5 Economics of Energy Efficiency

As discussed in Chapter 1, it is important to promote the adoption of renewable energy sources, modify our lifestyles, and increase energy efficiency to reach the energy transition. Currently, the economic systems of industrialised and developing countries are still characterised by significant levels of inefficiency in the use of energy, that is, by production and consumption processes that waste energy. Therefore, improving energy efficiency is one of the cheapest and most environmentally friendly strategies to transform the energy sector. For this reason, since the oil crises of the seventies of the last century, several countries worldwide have implemented important energy policy instruments to promote energy efficiency and reduce the wastage of energy.

In this chapter, we will introduce the definition of energy efficiency, discuss the approaches that can be used to measure it, and elucidate some of the common barriers towards achieving a high level of energy efficiency.

5.1 Energy Efficiency

5.1.1 Definition

While the definitions of energy efficiency vary between engineering and energy economics, in this book we provide a definition based on the microeconomic theory of production. In this theoretical framework, as depicted in Figure 5.1, and discussed in Chapter 3, alongside capital (such as insulation in a building and ventilation systems) and labour, energy is considered to be an essential input used in the production of goods such as machines, cars, and in the production of energy services such as heating and cooling.

This implies that the demand for such inputs depends on the demand for energy goods and services.

The relationship between the use of energy inputs and outputs is used to measure the level of energy efficiency. A production process is said to be energy efficient if it is not possible to produce the same level of energy services or goods with less energy. Similar efficiency measures can be defined for the other production inputs as well (e.g., labour efficiency or capital efficiency). More generally, the overall level of productive efficiency is based on the relationship between inputs and the output, that is, the final good or service produced.

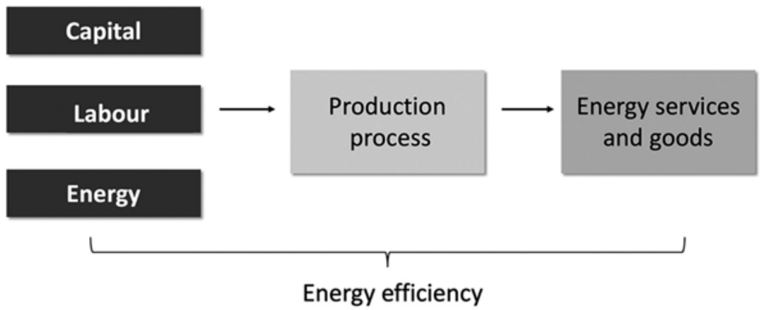

Figure 5.1 Energy efficiency and productive efficiency

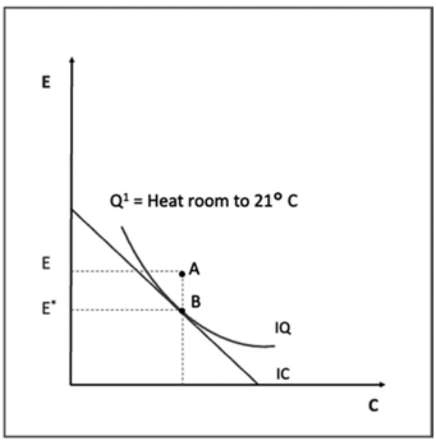

Figure 5.2 Inefficient use of technology

5.1.2 Reasons for Inefficiencies

Inefficiencies in the use of energy can arise in at least three situations: inefficient use of technology, inefficient combination of inputs to produce output, or employment of obsolete technologies.

In Figures 5.2 to 5.4, we illustrate these three situations that can give rise to energy inefficiency using isoquant and isocost lines. All graphs depict a simple production model with capital (C) on the x-axis and energy use (E) on the y-axis, as well as an isocost line (IC) and an isoquant curve (IQ). All points on the isocost line depict combinations of inputs with the same total cost, while all points on the isoquant curve are combinations of inputs that yield the same output. In the following examples, the energy service produced is the heating of a room to 21°C.

Consider a situation in which the inefficient use of technology leads to a loss in energy efficiency. In our example related to the production of a heating service, this could mean that a household does not use an optimal amount of energy to heat the room. This is shown in Figure 5.2 by the combination of capital and energy represented by point A (which is a point at the same output temperature of 21°C). At this point, if the capital input is held constant and the energy consumption is reduced from E to E^*,

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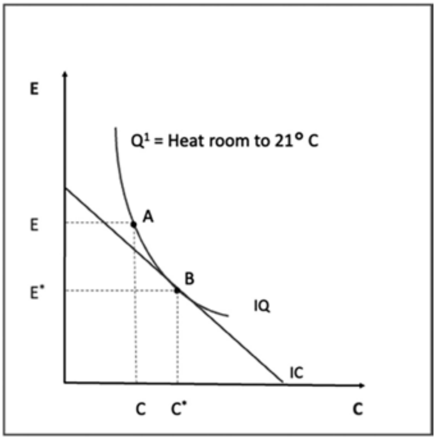

Figure 5.3 Inefficient combination of inputs

the desired level of output (i.e., the desired heating temperature) can be achieved using less energy at point B. In the context of heating, for example, situation A could arise when, during the winter, windows are kept open longer than necessary, which leads to a loss of heat. It may also arise if the use of a heating system is not optimised, such as when heat pumps are operational even if they are not required, or the parameters of the heating systems are not optimised.

Energy inefficiency resulting from a suboptimal combination of inputs is best explained through Figure 5.3. Here, the combination of inputs used to produce a room temperature of 21°C is represented by point A. At this point, the level of capital C is lower than the optimal one C^* and the household is using too much energy E. For instance, a building could still have been equipped with old single-glazed windows instead of new double-glazed windows. In this situation, if capital is increased to the optimal level C^*, for instance, with the substitution of the old with the new more insulated windows, it is possible to reduce the energy consumption to E^*, that is, the optimal combination of inputs represented by point B can be reached.

We should note that the use of energy-saving double-glazed windows can still be considered a standard technology. In fact, one classical approach currently used in the building renovation sector to improve heat retention is to use double-glazed windows instead of single-glazed windows.

Dependence on obsolete technologies is the third situation that characterises an inefficient use of energy. This could manifest when the household does not adopt newer technologies that can produce the same energy services or goods using a lower energy input. In the graph in Figure 5.4, old and new technologies are each represented by an isoquant. Note that both the isoquants denote the same level of output (heating a room to 21°C). Old technologies in the building sector are characterised by structures having poor insulation, no double-glazing of windows, and inefficient heating systems. New technologies in buildings imply better insulation and an air ventilation system equipped with heat exchangers that reduce energy consumption.

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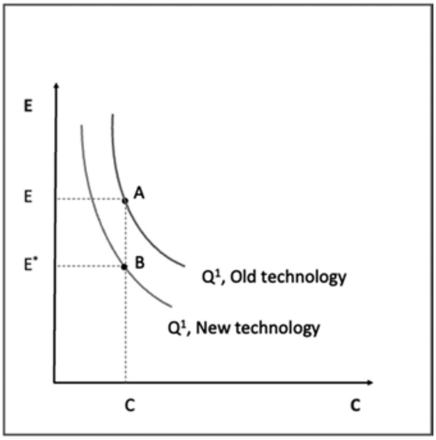

Figure 5.4 Use of obsolete technology

Generally, these technologies provide more comfort in terms of lower noise levels, uniform temperatures, and better air quality, in addition to energy savings.

