8}$$

$$CS = j(P_E,P_{CS},ES,P_{OG},Y) \tag{3.9}$$

In Equation 3.8, the household energy demand curve is in the long run. As can be deduced from the expression, the long-run energy demand depends on the price of energy (P_E), the price of the capital input (P_{CS}), the level of energy services produced (ES), the price of other goods (P_{OG}), and the household income (Y). The fourth expression represents the demand for capital stock, for instance, for appliances, heating systems, and so on, which is also very important for the analysis of energy demand.

In the short run, the capital stock is generally considered to be fixed, that is, it cannot be varied. For instance, in the short run, a household is not able to change an old and inefficient washing machine because of the increase in electricity prices. Often, households need time to substitute an old washing machine with a new energy-saving one. Therefore, it is normal to assume that the capital stock is fixed and therefore, the variation of the energy demand depends only on the variation in the demand for energy services. This implies that to reduce energy consumption, households can only engage in behavioural changes in energy consumption and not by investing in energy efficiency.

The optimisation problem faced by a household in the short run is almost identical to the long-run optimisation problem previously discussed. The only difference is that in the short run, the capital stock is fixed. The mathematical expression for the short-run problem is given by:

$$\begin{aligned} &max\ U(ES(E,\overline{CS}),OG) \\ &s.t.\ C(P_E,\overline{CS},ES) + P_{OG}OG \le Y \end{aligned} \tag{3.10}$$

U: Utility
ES: Energy services
E: Energy
$\overline{CS}$: Capital stock
OG: Consumption of other goods
P_E: Price of energy
P_{OG}: Price of other goods

P_{ES}: Price of energy services
Y: Household income

From this optimisation problem, we obtain:

$$ES = f(P_{ES}, P_{OG}, Y) \tag{3.11}$$

$$OG = g(P_{ES}, P_{OG}, Y) \tag{3.12}$$

$$\underbrace{E = h(P_E, \overline{CS}, ES, P_{OG}, Y)}_{\textit{short run energy demand}} \tag{3.13}$$

The third expression derived above ($E = h(P_E, \overline{CS}, ES, P_{OG}, Y)$) is the household energy demand curve in the short run. As can be deduced from the expression, the short-run energy demand depends on the price of energy (P_E), the fixed capital input ($\overline{CS}$), the level of energy services produced (ES), the price of other goods (P_{OG}), and the household income (Y).

This mathematical derivation of energy demand using household production theory is amenable for empirical researchers who want to perform an empirical analysis because it helps in specifying a model grounded in economic theory.

From the results of the optimisation process of the households in the short run as well as in the long run, we can learn three things:

1. In the long run, energy demand depends not only on the energy price but also on the price of the capital stock, that is, on the price of the technology that is used in the production process of the energy services.
2. In the short run, households are not able to change the capital stock. Therefore, the energy demand depends on the energy price, as well as on the level of capital stock. This implies that in the short run, the capital price is replaced with the capital stock.
3. The energy demand depends on the level of energy services consumed by a household, in both the short run and in the long run.

The models 3.8 and 3.13 are simplified representations of factors that influence energy demand. In empirical specifications, researchers generally augment these models with variables that represent geographical (cultural, climate-related, lifestyle-related, spatial organisation of the society, etc.) and technological factors (technical change and efficiency of the production process). Moreover, in case information on energy services is not available, researchers can use several socioeconomic variables (such as income, age, household size, dwelling size, etc.) to proxy the consumption of energy services.

3.3 Empirical Analysis of the Residential Energy Demand

As mentioned before, the main goals of these types of empirical analyses are:

- The estimation of the impact of price and income changes on energy demand.

- Analysis of the effect of socioeconomic and climate-based factors (e.g., age and climate) and of policy instruments (e.g., subsidies, standards, and carbon taxes) on the level of energy demand.
- Forecasting energy demand.

Empirical analysis of energy demand can make an important contribution to policy-making processes and is thus critical. Therefore, it is important to understand the methods for deriving the empirical results that are normally presented in scientific studies and reports. In this section, we provide a brief overview of this process.

3.3.1 Steps in the Empirical Estimation of an Energy Demand Model

Generally, researchers interested in the empirical estimation of an energy demand model follow five steps, as depicted in Figure 3.6. These steps are based on three components:

- Economic theory, for instance, household production theory.
- Data collection.
- Econometric methods (i.e., statistical and mathematical methods applied to the analysis of economic problems), such as regression analysis.

In the first step of the estimation of energy demand, researchers need to identify the main goals of their research. For instance, a study might set the aim to estimate price elasticity or the impact of a policy on energy demand.

