Bottom-Up Analysis of Energy Demand 4

Traditionally, energy economics has dealt with energy supply rather than demand. In contrast, this book gives demand precedence over supply, in keeping with the rule that without a minimum demand, supply does not come forth. Energy demand is often discussed in relation to the question of how to achieve 'energy savings', a term devoid of meaning without some prior knowledge of the factors affecting energy demand. These factors importantly derive from the profit-seeking actions of business managers and utility-oriented actions of consumers.

Over the years, two fundamentally different analytical approaches to the demand for energy have emerged: macroeconomic modeling (often called the top-down approach) and microeconomic process analysis (the bottom-up approach). The latter, to be expounded below, is based on the premise that energy demand is determined by the existing stock of energy-using capital, the intensity of its use, and its energy efficiency.

This approach gives rise to a series of questions:

– Why is it important to distinguish between energy-using capital and the intensity of its use for analyzing energy demand?
– What are the factors determining the acquisition of a particular energy-using capital good?
– What are the factors determining the intensity of their use?

In addition, the issue of energy efficiency needs to be addressed:

– Why is energy 'wasted' if it is a costly factor of production?
– How can efficiency be improved?
– Is there market failure in the case of investment in energy efficiency?
– How can innovation boost energy efficiency?
– How is energy efficiency defined to begin with?

The variables used in this chapter are:

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C	Total cost of ownership
c	Average cost
Cap	Stock of appliances (measured in units of installed capacity)
CCE	Cost of conserved energy
CDD	Cooling degree day
D	Variable affecting the stock of appliances
E	Annual energy requirement
HDD	Heating degree day
i	Interest rate
Inv	Investment expenditure
ν	Intensity of use
OC	Annual operating cost
p_E	Energy price
Q	Production volume
sh	Market share
$Temp$	Daily mean temperature
U, V	Utility indices
w	Probability
X	Stochastic variable

4.1 Process Analysis

In process analysis, aggregate energy demand is split up into energy sources on the one hand (electricity, heating oil, natural gas, gasoline, diesel, hydrogen, etc.), and types of energy consumers (branches of industry, households, small businesses, and the transport sector) on the other. Demand is further differentiated by types of use (low-temperature heat, high-temperature heat, work, lighting, and electrolysis).

The demand for each type of energy per unit of time depends on three factors:

- Energy-using capital stock (appliances, buildings, machinery, vehicles);
- Intensity of use of this capital stock (e.g. km driven per month);
- Energy efficiency (e.g. liters of gasoline per 100 km driven; miles per gallon, respectively in the United States).

Figure 4.1 exhibits the process-analytical model. Demand for energy $E(t)$ of a particular type in time period t is a function of the stock of energy-using capital $Cap(t)$ and the intensity $\nu(t)$ of its use at a given level of energy efficiency (which is not yet analyzed at this point in the interest of simplicity). Desired stock $Cap^*(t)$ generally deviates from the given stock $Cap(t-1)$. The gap between $Cap^*(t)$ and $Cap(t-1)$ is not immediately closed but at a rate α, $0 < \alpha < 1$. Partial adjustment makes economic sense for several reasons. Investors need to find out whether the changes in factors influencing $Cap^*(t)$ are really long-term or just transitory, they

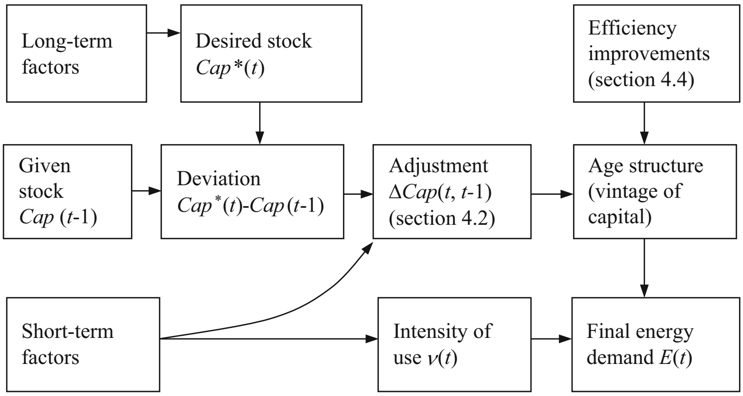

Fig. 4.1 Process analysis for modeling energy demand

may face financial constraints due to imperfect capital markets, and they may have to deal with delays in the construction and deliveries. Net investment $\Delta Cap(t)$ is therefore given by

$$\Delta Cap(t) = \alpha\left(Cap^*(t) - Cap(t-1)\right), 0 < \alpha < 1. \tag{4.1}$$

Note that α need not to be constant. Rather, it is a decision variable whose value depends on the cost-benefit ratio of fast adjustment in comparison to the cost-benefit ratio of slow adjustment. For instance, when the user cost of capital is expected to rise (say due to a surge in interest rates), the opportunity cost of slow adjustment becomes high, causing $\alpha \to 1$.