Figure 5.4 represents a situation in which consumers can choose between buildings with old technologies, or buildings with more modern technologies. Let's assume now that a household chooses to live in the building with the old technology, and that it chooses the inputs in the combination characterised by the point A (with inputs E and C). The alternative for the household would have been to choose to live in a new building, and for instance, choose the input combination represented by point B. In this case, point B is characterised by the use of the same level of capital as at point A, and would have implied a reduction of energy consumption from E to E^* without changing the achieved output. Thus, the use of obsolete technology in this case leads to higher levels of energy consumption than is possible with newer technologies.

5.2 Measurement of Energy Efficiency

There are three main approaches for measuring energy efficiency empirically: partial indicators, econometric approaches, and bottom-up engineering approaches. Two of these approaches – partial indicators and econometric approaches – are discussed in this chapter, because they better capture the concept of energy efficiency based on microeconomic theory, as discussed in Section 5.1. Additionally, the analysis of energy efficiency can either be done at a relatively disaggregated level, for example, using data from firms or households, or at an aggregated level with data from countries, regions, or cities.

5.2.1 Partial Indicators

When a partial indicator approach is used to measure energy efficiency, the simple ratio of the total output to energy consumption is computed, whereby both outputs and inputs can be measured in either quantity-based or monetary units.

Two central partial indicators in the literature are energy productivity, which is the ratio of the total output of a good or service to the total energy consumption, and energy intensity, which is the opposite, that is, the ratio of energy consumption to output. For instance, in the context of the efficiency of buildings, energy productivity could be measured as the ratio between the size of a house, measured in square meters, and the amount of energy consumed, measured in kilowatt-hours (kWh) or in British thermal units (BTUs), whereas energy intensity would be measured as the ratio between the amount of energy consumed and the size of a house. Another important example of the use of a partial indicator is the measurement of the level of energy intensity of an economic system. In this case, the level of energy intensity can be measured as the ratio between energy consumption at the country level (measured in BTUs) and GDP.

One of the advantages of the use of partial indicators to measure energy efficiency is the simplicity of the calculation. However, while these indicators provide a system to rank households, firms, countries, and regions on the basis of energy efficiency, they suffer from important limitations. For example, the differences in the levels of energy efficiency of households and firms obtained with partial indicators can arise due to several factors, such as climatic conditions, building age, differences in the technologies adopted, household size, type of firm, and behavioural components. Similarly, differences in the level of energy efficiency of economic systems across countries or regions may arise due to differences in their economic structures, the presence of energy-intensive sectors in some regions/countries, climatic conditions, or the level and type of urbanisation.

As a result of the uni-dimensional information that partial indicators provide, this approach cannot be used to easily benchmark or compare performances across different units, such as houses or countries. The risk in using the partial indicator approach would be to perform an unfair comparison of economic agents and countries. For instance, one country could be characterised by a low level of energy productivity or a high level of energy intensity because of cold weather conditions that require a high level of consumption of heating services, and not necessarily because of being a society that is wasteful in energy use.

Table 5.1 mentions the level of energy productivity and energy intensity for a sample of countries. We observe a great variation in the values of energy productivity measured across countries. For instance, some countries such as France and Italy exhibit relatively high levels of energy productivity, while Canada and India fare relatively worse. A part of this difference may be explained by an inefficient use of energy; however, it may also be due to other factors such as the climate, or the presence of heavy industries that can contribute significantly to energy consumption.

An interesting example of an indicator of energy intensity at the household level is the ratio of the energy consumption of a heating system to the size of the house. Figure 5.5 shows a histogram of frequencies (represented on the y-axis) across different energy intensity (EI) levels (x-axis), plotted using information from a sample of Swiss households. In this case, energy intensity is measured in units of KWh per square meter. Importantly, the figure illustrates that there is vast heterogeneity

Table 5.1 Cross-country energy consumption comparisons [78] [79]

Country	Primary energy consumption (TWh)	GDP (billions of 2020 USD)	Energy productivity (GDP/Energy)	Energy Intensity (Energy/GDP)
Australia	1,780.44	1,400	0.79	1.27
Brazil	3,445.40	1,840	0.53	1.87
Canada	3,948.35	1,740	0.44	2.27
China	39,360.93	14,300	0.36	2.75
France	2,688.65	2,720	1.01	0.99
Germany	3,649.98	3,860	1.06	0.95
India	9,460.98	2,870	0.30	3.30
Indonesia	2,475.35	1,120	0.45	2.21
Italy	1,770.42	2,000	1.13	0.89
Japan	5,187.15	5,080	0.98	1.02
Mexico	2,144.65	1,270	0.59	1.69
Norway	490.78	403	0.82	1.22
Russia	8,279.18	1,700	0.21	4.87
Saudi Arabia	3,065.43	793	0.26	3.87
Singapore	986.02	372	0.38	2.65
South Africa	1,500.24	351	0.23	4.27
South Korea	3436.34	1,650	0.48	2.08
Switzerland	313.93	703	2.2	0.45
The United Kingdom	2,177.83	2,830	1.3	0.77
The United States	26,291.36	21,400	0.81	1.23

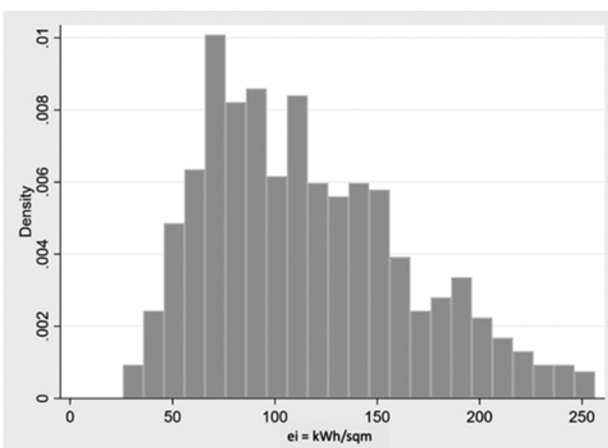

Figure 5.5 Energy intensity at the household level
Source: Data collected at CEPE (Centre for Energy Policy and Economics at ETH Zürich)

in energy intensity levels; some Swiss households in the sample merely consume 25 kWh/m^2, while others consume up to ten times as much. As mentioned, partial indicators only provide limited information, as the values of energy intensity do not convey the reasons for the observed differences. In fact, some of the households included in

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this sample live in mountainous areas where the heating requirements are higher than for households in the valleys.

5.2.2 Econometric Approaches

The second approach for measuring energy efficiency is based on using econometric methods and estimating different types of models, some of which are discussed in this chapter. One important econometric approach is the stochastic frontier model of energy demand, which has been introduced by Filippini and Hunt (2011, 2016) [28] [80]. This approach is based on the use of a special econometric method that enables estimating a frontier function based on data at the household, firm, or country level.

Generally, a frontier function indicates the maximum or minimum level of an outcome variable that an economic agent can attain in production or consumption activities. In the context of energy demand, a frontier function shows the minimum quantity of energy needed to produce any given level of goods and/or energy services.