In the second step, the empirical model needs to be specified while considering theoretical assumptions, such as the assumptions of household production theory.

The third step of the empirical analysis involves data collection and the construction of a data set. This step might be the most time-consuming step of the analysis.

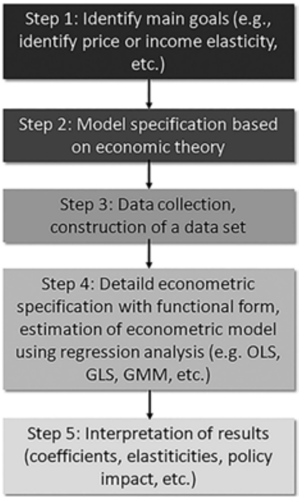

Figure 3.6 Steps for estimating the energy demand and capital stock demand models

In step four, the econometric model is specified in more detail using an appropriate functional form (choice between linear, log-log, etc.) and the model is estimated using the appropriate econometric methods.

As a last step, the estimated coefficients have to be interpreted in the context of the research question asked.

It is important to note that there are several types of data that can be used in the estimation of an empirical energy demand model for the residential sector. On the basis of the level of aggregation, we can have either aggregated or disaggregated data sets. This data is either collected by a researcher, or by a data collector or a marketing company by doing a survey, or it could also be administrative data, that is, data collected on a regular basis by an institution such as a statistical office or a firm. While the former are called primary data, the latter are also referred to as secondary data.

A disaggregated data set includes information at the unit or individual level (for instance, on the levels of consumption, preferences, characteristics, etc., of households). An aggregated data set contains information aggregated to the local or regional (or even national) level. This kind of data is often collected periodically by statistical offices of governments. In the next subsection, we discuss in some detail elements of steps 2 and 4, which are relevant for empirical analysis and provide a simple example of the estimation of an electricity demand function.

3.3.2 Model Specification

Following household production theory, a simple empirical energy demand model as the one specified in Equation 3.14 should include the energy price (P_E), capital price (P_{CS}), level of energy services (ES), and the level of energy efficiency of the technology (EE), which is usually approximated by using a time trend (a continuous variable capturing the change in time), as explanatory variables.

$$E = h(P_E, P_{CS}, ES, EE) \tag{3.14}$$

From an empirical point of view, it is important to enrich model 3.14 using other explanatory variables that may influence energy demand, such as weather conditions, or institutional or cultural factors. This is important to account for other potentially observed factors that play a role in affecting energy demand.

An enriched energy demand model can look like the following expression:

$$E = h(P_E, P_C, P_{OG}, I, ES, G, T) \tag{3.15}$$

E: Energy demand
P_E: Price of energy
P_C: Price of capital
P_{OG}: Price of other goods
I: Income
ES: Level of energy services
G: Vector of geographical factors
T: Vector of technological factors including energy efficiency (EE)

Table 3.1 Energy resources and market forms

Model	Equation	Slope (dE/dP)	Price elasticity
Linear	$E = \beta_0 + \beta_{P_E} \cdot P_E$	β_{P_E}	$\beta_{P_E}(P_E/E)$
Log-log	$\ln E = \beta_0 + \beta_{P_E} \ln P_E$	$\beta_{P_E}(E/P_E)$	β_{P_E}

We should note that information on the level of energy services, for instance, on the frequency of cooking, or on the use of dishwashers and washing machines per week, is generally not available, or can be difficult to collect. To overcome this issue, empirical researchers have proposed to approximate the level of energy services with several socioeconomic variables, such as the number of rooms in the house, income, household size, age, gender, or number of children. Another difficulty for empirical researchers is to obtain information about the price of capital, that is, the cost of using appliances such as washing machines and heating systems and the capital stock. Researchers try to solve this problem by assuming that the capital price or capital stock is the same for all households or by applying a specific econometric method such as a fixed effects model, which takes into account any unobservable factors that are time-invariant and may explain energy demand.

3.3.3 The Typical Functional Forms for Demand Analysis

The two most used functional forms in the estimation of energy demand models for the residential sector are the linear and the log-log forms. Table 3.1 presents these two functional forms for a simple energy demand model with just one explanatory variable (P_E).

Using these functional forms, it is possible to compute price and income elasticities, which provide information on the impact of a price change (or income change) on the demand for a good. These can be categorised as short-run or long-run own-price elasticities (E_p), cross-price elasticities (E_{pc}), and income elasticities (E_Q).