In addition to the user cost of capital, investment entails costs of procurement. While these costs do not necessarily affect desired capital stock $Cap^*(t)$, they do affect energy efficiency and hence the demand for energy. Due to technological innovation, the conversion of final energy into useful energy usually becomes more efficient with the procurement of new energy-using capital stock.[1]

The demand for energy also depends on the age structure of the energy-using capital stock. In the Vintage Capital Growth model, $Cap(t)$ consists of vintages $Cap_i(t)$, with $i = 1,\ldots$ symbolizing additions to capital ('layers' as it were) in a past period i. In this way, $Cap_{i-1}(t-1)$ is carried forward to $Cap_i(t)$:

[1]Note that improvements in energy efficiency do not necessarily imply that energy-using capital stock should be replaced sooner. One also has to take into account the costs of commissioning and decommissioning an appliance or a vehicle (in terms of money or of energy consumed). A shortened useful life implies an increase in these costs, which can only be balanced by marked increases in the energy efficiency of new vintages.

$$\begin{aligned} &Cap_i(t) = (1 - \delta_{i-1}) \cdot Cap_{i-1}(t-1), 0 < \delta_{i-1} < 1 \\ &Cap_1(t) = \Delta Cap(t-1) \\ &Cap(t) = \sum_i Cap_i(t) \end{aligned} \tag{4.2}$$

The variable $\delta_{i\text{-}1}$ denotes the rate of depreciation pertaining to a particular vintage *i*. Since current capital stock is the sum over vintages of many periods, improvements in energy efficiency affect only a small part of its total, causing adjustments to exogenous shocks such as a hike in the price of energy to be sluggish.

In Fig. 4.1, two sets of factors affecting the demand for energy are distinguished.

– Long-term factors: These affect the stock of energy-using capital as well as improvements in energy efficiency. Capital stock is adjusted in response to demographic and sociological variables, such as household size and composition, commuting distances, and lifestyle. Investment in energy efficiency is driven by technological change, government policy (e.g. the setting of efficiency standards for vehicles and appliances), and deliberate choices by pioneering companies and households. However, the most important determinants of both energy-using capital stock and efficiency belong to the economic sphere. These are business sales, disposable income and wealth, the rate of interest as a component of capital user cost, and the price of energy relative to other goods and services (e.g. public transportation), along with expectations concerning their future development.
– Short-term factors: These affect the intensity with which the stock of capital is used. These factors not only include fluctuations in temperature, the business cycle, and calendar effects, but also fluctuations in income and energy prices that are not expected to be permanent.

4.2 Stock of Appliances, Buildings, Vehicles, and Machineries

For modeling the demand for energy applying process analysis, it is useful to distinguish final users of energy (households, commercial businesses, industry, transport) and to match them with uses of energy (heat, work, lighting) on the one hand and components of capital stock (appliances, buildings, machinery, and vehicles) on the other. The variables listed in Table 4.1 have proved to be statistically significant in surveys and econometric studies of energy demand.

Taking household demand for electricity as an example, it is obvious that stocks of electricity-consuming household appliances (such as ovens, washing machines, refrigerators, and dishwashers) must be among the determinants. These stocks are in turn the product of the number of households and the probability of these households owning the appliances cited. While the number of households and their composition are usually viewed as demographic variables, ownership

Table 4.1 Indicators of energy demand

Consumption	Indicators
Households	
Heat	Number of households, heated living space
Work	Number of washing machines, dish washers, and other appliances
Lighting	Living space
Commercial	
Heat	Floor space
Work	Air-conditioned space, types, and numbers of electric appliances
lighting	Floor space
Industry	
Heat	Steel production, output of other energy intensive industries (chemistry, cement, glass)
Work	Installed capacity of electric appliances
Electrolysis	Aluminum production
Lighting	Floor space
Transport	
Fuels (cars)	Types and numbers of passenger vehicles, passenger-kilometers, length and quality of the roads
Fuels (trucks)	Number of light and heavy duty vehicles, distances travelled, production of raw materials and finished goods
Electricity	Length of electrified railways, train frequency

probabilities are susceptible to economic influences. Ownership probability is defined as a dichotomous stochastic variable X_n,

$X_n = 1$ (household n owns the appliance or vehicle in question);
$X_n = 0$ (household n does not own the appliance ore vehicle).

Economic theory predicts that decision-makers purchase an appliance or vehicle when its net utility exceeds that of all other alternatives under consideration. While subjective, individual utility depends on several objectively measurable factors (often called ‘drivers’) D_j. In the case of a household, they include the comfort and time-saving afforded by the appliance or vehicle, household size, and composition (in particular double-income status), disposable income, and type and location of residence. On the negative side, one has the total cost of ownership C (which includes the cost of energy consumed),

$$C = Inv + \sum_{t=1}^{T} \frac{p_{E,t} \cdot E + OC}{(1+i)^t}. \tag{4.3}$$

with Inv denoting investment outlay, $p_{E,t}$ the price of energy in period t, E the amount of energy consumed (per period), OC operating cost such as maintenance, and i the rate of interest applied in discounting to present value. For simplicity, E,

OC, and i are assumed to be constant up to the planning horizon T. For simplicity again, utility V_n of household n (an index rather than a cardinal quantity) is related in a linear way to its determinants D_j,

$$V_n = \beta_0 + \sum_j \beta_j D_{j,n}. \tag{4.4}$$

Here, β_0 denotes a baseline utility level, while the β_j symbolize the importance of determinant D_j for decision-maker n (note that this importance is assumed to be identical across decision-makers). However, in any practical application the complete set of determinants is never observed. There are unmeasured influences on utility which are represented by a stochastic term ε_n. Individual utility U_n derived from owning the appliance in question is then given by

$$U_n = V_n + \varepsilon_n = \beta_0 + \sum_j \beta_j D_{j,n} + \varepsilon_n. \tag{4.5}$$

Evidently, utility is split into a systematic, deterministic component V_n and an unsystematic, stochastic component ε_n. This approach is known as the Random Utility Model (McFadden 1974). It predicts that the probability w of owning an appliance or a vehicle increases with the net utility afforded by it.

A probability is bounded by the [0, 1] interval. Therefore, estimating a linear regression of the observed values ($X_n = 1$: household owns the appliance or vehicle, $X_n = 0$: does not own it) on the determinants of utility leads to the problem of rendering predicted values outside this interval. A regression function with a codomain in the [0, 1] interval is called for. Sigmoid functions of the type shown in Fig. 4.2 meet this condition and are often employed in this context. The main choices are the standard logistic function used in the Logistic (also called Logit) regression model and the cumulative distribution function of the standard normal distribution used in the Probit regression model.