In Figure 5.6, we present the situation of a household that is producing and consuming an energy service. The horizontal axis shows the level of energy services produced (ES), the vertical axis indicates the level of energy consumed (E), and the curved line represents the energy demand frontier function. This simple frontier function shows the minimum level of energy needed by an economic agent, in this case, a household, to produce any level of energy services. At an energy service production level of ES_1, energy inefficiency exists if instead of E_{pro}, the observed energy consumption is at the level E_{obs}. The level of inefficiency can be read as the vertical difference or ratio between points A and B.

Empirically speaking, this inefficiency is estimated using an econometric model, that is, the stochastic frontier model. In Figure 5.7, energy consumption (E) is again plotted on the vertical axis and energy services (ES) on the horizontal axis. The black and dark grey data points in the figure represent combinations of energy consumption

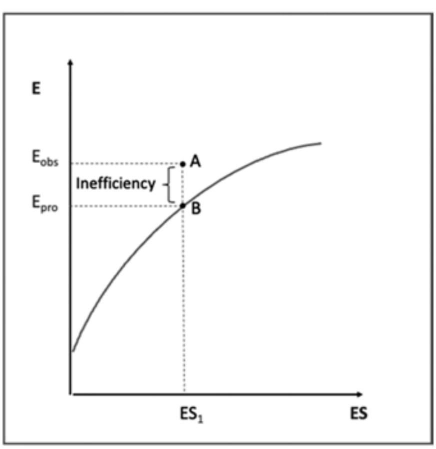

Figure 5.6 Frontier demand curve and inefficiency

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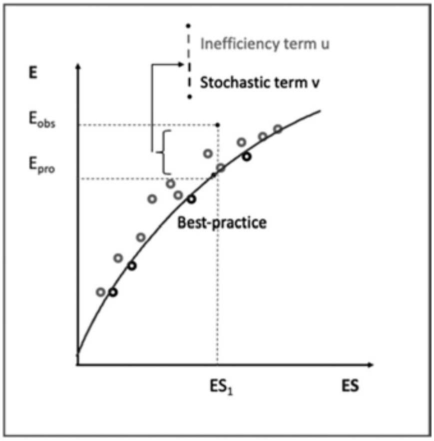

Figure 5.7 Stochastic frontier demand curve and inefficiency

and services observed for a household, a firm, or a country. The vertical distance between the dark grey points and the stochastic frontier is made up of both an inefficiency term (μ), which indicates the level of energy inefficiency, and a stochastic term (v), which is the typical residual term of a regression model, and captures unobserved variables and accounts for a lack of perfect goodness of fit.

In order to estimate the level of energy inefficiency of an economic agent, the researcher should first specify an energy demand function. For instance, for households, the energy demand frontier function could be specified as:

$$E = f(PE, HS, AS, HDD, ES, EINEFF) \tag{5.1}$$

Where:
E: Energy demand
PE: Energy price
HS: Household size
AS: Area or size of dwelling
HDD: Heating-degree days
ES: Level of energy services
$EINEFF$: Level of inefficiency in energy use

After having specified it, the researcher should collect data on all the variables included in such a model as that in Equation 5.1, and estimate it using an econometric methodology that derives the coefficients of the variables as well as the two components of the general error term, that is, μ and v. For instance, the econometric specification of model 5.1 using a log-log functional form can be expressed as follows:

$$\begin{aligned} \ln(E) = \alpha_0 + \alpha_p \ln(PE) + \alpha_{HS} \ln(HS) + \alpha_{AS} \ln(AS) \\ + \alpha_{HDD} \ln(HDD) + \alpha_{ES} \ln(ES) + v + \mu \end{aligned} \tag{5.2}$$

In this example, the natural logarithm of a household's energy demand is for instance explained through the natural log of the energy price (PE), of the household size

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(HS), of the area or size of the house (AS), of the heating-degree days (HDD) (a measure of how many days the temperature was less than a threshold temperature, and by how much, indicating cold weather severity), of the level of produced energy services (ES), the stochastic term (v), and the level of energy inefficiency (μ). The researcher will first estimate the model by applying a maximum likelihood-based estimator, and then using a formula to split the general error term into the two components. Afterwards, the level of energy inefficiency can be calculated using the values of μ. We should note that the level of inefficiency measured by μ may be due to inefficient use of technologies in generating energy services as well as due to inefficient investment decisions, that is, the choice of energy-inefficient technologies.

The main advantage of using this econometric approach (over the partial indicator approach) is that it provides a fairer comparison of the levels of energy efficiency of households; the econometric specification includes explanatory variables that can potentially explain differences in consumption across households, which may also be factors beyond the household's control, such as the number of heating degree days or household size. To note, that the level of inefficiency may be due inefficiency behaviours in consumption or investment.

Stochastic frontier energy demand function

A study on the level of energy efficiency of US households conducted by Alberini and Filippini (2018) [27] computed a level of energy inefficiency of approximately 25 per cent among US households. This implies that US households could potentially have saved up to 25 per cent of their energy, without reducing the number or level of energy services consumed. In another study on the level of residential electricity demand in Switzerland, Blasch et al. (2017) [81] found that the aggregate level of inefficiency in the use of electricity was around 30 per cent among Swiss households. These studies suggest relatively high levels of energy inefficiency at the aggregate level in these countries, with the potential for improving energy efficiency.

5.3 Investment in Energy Efficiency

As discussed in Chapter 4, investment decisions in the energy sector can heavily influence the level of energy demand and energy efficiency of a household, firm, or country, and over long periods. This is because technologies used in the production of energy services have a very long lifespan. For example, a heating system may have a lifespan of around 30 years, and windows have a lifespan of around 20–30 years. This implies that a suboptimal investment choice from an energy point of view can have negative repercussions on energy consumption for a very long time. These investment decisions are rather complex, as they depend on a multitude of factors, such as the initial prices of technologies, their operating costs, expected prices, discount rates, behavioural factors, policy measures, and the long lives of these technologies. In this subsection, we will focus on investments made by households.

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A quantitative and qualitative analysis of the super-efficient equipment programme subsidy in India

Troja (2016) [82] discussed the growing need for energy efficiency in the Indian energy sector, which is facing unprecedented pressures due to high population growth and urbanisation rates. The main focus of this study was to analyse the impact of a policy, the Super Efficient Equipment Program (SEEP) in the housing sector. The aim of this scheme was to reduce energy consumption in the residential sector in India, by incentivising producers, that is, by providing subsidies for the production of more energy-efficient fans. The author accounted for economies of scale and the market power of producers. Additionally, he used an econometric model to factor in the preferences and behaviour of consumers. He found that the SEEP was able to achieve its goal of reducing energy consumption, but only to some extent. The weaker-than-expected results arose because even despite the subsidies, the more efficient fans tended to cost about INR 300 (about $5) more than regular fans. Also, the demand for fans was rather price inelastic. These two factors contributed to the low switching rates between the less efficient and more efficient technologies. The author suggested various government interventions that could help promote energy efficiency in India, such as:

1. To impose bans on the consumption and production of technologies that are inefficient.
2. To undertake information and awareness campaigns to highlight the resulting costs and energy-saving benefits.
3. To evaluate programmes such as SEEP using econometric models, to fully understand their impact.