The own-price elasticity of demand (E_p) measures the percentage change in quantity demanded of a good as a result of a percentage change in the price of the same good. The mathematical expression of the own-price elasticity is:

$$E_p = \frac{\Delta Q}{\Delta P} * \frac{P}{Q} \tag{3.16}$$

Where E_p is the own-price elasticity, Q is the quantity demanded, and P is the price of the product. A value of $E_p > 1$ indicates price-elastic demand, a value < 1 suggests price-inelastic demand.

The cross-price elasticity of demand (E_{pc}) measures the percentage change in the quantity of a product demanded by consumers as a result of a percentage change in the price of another product. The mathematical expression of the cross-price elasticity is:

$$E_{pc} = \frac{\Delta Q}{\Delta P_O} * \frac{P_O}{Q} \tag{3.17}$$

Where E_{pc} is the cross-price elasticity and Q is the quantity of the product demanded, and P_O is the price of the other product.

The income elasticity of demand I_Q measures the percentage change in consumption of a product as a result of a percentage change in the income of the consumers. The mathematical expression of income elasticity is:

$$I_Q = \frac{\Delta Q}{\Delta I} * \frac{I}{Q} \tag{3.18}$$

Where I_Q is the income elasticity, I is the income of the consumers, and Q is the quantity demanded by the customers.

In the regression model using the linear functional form, the own-price elasticity is computed by multiplying the coefficient β_{P_E} with the price of energy P_E, and dividing by the level of energy consumption (E). Therefore, the value of the elasticity depends on the values taken by P_E and E. This implies that the elasticity varies with both the price level of energy and the level of energy consumption. In applied work, it is a common practice to measure elasticity at the mean or median point of the variables for P_E and E.

On using the log-log functional form, the defined own-price elasticity only depends on the coefficient β_{P_E}, that is, it is independent of the level of energy consumption. This is an interesting property of the log-log functional form, as it means that the elasticity may be directly inferred from the regression output.

3.3.4 Estimation of a Simple Electricity Demand Function: Example from a Developing Country

The following example, based on data on Indian households, serves to explain how an electricity demand function might be estimated in practice in an intuitive fashion, using a simplified model. The general model specification is denoted as:

$$E = h(P_E, Y) \tag{3.19}$$

Using a log-log functional form, Equation 3.19 can be rewritten as:

$$\ln E = \beta_0 + \beta_{P_E} \cdot \ln P_E + \beta_Y \cdot \ln Y + \epsilon \tag{3.20}$$

where:
E: Energy demand
P_E: Price of energy
Y: Household income
ϵ: Idiosyncratic error term

To estimate this model, we used household expenditure data collected by the National Sample Survey Organisation, Department of Statistics, Government of India. An enlarged version of this data set has been used for the estimation of more rich electricity demand models by Filippini and Pachauri (2004) [41]. Equation 3.20 is normally estimated using the popular regression-based econometric methodology – Ordinary

Table 3.2 STATA regression output of OLS estimation

Explanatory variables	Value of coefficient	Standard errors	t-values	$P > \|t\|$	95% confidence interval	
$\ln P_E$	−0.309	0.038	−8.12	0.0	−0.383	−0.234
$\ln Y$	0.762	0.023	33.18	0.0	0.717	0.807
Constant	−1.770	0.135	−13.16	0.0	−2.034	−1.506

Least Squares (OLS). Table 3.2 reports the STATA regression output of an OLS estimation of Equation 3.20 using information for a sample of 1999 Indian households. The value of the coefficient of determination (or R-squared) for this model is 0.35. This indicator provides information on the goodness-of-fit measure for linear regression models. A value of 0.35 indicates a good fit for a demand model estimated using cross-sectional data. The F-statistic for this model is 553, indicating that the model with these two explanatory variables provides a better fit than a model with no independent variables. The coefficient β_{P_E} is estimated to be −0.31, while the coefficient β_Y is estimated as 0.76. Given the functional form of a log-log regression, these estimates can be directly interpreted to be the price elasticity and income elasticity, respectively. The standard errors and t-values presented in the table can be used to ascertain the statistical significance of the estimation results. As a general rule, results are considered statistically significant if the t-value in absolute terms is equal to or larger than 1.96. At this value, the significance level of the estimation results is 95 per cent or higher, or the p-values (mentioned in the fourth column of the table) are lower than 5 per cent. As this condition is fulfilled for both of the coefficients, they can be said to be statistically different from 0. STATA is one example of statistical software that can be used for conducting econometric analysis of this nature. R, Python, and LIMDEP are some other software packages which are commonly used.