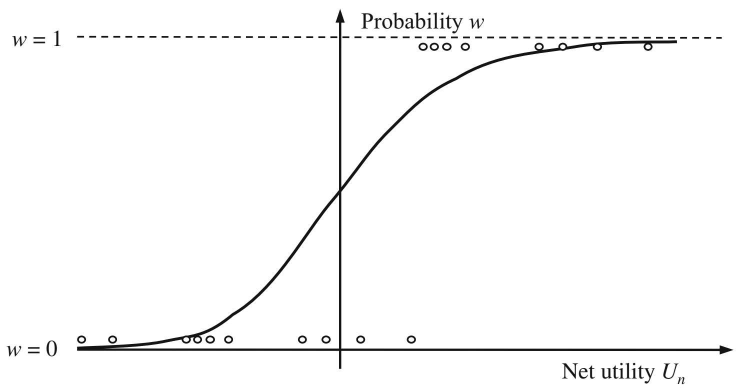

Fig. 4.2 Logistic function for modeling ownership probability

In the case of the Logistic regression (this choice is justified below), the probability w of owning an appliance or a vehicle is estimated using the logistic function of the individual utility U_n,

$$w = \text{logistic}(U_n) = \frac{e^{U_n}}{1 + e^{U_n}} = \frac{1}{1 + e^{-U_n}}. \tag{4.6}$$

Equivalently, individual utility U_n can be expressed as a function of the probability w of owning an appliance or a vehicle using the inverse of the logistic function defined in Eq. (4.6), the so-called logit function,

$$U_n = \text{logit}(w) = \text{logistic}^{-1}(w) = \ln\left(\frac{w}{1 - w}\right). \tag{4.7}$$

Using household survey data, the unknown coefficients β_0, β_1, β_2, etc. can be estimated by maximizing the pertinent log-likelihood (see Greene 2011),

$$\begin{aligned} &\ln\ L(\beta_0, \beta_1, \ldots | X, D_1, D_2, \ldots) = \sum_n X_n \cdot \ln w_n + (1 - X_n) \cdot \ln(1 - w_n) \\ &\text{with} \quad w_n = \frac{1}{1 + e^{-V_n}}. \end{aligned} \tag{4.8}$$

Provided the stochastic component ε_n follows the logistic distribution, this results in consistent, efficient, and asymptomatically normally-distributed estimates of the parameters β_j.[2]

For an assessment of the econometric evidence and public policy, one would like to know the importance of a particular influence D_j. This is usually measured as the marginal impact of D_j on ownership probability w (the household index n is omitted for simplicity). Partial differentiation of Eqs. (4.4) and (4.8) yields

$$\begin{aligned} \frac{\partial w}{\partial D_j} &= -\frac{1}{(1 + e^{-V})^2} \cdot (-\beta_j) \cdot e^{-V} \\ &= \beta_j \cdot \frac{1}{1 + e^{-V}} \cdot \frac{e^{-V}}{1 + e^{-V}} = \beta_j \cdot w \cdot (1 - w) \end{aligned} \tag{4.9}$$

Clearly, the marginal effect of a determinant on the probability of ownership w depends on the initial value of w. This effect is most pronounced at $w = 0.5$ since w (1–w) attains its maximum at $w = 0.5$. On the other hand, the predicted effect of D_j goes to zero when $w \to 0$ or $w \to 1$. A remaining problem is the fact that a determinant can be measured in different ways. For instance, disposable income can be expressed in thousands of EUR rather than EUR, and per month or per year. The solution is to denote the change in the parameter D_j in relative terms, resulting in a so-called semi-elasticity,

[2]Consistency means that the estimated β values approach the true parameters with increasing sample size; efficiency means that the variance of the estimates is minimal.

$$\eta^* = \frac{\partial w}{\partial D_j / D_J} = \frac{\partial w}{\partial D_j} D_j = \beta_j \cdot D_j \cdot w \cdot (1 - w). \tag{4.10}$$

The induced change in w is still expressed in percentage points rather than a percentage. If one prefers to relate percentage changes in w to percentage changes in D_j, one can calculate a conventional elasticity by dividing Eq. (4.10) by w.

As indicated above, an alternative specification is the Probit model, which is in fact nothing but the cumulative distribution function Φ of a normal random variable,

$$w(X_n = 1) = \Phi(U_i) = \int_{-\infty}^{U_n} \frac{1}{\sqrt{2\ \pi}}\ \exp\left(\frac{-X^2}{2}\right)\ dX. \tag{4.11}$$

While the Probit model has the advantage of reflecting the normality assumption (which in turn is based on the Central Limit Theorem), the Logit model permits a much simpler interpretation of the market share of an appliance (or vehicle). Consider two competing heating systems, assuming that they are identical except for their expected operating costs c_1 and c_2, respectively. According to economic theory, their market shares sh_1 and sh_2 should be inversely related to their relative cost c_1/c_2, however without suggesting that one of the two systems will be driven from the market when its operating cost is but marginally higher than that of its competitor. A functional relationship with these properties is

$$\frac{sh_1}{sh_2} = \left(\frac{c_2}{c_1}\right)^g \quad \text{or} \quad \ln\left(\frac{sh_1}{1 - sh_1}\right) = g\ \ln\left(\frac{c_2}{c_1}\right) \quad \text{with } g > 0 \tag{4.12}$$

In the unlikely case of parity in terms of cost ($c_1 = c_2$), Eq. (4.12) implies a market share of 50% for each. Since market shares reflect aggregate ownership probabilities, $\ln(sh_1/(1–sh_1))$ is analogous to $\ln(w_2/w_1) = \ln(w_1/(1–w_1))$ in Eq. (4.7) and thus to the Logit model. The parameter g indicates the extent to which small cost differentials between competing heating systems affect their market shares. It therefore shows the ease with which they can be substituted for each other. In the extreme case of $g \rightarrow \infty$, a small cost advantage is predicted to drive the market share of the cheaper system toward 100% (note that this is the optimal solution of a linear programming model, which is non-stochastic but fully deterministic).