5.3.1 Investment Decisions

Investment decisions influence the stream of benefits and costs over a long period of time. This implies that appropriate investment levels in energy efficiency can be identified through intertemporal optimisation, as is done in microeconomics. To take such a decision, individuals need to collect information and make assumptions regarding the future, especially regarding their usage and future energy prices. They then need to perform an investment analysis (as discussed in Chapter 4) or calculate lifetime costs. If it turns out that the benefits that manifest from investing are the same across all technologies and the lifetimes are similar, then the use of lifetime cost, that is, the sum of the upfront cost or initial price and the operating costs incurred during the lifetime of the technology, is a viable means for decision-making. However, if the said benefits vary with the type of technology, then the use of an investment analysis that fully considers all the costs and benefits over the lifespan of a technology would be more appropriate to conclude. In this chapter, we focus on the discussion of using lifetime costs as a criterion for making investment decisions. For example, if a household wants to buy a heating system, then this household should compare the lifetime costs of the potential heating systems with similar lifespans that could be installed in their house.

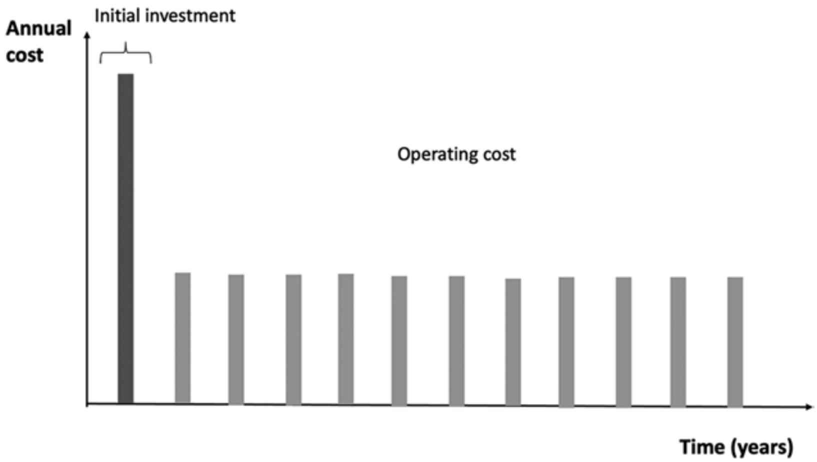

Figure 5.8 Lifetime costs

5.3.2 Lifetime Cost Calculations

Lifetime costs are obtained by summing the initial purchase price (initial investment) of the technology with the operating costs of the technology over its lifetime. In Figure 5.8, the first vertical bar (the red bar) represents the initial fixed costs paid for the purchase of the new durable or technology, and the subsequent bars (blue bars) indicate the operating costs that are incurred over its lifetime.

Sometimes, we can observe situations where the initial price of a durable good, for instance, a washing machine, is lower than the price of an alternative model that is relatively more energy-efficient and that consumes less electricity. However, if one were to consider the lifetime costs of these two washing machines, we may well observe that the washing machine having a higher initial price would actually have lower lifetime costs, because of its relatively lower operating costs (compared to the cheaper washing machine).

The formula for the computation of the lifetime cost of a technology used to produce energy services is:

$$LTC = P^I + \sum_{t=1}^{T} \frac{P_t^E \cdot C_t}{(1+r)^t} \tag{5.3}$$

Where:
LTC: Lifetime cost (present discounted value (PDV) of a stream of costs over time)
P^I: Price of the durable
P_t^E: Energy price at period t
C_t: Energy consumption at period t
r: Discount rate
t: Time
T: Total lifespan of the durable

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In this expression, the first term P^I refers to the initial cost and the composite term $\sum_{t=1}^{T} \frac{P_t^E \cdot C_t}{(1+r)^t}$ indicates the total operating costs, which depend on the price of energy (P_t^E), the level of energy consumption (C_t), the discount rate used to calculate the present value of future cash flows (r), as well as the lifetime of the durable (T).

We should note that in cases where the choice set includes durable goods such as cars, appliances, or heating systems that are somewhat dissimilar, information on the lifetime costs is still important in the decision-making process but is likely to not be the only determinant of the final choice made by individuals. In this case, individuals will consider the lifetime costs as well as other characteristics of the durable good when making their choice.

5.3.3 Examples: Comparing Lifetime Costs of Cars and Refrigerators

As an example to compare the lifetime costs of two cars, Table 5.2 provides real data on two similar car models that could have been bought in Switzerland in the year 2020. As can be seen from the table, one car is more energy-efficient; however, it is also characterised by a higher purchase price. Further, the different efficiency ratings have an impact not only on the operating costs but also on the level of the annual registration tax. For the diesel model, there is an annual registration bonus of CHF 214, that is, the amount of registration tax paid by owners of this model is CHF 214 less than that paid by owners of the gasoline car. Due to the better fuel economy of this car, its lifetime cost is lower than the lifetime cost of the gasoline-powered car. This calculation has been done assuming a lifespan of 10 years, usage of 10,000 km/year and a common discount rate of 3 per cent. If a consumer were to only compare the purchase prices of these cars, then the consumer may have chosen the gasoline car. However, by considering total lifetime costs, the choice should be expected to reverse.

Another example of the computation of the lifetime costs is summarised in Table 5.3, which shows details of two refrigerators with similar characteristics. Fridge

Table 5.2 Lifetime costs of cars

	Ford focus SW 1.5 SCTi 150	Ford focus SW 1.5 TDCi 120
Fuel type	Gasoline	Diesel
Fuel price	CHF 1.43	CHF 1.75
Efficiency rating	F	A
Fuel consumption (L/100 km)	5.6	3.8
Initial price	CHF 26,200	CHF 27,800
Registration tax (ZH bonus)	CHF 268	CHF 54 (CHF 214 bonus)
Fuel + tax + price	CHF 36,880	CHF 34,990
Fuel + tax + price + CO_2 tax	CHF 37,430	CHF 35,485

Source: Data collected at CEPE

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Table 5.3 Lifetime costs of refrigerators

Appliance	Discount factor	Electricity price ($/kWh)	Consumption per year (kWh)	Expenditure per year ($)	Initial price ($)	Lifetime cost for 10 years ($)
Fridge A	0.03	0.25	100	25	3,000	3,213
Fridge B	0.03	0.25	200	50	2,900	3,327

Source: Data collected at CEPE

A is more expensive at purchase; however, due to its lower energy consumption compared to Fridge B, the lifetime cost of Fridge A is lower than that of Fridge B. If a consumer only compares the purchase prices of the two appliances, then he or she will probably choose Fridge B. However, if a consumer considers the total lifetime costs, then the consumer should choose Fridge A. Again, as with the previous example, we should keep in mind that we are discussing the choice between two very similar refrigerators. The calculation has been done assuming a lifespan of 10 years, an electricity price of 0.25 dollars per kWh, and a discount rate of 3 per cent. We should keep in mind that with sufficiently high discount rates, the less efficient fridge may look more attractive from a lifetime cost perspective, because the operating costs will be more heavily discounted. For instance, individuals with high subjective discount rates may then prefer to buy Fridge B compared to Fridge A.