3.3.5 Estimation of a Capital Stock Demand Model

As shown in the theoretical discussion of household production theory, the demand for capital stock, that is, demand for electrical appliances, heating systems, and cars, plays an important role in determining the level of energy consumption. Therefore, the empirical estimation of this type of demand is also insightful. The demand for capital stock can be represented by the following model:

$$CS = j(P_E, P_{CS}, ES, P_{OG}, Y) \tag{3.21}$$

where:
CS: Capital stock or capital
P_E: Price of energy
P_{CS}: Price of capital
ES: Energy services
P_{OG}: Price of other goods
Y: Household income

The estimation of a capital stock demand model is similar to the one of an energy demand model with two small differences:

- First, the dependent variable measuring the capital stock can either be continuous (e.g., the installed capacity of electrical appliances in Watts, the capacity of a heating system, and the number of electrical appliances or cars) or dichotomous (ownership of an appliance, of a car, or of a heating system). A continuous dependent variable can take on any value in the range of the corresponding mathematical function, while a dichotomous dependent variable will only take on values of zero or one and can be used to estimate the probability with which a household is likely to own or buy an energy-efficient washing machine, for instance.
- Second, and relatedly, the econometric models used to estimate the demand for capital stock when the dependent variable is dichotomous are usually probit or logit regression models, that is, non-linear estimation models, and not the OLS method. Of course, some researchers in this case may also choose to use a linear probability model using the OLS method, and therefore reduce the non-linear specification to a linear one. However, this approach has some econometric limitations, as discussed by Greene (2018) [42]. In the case of the estimation of a capital stock demand model, researchers proceed in steps as with the estimation of energy demand models, and as previously illustrated in Figure 3.6.

3.3.6 Estimated Residential Energy Price Elasticities

Table 3.3 lists the values of the residential energy own-price elasticities obtained across several empirical studies. As these entries suggest, the majority of the values are less than 1. Moreover, studies that are able to estimate both short-run and long-run elasticities obtain, as expected, values for the short-run elasticities that are smaller than the long-run values. This is due to the fact that in the short run, as previously discussed, it is not possible to change the capital stock. Therefore, the only way to reduce energy demand in the short run is through a reduction in the use of energy. It is important to note that in Table 3.3, if we do not mention whether the computed elasticities are short-run or long-run in the first column, then the study does not distinguish between both time horizons in calculating elasticities.

Empirical Example of Using Energy Services in Electricity Demand Estimation

In a study on residential electricity demand estimation for Switzerland, Boogen et al. (2021) [43] estimated an empirical model derived by applying household production theory, and the study used disaggregated data on about 5,000 households collected using a longitudinal household survey. The electricity demand levels estimated in this study were said to depend on the level of energy services.

The authors described two different types of energy demand models, and both were estimated using a log-log functional form. One identification strategy was based on using household activities (such as cooking, washing, and entertainment) to infer the level of energy services, as electricity is consumed to provide these energy services; the other model specification used a number of household and socioeconomic characteristics to proxy for this variable [43].

In the first model specification, the demand for energy can be considered to be guided by the price of capital (P^K) (such as the prices of household appliances), the price of electricity (P^E), and the energy services (S) consumed by the household, as presented in Equation 3.22.

$$E^* = E(P^E, P^K, S^*) \tag{3.22}$$

In the absence of data on energy services, however, we can also express the demand for electricity in a more simplistic form, by approximating the amount of energy services (S) using socioeconomic variables (denoted by (Z)) and household income (M):

$$E^* = E(P^E, P^K, M, Z) \tag{3.23}$$

Of course, the use of socioeconomic variables to substitute for energy services can lead us to miss out on some important information and thus may result in omitted variable bias. The estimated price elasticity using both model specifications is around −0.7 in this study. This implies that the use of pricing policies can potentially help to reduce the consumption of electricity in Switzerland.

Table 3.3 Values of residential energy price elasticities

Elasticity	Energy Type	Region	Study
[−0.5, −0.4]	Electricity	India	Filippini and Pachauri, 2004 [41]
−0.2	Electricity	United Kingdom	Dimitropoulos et al., 2005 [44]
Long−run: [−0.7, −0.2]	Electricity	Japan	Hunt and Ninomiya, 2005 [45]
Short−run: [−0.1, −1.7] and Long−run: [−1.6, −1.5]	Electricity	G7 countries	Narayan, Smyth and Prasad, 2007 [46]
[−0.7, −0.6]	Electricity	OECD countries	Krishnamurthy and Kriström, 2015 [47]
−0.4	Electricity	Germany	Schulte and Heindl, 2017 [48]
[−0.5, −0.3]	Electricity	India	Chindarkar and Goyal, 2019 [49]
−0.06	Electricity	China	Li et al. 2020 [50]
Short to medium run: −0.7	Electricity	Switzerland	Boogen et al. (2021) [43]
[−0.36, −0.26]	Gasoline	India and China	Dahl, 2012 [51]
[−0.22, −0.13]	Diesel	India and China	Dahl, 2012 [51]
Short-run: −0.23 and Long-run: −0.51	Gasoline	Switzerland	Filippini and Heimsch (2016) [52]

Table 3.3 (cont.)