The binary Logit model can be refined in numerous ways. In particular, it can be generalized to K choice alternatives (McFadden 1974). In Eq. (4.13) below, $w_k(n)$ symbolizes the probability of household n favoring alternative k over all others. Omitting the household index n again, the so-called multinomial Logit model reads

$$
\begin{aligned}
w_k(n) &= w_k = w(X=k) = w(U_k = \max\{U_1, U_2, \dots, U_K\}) \\
&= w\left(U_k > U_j \forall j \neq k\right) \\
&= w\left(V_k + \varepsilon_k - V_j - \varepsilon_j > 0 \forall j \neq k\right) \\
&= w\left(\varepsilon_j - \varepsilon_k < V_k - V_j \forall j \neq k\right) \\
&= \frac{\exp(V_k)}{\sum_{j=1}^{K} \exp\left(V_j\right)} \\
&= \frac{\exp\left(\beta_{0,k} + \beta_{1,k} \cdot D_1 + \beta_{2,k} \cdot D_2 + \dots\right)}{\sum_{j=1}^{K} \exp\left(\beta_{0,j} + \beta_{1,j} \cdot D_1 + \beta_{2,j} \cdot D_2 + \dots\right)}, \; k = 1, 2, \dots, K.
\end{aligned}
\tag{4.13}
$$

Due to the fact that only differences between utilities play a role in this model, the parameters $\beta_{0,\mathrm{k}}$, $\beta_{1,\mathrm{k}}$, $\beta_{2,\mathrm{k}}$,... are not identified unless they are fixed in some category. Usually, one chooses the first alternative ($k = 1$) as the benchmark category by setting $\beta_{0,1} = \beta_{1,1} = \beta_{2,1} = \dots = 0$.[3]

The multinomial logit model is based on the assumption that the available alternatives are independent of one another (the so-called independence of irrelevant alternatives or IIA assumption). This assumption often does not hold. For example, the IIA assumption in Fig. 4.3 would require the probability of owning a second car to be independent of whether or not there is already a car in the household. In reality, the alternatives 'no car', 'one car', and 'two cars' usually depend on each other.

The nested logit model permits to take dependencies of this type into account (see Greene 2011). For example, let the probability of owning two cars be related to the probability of already having one. This means that first the probability of owning one care needs to be determined. Then, the probability of purchasing a second one given this initial probability can be analyzed. This results in the following two equations,

$$
\begin{aligned}
w(X=1) &= \frac{\exp(V_1)}{\exp(V_0) + \exp(V_1)}; \\
w(X=2) &= \frac{\exp(V_2)}{\exp(V_1) + \exp(V_2)} w(X=1).
\end{aligned}
\tag{4.14}
$$

A logit model for car ownership was estimated by Brendemoen (1994), based on 1547 Norwegian households observed in the year 1985. While a bit dated, this sample is of interest because 23% of the households did not own a car at the time, justifying analysis of single-car ownership (which had a share of 60%). However, 15% of households owned two cars and 2%, three or more cars. Rather than applying the nested logit model in the guise of Fig. 4.3, the author directly estimates the probability of owning e.g. two cars (and not of none, one, and three or more cars).

[3]Provided the stochastic variable ε_k follows an extreme value distribution (also referred to as the Weibull or Gumbel distribution), the remaining β's can be estimated in a consistent way.

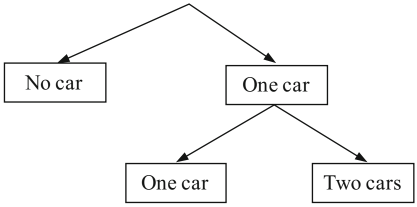

Fig. 4.3 Structure of a nested logit model (example)

In addition, there are two extensions to the usual choice model as presented in Eq. (4.4). First, the utility function $V_n(\cdot)$ contains a term for the availability of one or more cars. Second, there is an explicit budget constraint stating that the sum of consumption expenditures of the household, including on operating j cars, is equal to the net income after deduction of the fixed cost of ownership jc, where c is the cost per car (whose average value in 1985 is known). Note that the impact of prices cannot be identified because they are approximately the same for all households across Norway. The utility function associated with having one rather than no car estimated in the author's preferred model C has the form (t ratios in parentheses),

$$\begin{aligned}
&V_n = 3.58(7.40)\\
&+0.12(0.86) \times \text{Number of adults in household}\\
&+0.22(2.07) \times \text{Number of children in household}\\
&-0.029(-5.56) \times \text{Age of head of household}\\
&-0.573(-3.03) \times \text{Dummy for residence in Oslo, Bergen, and Trondheim}\\
&-1.556(-4.76) \times \text{Number of business cars available}\\
&+0.267(2.18) \times \text{Number of employed household members}\\
&+15.35(9.17) \times \ln(\text{Household income net of fixed cost of ownership})
\end{aligned} \tag{4.15}$$

with a *pseudo*-$R^2 = 0.44$ (this is the relative increase in the log likelihood).