5.4 Energy Efficiency Gap

5.4.1 Private and Social Perspectives

In some situations, consumers or firms do not adopt durable goods that minimise their lifetime costs when facing a choice between very similar goods. This describes the inefficient behaviour of consumers or firms, that is, there exists a gap between the optimal choice and the actual choice they make.

There are two definitions of the energy efficiency gap: one definition is focused on a private perspective, while the other definition is based on a social perspective. From a private perspective, an energy efficiency gap arises when economic agents do not opt for the most energy-efficient technology, even though this technology may minimise their private lifetime costs and is therefore cost-effective. In this situation, we have the following inequality:

$$P_e^D + \sum_{t=1}^{T} \frac{P_t^E \cdot C_{et}}{(1+r)^t} < P_I^D + \sum_{t=1}^{T} \frac{P_t^E \cdot C_{it}}{(1+r)^t} \tag{5.4}$$

Where:

P_e^D: Price of the efficient durable

P_I^D: Price of the inefficient durable

P_t^E: Energy price at period t

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C_{et}: Energy consumption at period t for an energy-efficient durable
C_{it}: Energy consumption at period t for an energy-inefficient durable
r: Discount rate
t: Time
T: Total lifespan of the durable

Both sets of lifetime costs (the one for the efficient technology on the left-hand side of the expression above and the one for the inefficient technology on the right-hand side) are based on an energy-efficient usage of the durable or technology, but one technology (the efficient one) is associated with lower operating costs due to lower energy consumption.

An energy efficiency gap, from a social point of view, is said to occur when consumers or firms do not opt for the most energy-efficient technology, even if it minimises social lifetime costs and is therefore cost-effective. Mathematically, this can be expressed as the following inequality:

$$P_e^D + \sum_{t=1}^{T} \frac{P_t^E \cdot C_{et}}{(1+r)^t} < P_I^D + \sum_{t=1}^{T} \frac{P_t^E \cdot C_{it} + EC_t}{(1+r)^t} \tag{5.5}$$

Where:
P_e^D: Price of the efficient durable
P_I^D: Price of the inefficient durable
P_t^E: Energy price at period t
C_{et}: Energy consumption at period t for an energy-efficient durable
C_{it}: Energy consumption at period t for an energy-inefficient durable
r: Discount rate
t: Time
T: Total lifespan of the durable
EC_t: External costs at period t for the energy-inefficient durable

On the right-hand side of this inequality, the social cost of using the inefficient technology (EC_t) is included in the operating costs. Note that even though we do not mention external costs on the left-hand side of this expression, we cannot always rule out that efficient technologies do not have external costs. An example to illustrate these different lifetime costs could be the choice of a heating system using renewable energy on the left-hand side of the inequality, in comparison to a heating system relying on oil on the right-hand side. The environmental impact of the oil-based heating system is represented by the social cost EC. It is important to note that the absence of an energy efficiency gap from a private perspective does not imply that there is no social energy efficiency gap. In fact, we can observe situations where the least efficient and most environmentally damaging technology has lower lifetime costs than the most efficient and sustainable technologies, if we do not consider the external costs. In such cases, the decision of consumers who choose the technology that damages the environment is an optimal decision from a private point of view, but it is not optimal for society.

Table 5.4 Factors contributing to energy efficiency gap

Traditional market failures	Behavioural anomalies	Non-market failures

• Negative externalities
• Imperfect information
• Asymmetric information
• Split-incentive/ principal–agent issue
• Positive externalities
• Capital market imperfection
	• Bounded rationality
	  • Cognitive limitations to performing an investment analysis
	  • Loss aversion
	    ◦ Status quo bias
	    ◦ Endowment effect
	  • Limited attention
	  • Present bias
	• Bounded willpower
	  • Cognitive dissonance
		• Hidden costs
		• Uncertainty

5.4.2 Barriers to Energy Efficiency

Several factors contribute to the energy efficiency gap, each of which can be categorised as either traditional market failures, behavioural anomalies that can also be considered to be market failures as discussed in Chapter 2, or non-market failures. Table 5.4 presents the barriers to energy efficiency investments.

The most important market failures that serve as barriers to investments in energy efficiency, which we also discussed in Chapter 2, are recapped here. As already mentioned, the presence of negative externalities implies that the operating cost of using energy-inefficient and polluting technologies does not capture the true social cost and, therefore, these technologies may appear to be less costly for buyers. Asymmetric and imperfect information imply a situation wherein buyers of energy technologies may be partially ignorant of the existence of new and energy-efficient technologies, while sellers, having more knowledge, could try to exploit this information to their advantage, potentially hurting the welfare of buyers. Split incentives arise when the person or institution ultimately responsible for making investments in energy efficiency (the agent) is not the one responsible for the payment of bills for energy consumption. Positive externalities give rise to situations in which the early adopters of a new energy-efficient technology share their experiences of using it with potential (new) adopters without being paid for this service. Imperfections in the capital market can also serve as a barrier to energy-efficient investments.

The presence of behavioural anomalies, as also explained in Chapter 2, may further create barriers towards achieving energy efficiency. For instance, the presence of cognitive limitations may lead to difficulties in computing the lifetime costs of different energy technologies. This situation could induce the buyer of an energy technology to choose a technology based on the purchase price, and not on its lifetime costs. Likewise, buyers may give limited attention to the future operating costs of an energy technology, because they are not as salient as the purchase price at the moment the consumer makes the purchase decision. In this case as well, the lifetime costs are

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not being factored in. Furthermore, the presence of status-quo bias and/or the endowment effect, that is, a tendency to give more value to technologies that are owned and better known, also reduces the probability of opting for new energy-efficient technologies. Finally, the presence of the so-called cognitive dissonance gap and myopia in intertemporal choices can create additional barriers to investment in energy efficiency. We observe a cognitive dissonance gap when there is a mismatch between our beliefs and actions. For instance, we may believe that buying a less powerful car is essential for the environment, yet fail to do it. Myopia is mainly due to present bias, that is, the tendency of people to give more weight to rewards in the near future rather than in the distant future, because of varying discount rates. For instance, buyers may give more weight to the upfront cost of a heating system and tend to undervalue future operating costs.

Finally, non-market failures may also serve as barriers towards energy efficiency investments; examples include the hidden costs of installing and operating a new energy technology or uncertainty about the advantages and disadvantages of using this new technology. For instance, a wood pellet-based heating system has some hidden costs, such as the time it takes to load the stove with wood or to clean the stove. The uncertainty about the true advantages of owning a new energy-efficient technology can also be large, because of its long life cycle, as previously mentioned, and the irreversibility of typical energy investments.

For instance, the real advantages of using a heating system based on new technology can only be assessed after 15–20 years. Moreover, in this case, delaying the decision to adopt a new heating system in order to acquire more information about its functioning from other adopters creates an option value. Such situations imply that the implicit discount rate used by the buyers to value these technologies is likely to be much higher than the one defined by the market, and therefore, the importance of future operating costs in the investment analysis diminishes.

From an energy policy perspective, it is important to underline that only the presence of barriers in the form of market failures and behavioural anomalies (and not non-market failures) justify state intervention.