Elasticity	Energy Type	Region	Study
−0.73	Gas	Switzerland	Filippini and Kumar (2021) [53]
Long-run: −1.25	Gas	Forty-four countries	Burke and Yang (2016) [54]
Short-run: −0.08 and Long-run: [−0.08, −0.06]	Gasoline	USA	Coyle et al. (2012) [55]
Short-run: −0.16 and Long-run: −0.43	Gasoline	Fourteen OECD countries	Liddle (2012) [56]
Short-run: [−0.06, −0.15] and Long-run: [−0.06, −0.39]	Gasoline	Mexico	Crotte et al. (2010) [57]

3.4 The Empirical Analysis of the Industrial Energy Demand

Besides residential demand, another topic of natural interest is industrial energy demand. In this section, we will discuss how industrial energy demand can be empirically estimated.

According to production and cost theory, firms use inputs (in general – capital, labour, and energy) in a production process to produce goods, while trying to minimise their costs. We can represent the typical production function for the industrial sector as follows:

$$Q = Q(E, C, L) \tag{3.24}$$

where:
Q: Output
E: Energy
C: Capital
L: Labour

Generally, these inputs (energy, capital, and labour) can be substituted for one another in production. Given a predefined level of production, by substituting across inputs, firms can then attempt to minimise their costs.

The optimal choice of inputs to produce a predefined level of output by minimising costs can be represented either graphically or by using mathematical expressions. In the first illustration, in order to simplify the representation, just two inputs are considered: capital and energy. However, while using mathematical expressions, it is possible to consider all inputs in the empirical analysis.

As is apparent from Figure 3.7, with energy (E) on the horizontal axis and capital (C) on the vertical axis, the goal of the firm is to minimise its production costs (still captured by the isocost line IC_1) of achieving a predefined level of output (denoted by the isoquant Q_1). Such an optimal point is reached, as illustrated when the isocost line is tangential to the isoquant curve at point A.