While the number of adults in the household is not statistically significant, the number of children is, indicating an increased demand for transportation. Households with an older head, living in one of the country's major cities, and having access to business cars derive less utility from owning a car and are therefore less likely to own one. Conversely, probability of ownership increases with the number of employed persons in the household; it also increases with income (after deduction of the fixed cost of owning one car). The pertinent coefficient of 15.35 looks out of line; however, since net income is measured in logs, the partial derivative is $\partial V_n/\partial D_j = (\partial V_n/\partial D_j)(\partial\ D_j/\partial \ln D_j)$ rather than $\partial V_n/\partial D_j$ as indicated in Eq. (4.4). The estimated partial relationship thus amounts to $(\partial V_n/\partial D_j) \cdot D_j$. Therefore, the coefficient of 15.35 in Eq. (4.15) equals $\beta_j \cdot D_j$, implying $\beta_j = 0.109$ ($= 15.35/141$) since average income is $D_j = 141$ (measured in thousands of NOK). This value is comparable to the other ones shown in Eq. (4.15).

Of course, the estimated income elasticity is of crucial interest because incomes in Norway were expected to rise (and indeed did since). Brendemoen (1994) calculates the income elasticity of the probability of having one car (rather than none, two, three or more) as 0.12. This value results from deducting the income

Table 4.2 Income elasticities of probability of car ownership (Norway, 1985)

Elasticity	No car	1 car	2 cars	3 cars
Total sample	−0.94	0.12	0.82	1.17
Income quartile 1 (lowest)	−0.89	1.04	3.34	6.28
Income quartile 2	−1.12	0.09	1.51	3.04
Income quartile 3	−0.98	−0.14	0.88	1.98
Income quartile 4 (highest)	−0.78	−0.19	0.39	0.80

elasticities associated with having a number of cars unequal to one and therefore cannot be calculated from Eq. (4.15) using Eq. (4.10).

In addition, income elasticities depend on the level of income (see Table 4.2). Among households in the lowest quartile of the sample, a 10% increase in income is estimated to raise the probability of owning one car by 10.4%, that of owning two cars, by 33.4% (albeit from a very low initial value). In the top income quartile, the same relative increase in income would primarily reduce the probabilities of owning no car or just one car. Households in that quartile would respond by owning two and three cars, with ownership probabilities increasing by 3.9% and 8.0%, respectively. Of course, with car ownership close to 100% by now, analyzing the demand for cars with certain characteristics (e.g. categorized by fuel consumption) would be more important than just predicting car ownership *per se*.

An application of the multinomial logit model by Henkel (2013) goes in this direction. It seeks to identify the determinants of the market development of eight different heating systems: natural gas (baseline), fuel oil, wood pellets, heat pump, fuel oil & solar, natural gas & solar, wood pellets & solar, and heat pump & solar. The quantitative analysis is based on a survey carried out in 2009–2010 involving German households who recently had installed a new heating system; the survey also asked the reasons for their choice. In the Logit model, the independent variables are classified into decider-specific and alternative-specific ones.

– The alternative-specific variables are the net present value of the life-cycle cost of the alternatives (calculated by using an interest rate of 4.3%) and the annuity of the investment costs divided by the monthly household income (indicating the financing capacity of the household).
– The decider-specific variables are
  – *Eco-friendly*: environmental friendliness of the heating system is important;
  – *Space*: required space for heating system is important;
  – *SmallVillage*: place of residence has fewer than 5000 inhabitants;
  – *Maintenance*: maintenance of the heating system is important;
  – *PanelHeating*: existence of a panel heating system.

Decider-specific variables are equal for all heating systems while alternative-specific variables vary across heating systems. Given eight alternatives, every alternative-specific variable adds one parameter to be estimated to the model.

Table 4.3 Marginal effects of decider-specific variables on probability of ownership

In percent[a]	Fuel oil	Natural gas	Wood pellets	Heat pump	Fuel oil and solar	Nat. gas and solar	Wood pellets and solar	Heat pump and solar
Eco-friendly	−3.8	−4.9	0.9	*0.5*	2.2	4.2	0.5	0.5
SmallVillage	15.4	−16.4	0.9	−1.1	1.7	*−0.9*	*0.0*	0.4
Space	*0.1*	−6.6	−1.3	2.1	0.0	5.7	−0.4	0.5
Maintenance	6.2	*2.6*	−1.1	−4.5	1.4	−3.0	−0.8	−0.9
PanelHeating	−6.2	*−1.6*	1.1	1.9	−0.8	4.6	*0.3*	0.6

[a]Figures in italics are insignificant (significant at 10%, respectively); the others are significant at 5% or better

With every decider-specific variable, which relates to one of the eight systems, another seven are added (eight minus one for the base alternative).

The model as a whole and the majority of estimated parameters are statistically significant at the 1% level. The R^2 (McFadden) is 0.321, which represents an acceptable model fit. According to the Hausmann test (see Hensher et al. 2005), the IIA assumption cannot be rejected for seven of eight alternatives (except for 'natural gas & solar'). The marginal effects of the decider-specific variables are shown in Table 4.3. As all decider-specific variables are binary dummy variables, the marginal effect is the gain (or loss) in choice probability if households assume the variable to be important (unimportant, respectively). The rows in Table 4.3 sum up to zero: If the choice probability for one alternative increases, it must decrease for the others.