Finally, it can be interesting to see how some of the barriers discussed and illustrated in Table 5.4 affect elements of the expression used to compute the lifetime costs. For instance, as can be seen in Equation 5.6, limited attention suggests that individuals do not completely consider the operating costs ($P_t^E \cdot C_t$) in their choice. Present bias influences the choice of the discount factor; consumers characterised by present bias tend to give more weight to the initial price than to operating costs. Bounded rationality, which can be characterised by the endowment effect, *status quo* bias, or cognitive limitations, influences the exactitude with which individuals undertake calculations of lifetime costs.

Given that investment decisions are very relevant for the energy transition and behavioural anomalies can be important barriers, in Section 5.5, we propose an in-depth discussion on the role of bounded rationality, cognitive skills, and knowledge in decision-making strategies related to households' investments in the energy sector.

$$P_E^D + \sum_{t=1}^{T} \frac{\overbrace{P_t^E \cdot C_{e_t}}^{\text{Energy cost: limited attention}}}{\underbrace{(1+r)^t}_{\text{Discount factor: present bias}}} < P_I^D + \sum_{t=1}^{T} \frac{(P_t^E \cdot C_{i_t}) + \overbrace{EC_t}^{\text{Externality}}}{(1+r)^t} \tag{5.6}$$

5.5 Bounded Rationality and Energy-related Financial Literacy

As we discussed in Section 5.4 of this chapter, in order to make informed decisions on the purchase of durables, individuals and firms need to have information as well as the skills to perform an investment analysis or to compute the lifetime costs. In this section, we explore the role of bounded rationality, and in particular the lack of financial or investment knowledge and skills in the selection of the decision-making strategy related to the choice of energy technologies in more detail. We are, therefore, interested, to discuss more in details the specific anomaly of cognitive and knowledge limitations related to investment decisions.

5.5.1 Decision-making Strategies

A household or a firm may adopt two kinds of strategies in the choice of a new energy technology (such as an electrical appliance or a heating system), as described in Figure 5.9. An economic agent who adopts a rational decision-making approach will make the effort to actually calculate the lifetime cost of various possible technologies, and then choose the technology that minimises these costs based on the upfront price, energy price, intensity of use, the discount rate, and the lifetime of the technology.

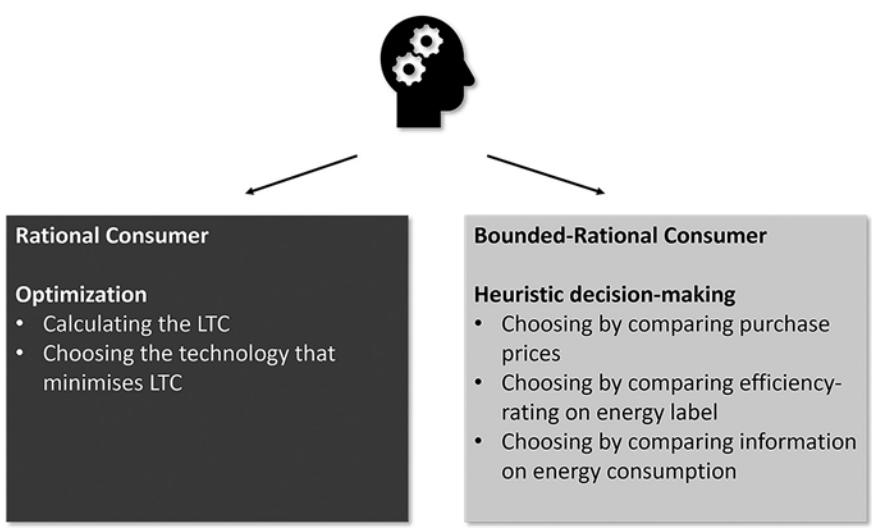

Figure 5.9 Different decision-making strategies

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A less rational economic agent would adopt a heuristic decision-making strategy, which in this context could involve making the decision based on a simple comparison of purchasing prices, efficiency ratings, energy consumption levels, as well as technology choices.

Generally, the choice of the decision-making strategy depends also on the level of financial knowledge for making investment decisions in energy technologies. This type of knowledge can be measured using the energy-related financial literacy concept, which is defined as 'the combination of energy-related knowledge and cognitive abilities that is needed in order to take decisions with respect to investments for the production of energy services and their consumption' (Blasch et al., 2021) [83]. In general, consumers who have higher levels of energy-related financial literacy tend to follow a more rational decision-making process than consumers or firms characterised by low levels of energy-related financial literacy.

To measure the level of energy-related financial literacy, researchers organise surveys with households, asking questions related to:

- Their knowledge of energy consumption, energy prices, as well as on levels of energy efficiency of energy technologies.
- Their ability to calculate the lifetime costs in simple situations.
- Their capacity to know and use interest rates in simple calculations.

For instance, Blasch et al. (2021) [83] use the following question to measure the ability to compute the lifetime cost: 'Suppose you own your home, and that your fridge breaks down and you need to replace it. As a replacement, you can choose between two alternatives that are identical in terms of design, capacity, and the quality of the cooling system. Fridge A sells for CHF 400 and consumes 300 kWh of electricity per year. Fridge B has a retail price of CHF 500 and consumes 280 kWh of electricity per year. Assume that the average cost of energy is CHF 0.20 per kWh, that the two models both have a lifespan of 15 years and that you would get a return of 0 per cent from any alternative investment of your money. Which purchase choice would minimise the total costs of owning the fridge over its lifespan?'

- Fridge A
- Fridge B
- Fridges A and B are equivalent in terms of total costs
- Don't know

In this case, the correct answer is Fridge A, that is, the less efficient fridge actually has a lower lifetime cost.

Empirical studies suggest that in general, both in industrialised and developing countries, the level of energy-related financial literacy is weak [83, 84]. One implication of a low level of energy-related financial literacy is that individuals will tend to ignore the lifetime costs during the decision-making process. Indeed, some studies indicate that people with low levels of energy-related financial literacy tend to adopt less energy-efficient technologies [83].

Empower the consumer! Energy-related financial literacy and its implications for economic decision-making

Blasch et al. (2021) [83] measured the levels of energy-related financial literacy by conducting a relatively large-scale European household survey, and explored the socioeconomic factors that influenced its levels. The empirical results showed that energy-related financial literacy was low, with female respondents faring worse than males. This gender gap existed in various countries: females were found to have lower levels of literacy compared to males in Italy, Switzerland as well as in the Netherlands. The total score used to assess energy-related financial literacy was based on the number of correct responses in eight questions, with the score for each correct answer being 1, and there was no penalty for wrong answers. The empirical results also suggest that survey participants did not perform equally well in all aspects of energy-related financial literacy. Knowledge of energy prices was relatively low, and only 45 per cent of the participants answered questions about calculating the lifetime cost of appliances correctly. Most importantly, the authors empirically show the association between limited energy knowledge and skills in performing investment analysis on the adoption of energy-efficient light bulbs. The results reported in this study suggest that introducing programmes that increase the energy-specific financial knowledge could increase the adoption of energy-efficient durables.