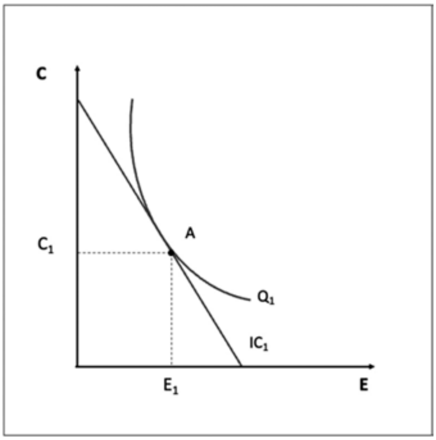

Figure 3.7 Finding the optimal choice of inputs

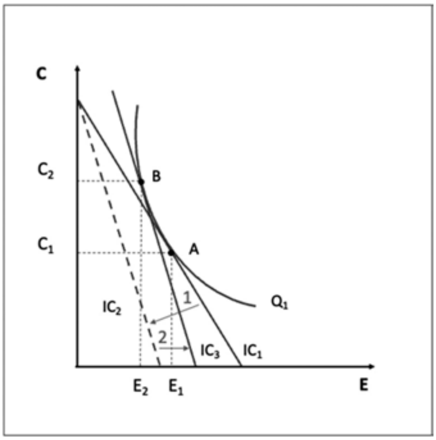

Figure 3.8 Impact of price increase on capital and energy demand of firms

It is useful to graphically represent the change in the energy demand of a firm when energy prices increase. This change is shown with the help of Figure 3.8 with capital (C) on the y-axis and energy demand (E) on the x-axis. If the price of energy increases, the isocost curve IC_1 changes its slope to reflect this change (as denoted by shift 1). In this case, the slope of the isocost line IC_2 is steeper (since energy prices have increased). When energy becomes more expensive, firms can buy less energy with the same amount of financial resources. However, with this rotation of the isocost line from IC_1 to IC_2, a firm can no longer maintain the same level of output (if it is constrained to the same cost). This is reflected in the graph by the distance between the rotated isocost curve IC_2 and the initial isoquant Q_1 denoting a specific level of output. In order to attain the original level of output denoted by Q_1, firms are forced to increase their cost, which would then lead to a shifting of the isocost curve from IC_2 to the IC_3 (denoted by shift 2). The final allocation of resources once again lies on the initial isoquant; however, the new combination shows an increase in capital and a decrease in energy inputs at point $B(E_2,C_2)$, compared to the initial capital and energy combination at point $A(E_1,C_1)$. The substitution of energy with capital can depend on many factors, such as the technology used for production, the sector or industry, the kind of goods that are produced, and so on. A measure of the ease with which a factor like energy can be substituted for another input is called the elasticity of substitution. This elasticity indicates the degree to which one input can be substituted with another input. From an empirical point of view, the elasticity of substitution is also an interesting parameter to estimate using empirical methods.

3.4.1 Energy Demand Function

In this section, we use mathematical approaches to derive input demand functions of firms, whereas in the previous section, we used the graphical approach. From a microeconomic point of view, it is possible to mathematically derive the firm-level energy demand model by solving a cost minimisation process. In this framework, a firm wants to produce an output using inputs; in general, labour, capital, and energy. The objective of the firm is to minimise its production costs, given its level of output. To derive an energy demand function in the long run, the minimisation problem is defined as:

$$\begin{aligned} &\min\,(P_E\cdot E+P_C\cdot C+P_L\cdot L)\\ &s.t.\,Q=Q(E,C,L)\end{aligned} \tag{3.25}$$

Where:
P_E: Price of energy
E: Energy
P_C: Price of capital
C: Capital
P_L: Price of labour
L: labour
Q: Production output

Intuitively, this means that the firm tries to minimise the expenditures on production inputs, given the production function. From this optimisation exercise, we can derive the long-run demand functions for the three inputs – energy, capital, and labour, respectively:

$$E=h(P_E,P_C,P_L,Q) \tag{3.26}$$

$$C=c(P_E,P_C,P_L,Q) \tag{3.27}$$

$$L=l(P_E,P_C,P_L,Q) \tag{3.28}$$

As in the case of households, the short-run optimisation process for the firm is similar to the long-run optimisation, with the difference that capital is now a fixed input. Accordingly, the optimisation for the firm in the short run is given by:

$$\begin{aligned} &\min\,(P_E \cdot E + P_C \cdot \overline{C} + P_L \cdot L) \\ &s.t.\, Q = Q(E,\overline{C},L) \end{aligned} \tag{3.29}$$

P_E: Price of energy
E: Energy
P_C: Price of capital
$\overline{C}$: Capital (fixed)
P_L: Price of labour
L: Labour
Q: Production output

From this, the demand functions for the two variable inputs in the short run are derived as follows:

$$E = h(P_E,\overline{C},P_L,Q) \tag{3.30}$$

$$L = l(P_E,\overline{C},P_L,Q) \tag{3.31}$$

From an empirical point of view, to obtain values of the elasticity of substitution, and own-price and cross-price elasticities of the inputs, the system of equations represented by Equations (3.26)–(3.28) or (3.30)–(3.31) is estimated. Another approach used in empirical studies is to add a cost function to this system of equations.

Researchers interested in the empirical estimation of elasticities of substitution can follow the same five steps discussed and depicted in Figure 3.6. The typical functional form used in this type of research is the trans-log functional form that is based on Taylor's approximation of a true function and thus includes squared and cross-terms of the explanatory variables.

3.4.2 Estimated Industrial Energy Price Elasticities

In Table 3.4, we exemplify the values of the price elasticities for firms and provide evidence from several empirical studies. These values are relatively low and indicate that the energy demand in the industrial sector tends to be rather inelastic. This means that it is not very easy to substitute away energy with capital. Some studies also estimate the elasticities of substitution, as depicted in Table 3.5. Based on a study for ten OECD countries, Kim and Heo (2019) [58] also provide a comprehensive review of the studies that estimate the elasticities of substitution and reach the conclusion that there is an asymmetry in terms of the elasticities of substitution of energy and capital, wherein they discuss that the substitution of energy for capital dominates (i.e., is easier) than the substitution of capital for energy.