The interpretation of the marginal effects is as follows. If environmental friendliness *Eco-friendly* is regarded to be important, decision-makers have a lower probability of choosing conventional heating systems (by −4.9% in the case of natural gas, −3.8% in the case of fuel oil) but are more likely to choose a 'natural gas & solar' system. Living in a village with fewer than 5000 inhabitants reduces the probability of choosing a natural gas heating system by −16.4% while increasing that of adopting a fuel oil-based one (the benchmark category) by 15.4%. If a decision-maker considers *Maintenance* to be important, this reduces the probability of opting for a heat pump and wood pellets but increases the probability of choosing one of the conventional heating systems. Decision-makers who own a house with a panel heating system (*PanelHeating*) are less likely to prefer a conventional heating system but more likely to select one of the (unconventional) alternatives, in particular a heat pump. While all these findings are plausible, the results for the variable *Space* are surprising: If the space requirement of a heating system is considered to be important, the probability of buying one based on natural gas decreases (one would expect the opposite), mainly in favor of combined natural gas & solar. Violation of the IIA assumption for this alternative may be responsible for this implausible result.

4.3 Energy Efficiency

4.3.1 Definitions

In economic theory, the following hierarchy of terminology is employed. The highest-ranking criterion is (Pareto) optimality; it is achieved when demand preferences are served in the best possible way given the best use of productive resources available. Optimality requires the slopes of the representative consumer's indifference curve and the economy's transformation curve to be equal (in technical terms, the marginal rate of substitution in preference equals the marginal rate of transformation in production). Efficiency is next; it is achieved when the factors of production are employed in such a way that a point on the transformation curve is reached and the ratio of marginal productivities equals the ratio of factor prices. Productivity comes last; it is a one-dimensional concept meaning that the input of one factor of production (an energy source in the present context) generates the maximum possible output.

In energy economics, however, a different terminology prevails. Here, energy efficiency is understood as the productivity of the single input 'energy'. This entails the risk of losing sight of the fact that energy is not the only factor of production. A reduced use of energy comes at the price of increased inputs of capital in particular (e.g. for insulating buildings) and land (e.g. for solar panels or growing crops for use in energy generation). Energy could in principle be substituted by labor, too; yet in today's developed economies, the proposal to do away with gas-guzzling caterpillars in favor of ditch-diggers in construction would likely be met with resistance. One could argue that improvements in energy efficiency (as defined above) permit to reduce energy consumption without an increase in other inputs. Yet on closer inspection, it becomes evident that these improvements require an investment of physical as well as human capital (in the guise of skilled labor).

There exist a variety of approaches for the measurement of energy efficiency. The thermodynamic efficiency factor

$$\omega = \frac{\text{useful energy output}}{\text{energy input}} \tag{4.16}$$

is often employed, with both numerator and denominator expressed in units of energy (lower heating value).

However, this definition neglects the energetic quality of input and output. This is taken into account by the exergetic efficiency factor, which is based on the second Law of thermodynamics,

$$\omega = \frac{\text{useful energy output}}{\text{exergy input}}. \tag{4.17}$$

Exergy is defined as the quantity of energy that can be converted to work (rather than heat, which is viewed as being of inferior quality because it cannot be transformed into work without considerable losses, if at all).

When output variables other than energy or exergy are used, energy efficiency approaches the concept of productivity in the economic sense. Some of the corresponding indicators are

$$\frac{\text{heated living space}}{\text{energy input}}, \quad \frac{\text{passenger-kilometers}}{\text{energy input}}, \quad \frac{\text{steel production}}{\text{energy input}}.$$

Their inverses indicate the energy input required for producing a given quantity of energy services. As stated above, these indicators neglect the fact that a reduction of energy inputs (holding production constant) can ultimately be achieved only by the increased input of other factors of production. For example, a ton of steel can be produced with less energy if blast furnaces are better insulated. This however means an increase in the use of insulation materials, and therefore of capital in the form of building investment. If the reduction of energy inputs results from technological advances, an increase in expertise or of human capital (achieved through education of the workforce) is required.

Generally, provision of goods and services requires the input of factors of production whose scarcity is expressed by their price (neglecting external effects at this point). Energy is one such scarce factor of production, whose money value can be compared with the money value of outputs produced. Examples of such efficiency indicators are

$$\frac{\text{rental payments received}}{\text{energy input of the building}}, \quad \frac{\text{value added}}{\text{energy input}}.$$

The first of the two is still a one-dimensional concept, whereas the second can be said to measure efficiency in the economic sense because value added comprises the whole set of goods and services produced by an economy. Its inverse is often called 'energy intensity of a country's Gross Domestic Product GDP'.

The efficiency indicators cited not only serve to describe and forecast energy demand but also assume the status of norms because the supply and consumption of energy is intricately tied to problems of sustainability and environmental degradation. From a normative perspective, energy efficiency means conversion of energy with the lowest possible losses. This view is beyond dispute in the public debate, but only as long as the cost of preventing these losses is neglected. Energy efficiency is enhanced by better resource management or by replacing devices with unfavorable energy ratings. Both cases imply substitution processes: Better resource management calls for the substitution of energy by human capital and know-how, while the upgrading of devices entails the substitution of energy by capital.

These processes are often associated with the term 'energy savings'. However, energy savings differ from efficiency improvements in the following ways:

– Energy savings can be forced upon consumers to the extent that they are caused by technical failures or supply shocks resulting from political, social, and military tensions and conflicts. In an attempt to ensure a fair distribution of energy, governments often resort to rationing, e.g. by using fuel cards and rotating brownouts and blackouts in the case of electricity or natural gas. None of these measures affect energy efficiency.
– Energy savings may be consumers' response to a price hike, causing them to curtail their demand for energy, as well as for energy services and energy-intensive products. For example, let heating oil become more expensive relative to other goods. The expected response is a lowering of room temperature during the heating season, resulting in a decline in energy consumption.[4] Other substitution strategies include moving to a smaller residence, replacing a mid-sized passenger car by a compact one, and switching to public transport for commuting. These strategies are remotely related to energy efficiency in that e.g. at smaller residence may also require less heating oil per square meter of floor space.
– Energy savings are often hoped for as a consequence of 'changed values' or 'change in lifestyle', i.e. a change in consumer preferences. Some experts even make normative statements, urging households and businesses to adopt new standards of behavior in consideration of global warming and the exhaustion of fossil fuel resources. In fact, most consumers in advanced economies would suffer little loss in terms of their quality of life if they were to marginally reduce their consumption of energy. Yet, changes in lifestyle have not occurred on a noticeable scale to this day, supporting the economic view that preferences are not easily modified.