Energy-related financial literacy and bounded rationality in appliance replacement attitudes: evidence from Nepal

Filippini et al. (2019) [84] studied the level and determinants of energy-related financial literacy using a sample of 2000 Nepalese households from Biratnagar, Nepal, the second largest city in the country. The empirical results indicated that the level of income, education, and gender played an important role in determining their energy-related financial literacy. Furthermore, the econometric analysis provides suggestive evidence that higher levels of energy-related financial literacy were associated with more rational decision-making. The paper showed that energy-related financial literacy could contribute towards ensuring sustainable development over the coming decades, as increased knowledge about lifetime costs and improved computational abilities may facilitate investment in energy-efficient technologies in developing countries.

5.6 Rebound Effect

Adopting a more energy-efficient technology generally reduces energy consumption per unit of energy services produced. This reduction in energy consumption leads to a reduction in the cost of producing energy services, at least a reduction in the variable costs (namely, energy costs). In turn, the decrease in the production cost per unit produced of energy services may increase the demand for the same. This may

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reduce the impact on energy consumption of the new, more efficient technology. This phenomenon is called the rebound effect.

For example, an increase in the energy efficiency of a car results in lower levels of gasoline consumption per kilometre, and thus at the margin, a lower cost per kilometre driven. This reduction in cost per kilometre may lead consumers to drive more kilometres, and thus chip off some of the energy savings due to the increase in fuel efficiency. As an extension of this example, some of the money saved in road transportation due to lower gasoline consumption could be used by the consumer in other energy-using activities, such as flying in aeroplanes for travel more frequently. This, again, would lead to a smaller overall reduction in energy use than initially projected. The first effect, that is, the change in energy consumption from the utilisation of the new technology, is called the direct rebound effect, whereas the second change, that is, the change in energy consumption in other activities unrelated to the use of the new technology, is called the indirect rebound effect.

The rebound effect can be illustrated graphically. For pedagogical reasons, in Figures 5.10 and 5.11, we assume that adopting a new energy-efficient technology leads to a decrease in the total costs of producing the same amount of energy services (represented by the parallel shift of the isocost line).

In Figure 5.10, we illustrate the effect of the introduction of an energy-saving technology on the optimal use of two inputs, energy and capital, and on the cost of producing the energy service. The vertical axis shows capital use (C) and the horizontal axis shows energy consumption (E). As is visible from the graph, it is possible to produce the same amount of energy services (ES_1) using a new and more energy-efficient technology which consumes less energy and more capital. The old optimal input combination is represented by point A, whereas the new combination that corresponds to the use of the new technology is represented by point B. From the graph, it is also clear that switching to the new technology reduces the total cost paid for producing the energy service (point B lies on a lower isocost line than point A). As a result, the unit price of the energy service decreases. This decrease in the unit price

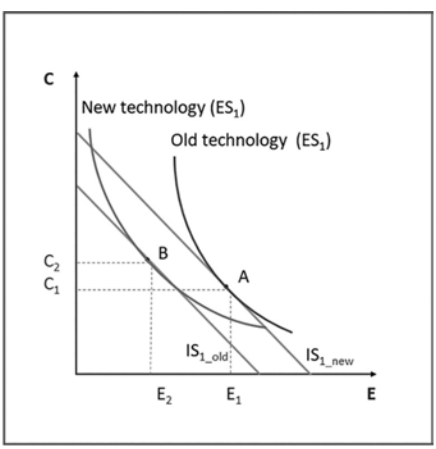

Figure 5.10 Simple rebound effects

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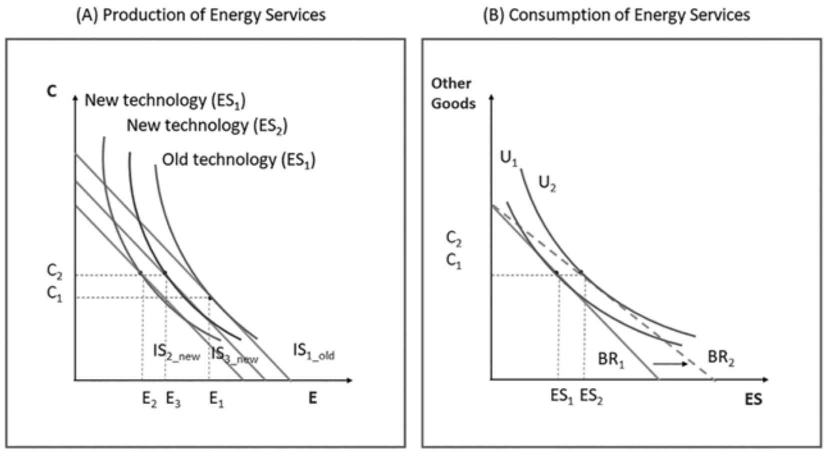

Figure 5.11 Rebound effect and production and consumption of energy services

can, depending on the value price elasticities, lead to an increase in the demand for energy services. In Figure 5.11, we illustrate this phenomenon in more detail.

Figure 5.11A shows the change in energy demand due to the new energy-efficient technology, whereas Figure 5.11B illustrates the change in the demand for energy services. The graph on the left is similar to the one in Figure 5.10, with capital (C) plotted on the y-axis and energy consumption (E) on the x-axis. The second graph, on the other hand, has energy service consumption (ES) plotted on the horizontal axis and consumption of all other goods on the vertical axis.

As in the Figure 5.10, Figure 5.11A shows that the newer technology initially results in lower energy consumption and higher capital consumption for the same level of energy service (ES_1), compared to the old technology. This change constitutes a decrease of energy consumption from E_1 to E_2 with an increase in capital from C_1 to C_2. However, this is not the end of the story. This is because lower levels of energy consumption will also decrease the unit production cost of the energy service (since energy is an input in the production process for energy services).

This may have an impact on the demand for energy services, which is best explained using Figure 5.11B. In this figure, the household is initially consuming ES_1 level of energy services produced using the older technology. Through the mechanisms put in force when the new technology is adopted, however, the budget restriction (BR_1) in Figure 5.11B rotates outwards because of the reduction in the unit cost of the energy service. This leads to a flatter slope for the budget restriction represented by BR_2. Thus, energy service consumption increases from ES_1 to ES_2, and therefore, energy consumption increases. This increase in energy consumption after the adoption of the new technology is illustrated in Figure 5.11A, by the shift from E_2 to E_3. The distance between E_2 and E_3 shows the rebound effect. In conclusion, the adoption of new technology leads to a final decrease in the energy consumption in this example (from points E_1 to E_3); however, this decline is lower than what would have been in the absence of a rebound effect (to point E_2).

The rebound effect and its size are commonly disputed among economists. Some economists argue that these effects are likely to be quite minor, given the inelasticity of demand for energy services and the small share that energy costs constitute of the total living expenses of a household. Other scholars maintain that the rebound effect might, in fact, offset a part of the energy savings gained from increasing energy efficiency.

5.7 Issues in Developing Countries

There are several challenges to achieving energy efficiency improvements in developing countries. In Chapter 2 as well as earlier in this chapter, we discussed the role of market failures in impeding energy efficiency improvements, and how some of these barriers are likely to be more prominent in low and middle-income countries (LMICs). In this section, we will discuss three of these factors again that are relevant for energy efficiency, especially in developing countries, credit/liquidity constraints (or capital market imperfections), and two behavioural anomalies, present bias as well as limited attention. We will then touch upon the notion of poor power quality as well as revenue losses of electric utilities in developing countries also serving as a barrier to energy-efficiency investments. Identifying and evaluating these barriers is important for policymakers to design future interventions.