Role of management practices in firm-level energy demand

A new stream of empirical economic literature has examined the role of management practices in determining the energy demand at the firm level, and several studies on industrialised countries have found that management practices are strongly correlated with reductions in energy intensity (energy demand per unit of output, measured in either physical units or in expenditure terms) (such as

Bloom et al. (2010) [59] and Martin et al. (2012) [60]). Grover and Karplus (2020) [61] investigated this question using cross-country data for a sample of countries, including some developing countries. The authors measured the effect of both general management practices (such as monitoring, incentives, targets, and operations practices) and energy-specific management practices (such as monitoring and target-setting related to energy efficiency) on energy intensity. They found that better general management practices were associated with declines in energy intensity (measured in expenditure terms), but not with declines in energy intensity measured in physical units. They attributed this difference, among other factors, to a focus of managers on saving costs, and not necessarily on mitigating environmental impact. Moreover, they found that energy-specific management practices didn't have any additional effects on improving energy intensity, over and above the general management practices. Thus, it is important to understand firms' incentives to reduce energy, as well as to what extent they may need to make adjustments such as capital investments in order to reduce energy demand. This study hints at the importance of future research to understand the role of management (as well as the behavioural traits of owners and managers) in determining energy demand at the firm level.

Table 3.4 Price elasticity in the industrial sector

Elasticity	Energy type	Region	Study
[−0.6, −0.4]	Electricity	United States	Kamerschen and Porter, 2004 [62]
Short-run: −0.2 Long-run: −0.2	Electricity (manufacturing)	United Kingdom	Dimitropoulos et al., 2005 [44]
Long-run: [−0.6, −0.5]	Electricity	OECD countries	Adeyemi and Hunt, 2007 [63]
Short-run: [−0.09, −0.3] Long-run: [−0.1, −0.6]	Electricity	Japan	Hosoe and Akiyama, 2009 [64]

Table 3.5 Elasticity of substitution in the industrial sector between energy and capital

Elasticity of substitution	Region and sector	Study
Energy with capital: 1.0295	Chinese machinery-based industry	Lin and Liu (2017) [65]
Capital with energy: 1.496	Irish manufacturing firms	Haller and Hyland (2014) [66]
Energy with capital: 1.543	Irish manufacturing firms	Haller and Hyland (2014) [66]
Energy with capital: 0.15–0.35	10 OECD countries	Kim and Heo (2013) [58]
Capital with energy: 1.11	Italian manufacturing firms	Bardazzi et al. (2015) [67]
Energy with capital:0.602	Italian manufacturing firms	Bardazzi et al. (2015) [67]

3.5 Issues in Developing Countries

Developing countries face challenges in terms of ensuring universal access to affordable energy. Furthermore, given credit/liquidity constraints, many households (and firms) are unable to invest in energy-saving technologies. In this section, we will highlight two elements of household production theory that we believe are likely to be more relevant for developing countries. We first discuss how the household production theory may need to be modified to account for different sources of energy used in developing countries, and the opportunity cost of time in collecting these sources. We then discuss the role of income in determining investment decisions of households with respect to the purchase of durables such as appliances, given that these countries are likely to experience significant growth in the coming years.

3.5.1 Household Production Theory in Developing Countries

Energy demand in developing countries is usually met by using a variety of energy sources, and the ‘energy-ladder’ theory suggests that as household incomes increase, they are more likely to switch from dirtier to cleaner sources of energy. However, in reality, households often follow the ‘energy-stacking’ model, whereby they use multiple energy sources at the same time. In this context, the household production theory that we introduced earlier is an interesting theoretical framework to evaluate energy demand in developing countries. This theory should be augmented to account for (1) the differences in types of energy used and (2) time spent in acquiring energy (such as firewood, kerosene, charcoal, etc.) in developing countries. For the first point, the theory should consider that production functions change over time due to the use of different fuels or energy sources (as well as appliances). For the second point, the production function for energy services should incorporate labour/leisure as an input.

Many people in the developing world still live without access to electricity: the number of households without electricity increased between 2019 and 2021 in sub-Saharan Africa, for instance. The start of the pandemic in 2020 made it difficult for households to be able to pay for using grid-based electricity, which implies that many households began to rely on small systems that provided fewer energy services. As we will discuss in more detail in Chapter 4, while these systems are useful for increasing initial access to energy services, they may not be optimal for intensifying the use of energy. In a similar vein, the transition to clean cooking has also witnessed a slowdown in recent years. The fuel-stacking literature suggests that households often use dirtier fuels or energy sources in tandem with cleaner fuels, even when their income levels increase, and this has been observed to be the case for the use of cooking fuels in developing countries. Households may not easily switch to cleaner energy sources such as liquefied petroleum gas (LPG) or electricity in entirety, as long as it is possible to acquire firewood, charcoal, or kerosene at a relatively inexpensive cost. The pandemic also made it difficult for households to be able to pay for modern fuels, which implies that many households increased their use of traditional biomass and firewood, and spent more time at home with increased exposure to indoor air pollution. An application of household production theory to developing countries needs to take into account these facts.