Engineers are able to point out a multitude of opportunities for increasing energy efficiency. However, decision-making in the economic sphere revolves around the provision of energy services at minimum cost. There is an interest in enhancing energy efficiency only to the extent that the corresponding investment pays off. The relevant parameters are the associated (extra) investment outlay ΔI, the attainable reduction in energy consumption energy ΔE [kWh/a], the expected price of energy p_E [EUR/kWh], and the present value factor $PVF_{i,T}$ (see Sect. 3.2) which depends on the investor's planning horizon T. When comparing alternatives for producing a given quantity of energy service, the investor will select the one promising the highest rate of return, given by the annuity AN,

$$AN = \frac{-\Delta I}{PVF_{i,T}} + p_E \;\; \Delta E > 0 \tag{4.18}$$

[4]At an average outside temperature of 4 °C, lowering the room temperature from 21 °C to 20 °C leads to an energy saving of 4%.

which needs to be positive to begin with. The first term is the investment outlay distributed over the T years of the project, taking into account the rate of interest i that could be earned on the capital market. The second term shows the return in terms of avoided expenditure on energy.

Dividing the inequality by ΔE and solving for p_E shows that the price of energy places an upper bound on the annuitized investment outlay per unit energy conserved,

$$CCE = \frac{\Delta I}{\Delta E}\ \frac{1}{PVF_{i,T}} < p_E \quad . \tag{4.19}$$

Thus, the so-called (marginal) cost of conserved energy (CCE) must not exceed the unit price of the energy whose consumption can be reduced. Note that the maximum-return solution is equivalent to a least-cost solution (calling for minimum capital user cost which is again an annuity).

However, minimum-cost planning often clashes with the attainment of maximum energy efficiency, the engineer's preferred solution. This is illustrated by Fig. 4.4, taking the insulation of a building as an example. A typical engineer would like to push insulation to the point where the investor does not lose money, implying that the project has a net present value (and hence annuity) of zero (indicated by point C). However, investors seek to maximize the net present value of the project, leading them to opt for a degree of insulation that minimizes their user cost of capital (recall that their capital has alternative uses, also outside the energy sector). The investor's optimum is marked as point B. Compared to the initial point A, there is an improvement of energy efficiency, which however still falls short of point C, which engineers consider economically viable.

Optimization of energy efficiency is not easy in actual practice. Reductions in energy consumption depend on users' individual behavior, which is unpredictable for the investor. In addition, devices often fail to reach their nameplate energy ratings. For instance, the newest generation of offshore wind turbines has been reported to have more downtime due to repair and maintenance than expected. Quite generally, the possibility of seemingly viable projects turning into loss-making ones cannot be ruled out.

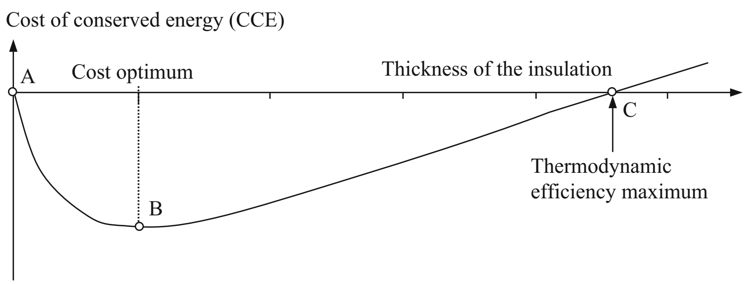

Fig. 4.4 Energy efficiency: engineering and economic definitions

4.3.2 Determining Energy Efficiency Potential

Often, more than just one opportunity for investment in energy efficiency presents itself. This situation calls for a ranking of projects according to their (marginal) cost of conserved energy (*CCE*), resulting in the staggered schedule labeled 'theoretical potential' of Fig. 4.5. In accordance with inequality (4.19), the *CCE* values are compared to the unit price p_E of avoided energy consumption. Note that p_E corresponds to the marginal return on investment. For the attainment of economic efficiency, marginal cost needs to equal marginal return. This condition is satisfied at point A of the figure.

A further complication is that efficiency-enhancing measures may influence each other. For example, installing turbines that are more efficient in converting hydro power into electricity often makes economic sense only if the voltage of power lines delivering the energy generated is increased as well. However, the efficiency gain thanks to higher voltage is limited by the capacity of the entire network. This bottleneck may prevent the new turbines from reaching their nameplate efficiency.

An iterative procedure is necessary in the presence of multiple projects. The initial step is to select the measure with the lowest *CCE* value, as before. Next, the marginal cost of all other measures needs to be calculated anew, adjusting their multipliers $\Delta I/\Delta E$ (see inequality (4.19) once again). Usually, this adjustment is upward, indicating that a given reduction in energy consumption now requires an increased investment. If the next-best investment still satisfies inequality (4.19), it can be added to the program—again with the consequence that the *CCE* values of the remaining projects have to be determined anew. Note that this procedure still revolves around theoretically given efficiency potentials.