5.7.1 Market Failures

Capital market imperfections may contribute towards individuals or households being credit-constrained, and thus unable to borrow easily. This situation is particularly salient, and strong, in developing countries. Credit constraints hinder the ability of low-income households from purchasing more energy-efficient technologies, which are likely to be more expensive, even if they are privately optimal. Limited attention, on the other hand, can make it difficult for individuals to be attentive to the operating cost savings from using an appliance, and to factor them in when making investment decisions. It is important to keep in mind that these two barriers are also interlinked: the impact of extending credit to purchase more energy-efficient technologies is plausibly dependent on how inattentive individuals are to future costs (since taking a loan involves postponing costs).

Role of credit provision and enhancing attention in facilitating adoption of energy-efficient technologies

In a study, Berkouwer et al. (2022) [85] used the setting of a field experiment among urban households in Kenya to evaluate the barriers towards the adoption of energy-efficient cook stoves. They found that an intervention that increased the salience to the energy savings from using this stove had no effect on the willingness to pay for these new stoves while extending access to credit (through loans) doubled the willingness to pay for them. The weak result on enhancing attentiveness to

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the cost savings may be due to the high value of savings that households would have experienced in this case. Thus, in this case, credit constraints served as the more critical barrier towards the adoption of more efficient technologies. However, the authors also articulated that there are challenges towards simply increasing the availability of credit to increase energy efficiency, such as adverse selection in credit markets and the associated information asymmetries.

Myopia or present bias is yet another important factor that may hinder the adoption of energy-efficient technologies. As we discussed in Chapter 2, present-biased individuals de-emphasise future energy (or cost) savings and weigh immediate costs more heavily. Since investment in energy efficiency involves trading off between short-run costs and long-run benefits, myopic or present-biased individuals are likely to experience time-inconsistent decision-making. A repercussion of this behaviour is that these individuals have high short-term discount rates, but a decrease in discount rates over the long run. Thus, these individuals have a tendency to procrastinate with respect to long-term investments (such as in energy-efficient heating systems). This is a relevant phenomenon in many developing countries.

Role of present bias in determining under-investment in energy efficiency

Using data from Delhi, India, Fuerst and Singh (2018) [86] evaluated whether present bias influences the decision of individuals to purchase more efficient appliances. They find that more patient (i.e., less present-biased) individuals are more likely to invest in certain types of energy-efficient appliances (such as refrigerators), but not in other appliances that are relatively cheaper, such as light bulbs. Thus, the authors argue that present bias, in turn, is also linked to credit constraints: in the purchase of relatively larger appliances such as fridges, time preferences are likely to play a larger role.

5.7.2 Poor Power Quality

In large parts of the developing world, power supply is either absent or irregular, at best. Many developing countries frequently experience outages, brownouts, and blackouts, as well as load-shedding, sometimes for several hours a day. This unreliability in power can significantly reduce the utilisation of electric appliances as well as households' incentives to invest in energy efficiency, given that operating cost savings may be less than what may be achieved with full-time use of the appliances (i.e., with continuous power supply).

This situation is described in Equation 5.7. The inequality condition that needs to be satisfied for agents to purchase energy-efficient appliances helps us to understand why.

$$P_e^D + \sum_{t=1}^{T} \frac{P_t^E \cdot C_{et}}{(1+r)^t} < P_I^D + \sum_{t=1}^{T} \frac{P_t^E \cdot C_{it}}{(1+r)^t} \tag{5.7}$$

It is clear that in order for the above inequality to hold, it must be the case that the difference in discounted operating costs between energy-inefficient appliances and

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energy-efficient appliances should be greater than the difference in their purchase prices, P_e^D-P_I^D. However, an irregular power supply (or poor power quality) is likely to reduce the effective usage of appliances, which implies that households may not be able to recover the operating cost savings that are possible from switching to a more energy-efficient appliance (i.e., the difference in operating costs between the less efficient and more efficient appliance may not be higher than the difference in purchase prices). This risk may disincentivise households from investing in energy efficiency in the first place.

5.7.3 Revenue Losses and Investments in Efficient Electricity Networks

In many developing countries, utilities are not always able to recover their costs because of theft, or suboptimal metering or billing. This implies that households will not pay the full cost of electricity that they consume, and therefore the price they face will be lower than the official tariff. This low price will reduce incentives to make efficiency investments in the network. Policymakers often use different strategies to mitigate such losses, such as replacing a fixed monthly electricity fee with metered consumption, using smart metres, or using prepaid electricity metres. It is understood that some of these measures may increase the cost of electricity for poor households. However, these steps are critical to reducing inefficiencies in transmission and distribution, while low-income households should be compensated through other means (such as through receiving benefits from environmental tax reform).

Policy considerations for limiting electricity theft in the developing countries

Jamil and Ahmad (2019) [87] theoretically analysed the case of electricity theft in developing countries. They studied the impact of policy variables such as electric utility wage rates, tariff rates, conviction and fine rates, and the involvement of civil society on the outcome variable of electricity theft. The authors examined both the aspect of consumers involved in electricity thefts and the role of electric utilities. They found that individuals resorted to electricity theft and misreported electricity consumption either to reduce the cost of electricity consumption or to generate illegal incomes for private benefits and that they chose to steal electricity if they felt that the benefits from the activity exceeded the costs (e.g., the fines). They argue that corruption in society may also promote theft, as such activities often go undetected and are not fined. Electricity theft can lead to significant financial losses for utilities and create unattractive investment conditions for the sector. Thus, there is a need for greater involvement and intervention of civil society to help curb corruption and theft in the electricity sector.

Positive spillovers from improvements in energy efficiency in developing countries

Can energy efficiency improvements in developing countries lead to an increase in the reliability of supply? This is the question that Carranza and Meeks (2021) [88] investigated in their study, by implementing a randomised controlled trial in the Kyrgyz Republic. The authors provided subsidies to purchase relatively efficient

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light bulbs (compact fluorescent lamps (CFLs)) to some neighbouring households connected to each other through the same transformer. They found that a higher share of usage of CFLs at the transformer level (compared to the relatively inefficient incandescent bulbs) led to fewer outages for all households connected to that transformer, as well as a reduction in overall energy consumption. This study provides yet another example of the positive externalities that can materialise from improvements in energy efficiency.

Evidence on the rebound effect in developing countries

As shown in a study by Davis et al. (2014) [89], a large-scale appliance replacement programme in Mexico in which old appliances (such as refrigerators and air conditioners) were replaced by energy-efficient models was less effective than predicted by engineering estimates. While the authors attributed this underperformance to several factors (including the fact that appliances were not as old and inefficient as predicted in the engineering forecasts), one of the main factors was increased usage of energy-efficient air conditioners, given their lower operating costs, which also increased total energy consumption. Policymakers need to keep in mind that this form of rebound effect may mitigate the effectiveness of energy efficiency improvements in some cases.

5.7.4 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/).

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