Furthermore, as highlighted earlier, time spent collecting fuel can play a role in determining household welfare from using energy sources. Many households need to spend several hours collecting firewood for cooking or heating purposes, which has some opportunity costs (in terms of time spent for labour or leisure). This implies that labour/leisure should also be introduced as an input in household production theory, to make it amenable for developing countries. There is also an important gender dimension to this issue, as females in households are more likely to spend more time collecting fuel for cooking or heating purposes. Thus, different members of the same family can have different constraints, which is also important to consider when applying household production theory.

Given these considerations, financial support for poor households (such as through lower electricity tariffs or subsidised access to clean cooking fuels) may be necessary to hasten the switch to modern energy sources in these countries.

Economics of household technology adoption in developing countries: Evidence from solar technology adoption in rural India

Based on the case of solar-microgrid technology adoption, Aklin et al. (2018) [68] investigated the determinants of solar technology adoption by households in rural India. Potential differences across products were controlled for by offering identical solar technologies to all households in the study sample. The authors found that the main determinants of technology adoption decisions were high household savings and expenditures, along with an entrepreneurial attitude of the household members. On the other hand, community trust, acceptance of the risks related to the durability and quality of the product, and past fuel expenditures did not influence these decisions. Risk aversion was less important when compared to the entrepreneurial spirit of the people when adopting new technologies. However, the reliability of the technology played an important role in determining adoption. From this study, we learn that income and expenditure are important predictors of technology adoption, thus perverse policies such as providing generous subsidies for dirty fuels like kerosene have the potential to reduce the competitiveness (and appeal to consumers) of alternative renewable technologies such as solar power.

3.5.2 Energy-consuming Asset Ownership and the Role of Income

As we learnt from household production theory, capital stock is an important input in energy service production. Current levels of capital stock, such as appliances, are low on average in developing countries, but we can expect this to change, which will result in an increase in energy demand. Related to this point, a factor that is likely to contribute to the increase in energy demand in developing countries is a warming climate: for example, the demand for air conditioners is expected to increase significantly as many countries become warmer. Given that air conditioners consume significantly more energy than other cooling appliances, such as ventilators, this is also likely to catapult electricity demand.

While it is likely that only high-income households will start purchasing appliances such as air conditioners at the beginning, as incomes increase, this share is likely to increase as well. This has important implications for emissions, given that a large share of the electricity in developing countries continues to be generated using fossil fuels. On the other hand, energy efficiency levels have improved tremendously in the past few years, and at least some of these improvements are likely to continue in the coming decades. However, for sustained decarbonisation, other policies such as minimum energy efficiency standards, electricity pricing, as well as increased adoption of renewables, in particular solar, need to be implemented.

The demand for energy-using assets among the world's rising middle classes

Wolfram et al. (2012) [69] observed that there is an 'S-shaped pattern' between household consumption expenditure and energy-consuming asset ownership (such as refrigerators or cars); for instance, they showed that among the bottom 10 per cent of Mexican households in the year 2000 based on consumption expenditure, both fridge and car ownership were sparse. Middle-income households were more likely to become first-time owners of appliances and cars, whereas, at relatively higher levels of expenditure, adoption levels stabilised. At lower levels of income, due to the presence of credit constraints, for example, households may be unable to buy appliances or cars. Thus, ownership rates for durables such as appliances and vehicles are more likely to increase at middle-income levels (i.e., for households just emerging from poverty) than for upper-income households.

A model of energy poverty and access: Estimating household electricity demand and appliance ownership

Poblete-Cazenave and Pachauri (2021) [70] used a different approach based on a structural estimation approach to estimate energy demand. They relied on simulated data and incorporated different policy scenarios. The countries that they included in their analysis were Ghana, Guatemala, India, and South Africa. In the scenario analysis, the authors establish that higher levels of urbanisation and income growth were associated with higher electricity demand, even if population growth rates were reduced. An important result was that the share of electricity consumption for entertainment purposes (such as for televisions) was high in all countries and remained stable with income increases. On the other hand, the share of electricity consumption for food preparation and clothes maintenance only increased with increases in income. Thus, this study showed that there is significant heterogeneity in terms of the sources of increase in electricity consumption, and thus energy demand, among households in developing countries.

3.5.3 Review Questions and Problems

The online question bank contains review questions and problems for this chapter, including solutions (see https://wp-prd.let.ethz.ch/exercisesfortextbookeep/).