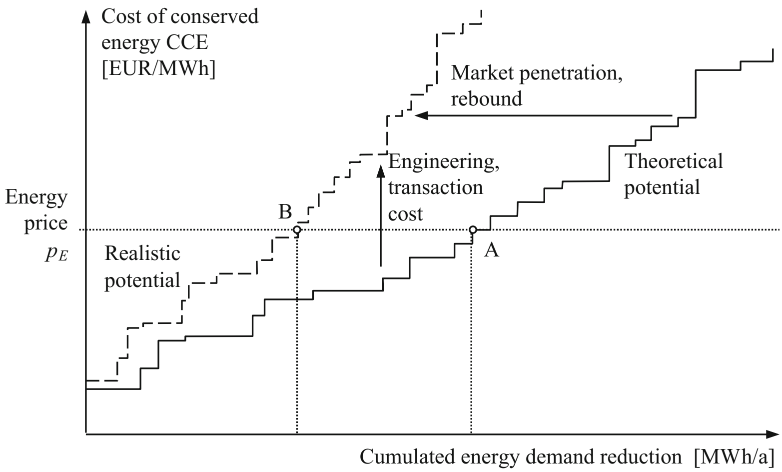

Fig. 4.5 Theoretical and achievable efficiency potentials

Yet theoretical potentials cannot be achieved in actual practice, as indicated by the distance between the dashed and solid schedules shown in Fig. 4.5. The gap between them has several causes:

– The implementation of efficiency-enhancing measures entails transaction costs, for example, for planning, engineering, and financing.
– According to the so-called rebound effect, energy efficiency measures have a much smaller impact on energy consumption than anticipated by simple calculations. A successfully implemented efficiency measure causes the cost of the associated energy service to decline, but this may stimulate the demand for this service. The increased efficiency of lighting provides a famous example. It lowers the cost of lighting but multiplies the use of electric light. A more indirect rebound effect is that the lowered cost of an energy service (e.g. space heating) enables consumers to purchase more other goods and services, which may have substantial energy requirements of their own.
– The so-called persistence effect refers to inertia on the part of investors and consumers, stating that efficiency-enhancing measures and investments are undertaken only when appliances, buildings, and vehicles need to be replaced.

There are economically viable prospects for the reduction of energy consumption (corresponding to point B of Fig. 4.5), as has been confirmed in many empirical studies. However, the effective amount of attainable reduction remains contested ground. Many observers attribute the gap between theoretical and effective potential to market failure, a topic taken up next.

4.3.3 Energy Efficiency: A Case of Market Failure?

Engineering specialists often claim that even cost-minimizing measures designed to improve energy efficiency are not undertaken. Since the markets involved (for appliances, buildings, and vehicles as well as engineering services) are reasonably competitive, there is no reason to suspect suppression of innovation by a monopolist. Economists have advanced the following explanations (see Sorrell 2004 in particular). On the whole, they suggest that much of what is seen as market failure by engineers, environmentalists, and politicians in fact reflect rational decisions by households and businesses.

– Perceived irrelevance of efficiency-enhancing measures: Research has shown that many energy consumers—large and small—have little knowledge of the options, technologies, and costs of efficiency-enhancing measures. Yet from an economic point of view, this ignorance can be rational. After all, information gathering entails costly effort (e.g. management time) with certainty, while returns are uncertain (they are zero if one finds inequality (4.19) not to be satisfied). Applying the economic decision rule, “marginal cost equal expected marginal return”, risk-averse potential investors stop collecting information at an early stage. In addition, their perception that effort directed at improvements in energy efficiency do not pay off may make them put expected returns close to zero, preventing information gathering from the beginning. Expectations of slowly rising prices or taxation of energy are hardly sufficient to change this. It likely takes shock-like energy price hikes and supply crises for the decision rule cited above to be affected.

- Divergence of decision-making powers (investor/user problem): In many cases, the economic benefits of an efficiency-enhancing measure do not accrue to the investor. An important example is the case of rental housing. While owners pay for improved heat insulation and more efficient boilers, tenants benefit from the reduction in energy expenditure. It is easy to conclude that owners lack the economic incentive to implement these measures. However, this may not be fully true as soon as a change of occupancy is considered. Potential new tenants will likely consider the total cost of housing, which includes outlays on energy. This gives owners an incentive to invest in energy efficiency.
- Myopia of decision-makers (see Hausman and Joskow 1982): Potential investors demand so-called payback times of a few months (in the case of households) or a few years (in the case of companies) when it comes to energy efficiency. This means that the reduction in energy expenditure must be sufficient to 'pay back' the investment outlay over a short time period. In terms of inequality (4.19) above, investors either think that they have alternatives outside the energy sector yielding a high internal rate of return *IRR* or estimate the useful life T of the project to be short, either resulting in a low value of $AVF_{i,T}$. This behavior of course clashes with the requirements of the energy economy, which tends to revolve around big investments with long payback periods.

Table 4.4 presents an example of two electrical heating systems A and B that have identical properties except that B is more efficient but calls for a higher investment outlay. Its extra investment outlay ΔI amounts to 2830 EUR. In return, its energy consumption is lower by 4500 kWh/year than B's. According to $AVF_{0.1,10} = 6.145$, the investment outlay is to be distributed over 6.145 (rather than 10) years. Capital user cost thus amounts to 2830/6.145 = 460.5 EUR annually, or 0.102 EUR/kWh, respectively. This is the cost of conserved energy *CCE*. As it is below 0.15 EUR/kWh, the assumed electricity price, the energy-efficient alternative B would be profitable. To calculate the internal rate of return *IRR* of this project, one has to set $AN = 0$ in condition (4.18) and solve for $PVF_{i,T}$,

$$PVF_{i,T} = \frac{\Delta I}{p_E \ \ \Delta E} = \frac{2830}{675} = 4.192. \tag{4.20}$$

Using trial-and-error over the interest rate i, it turns out that (4.20) holds for an interest rate $i = 20\%$ (assuming $T = 10$ years).

An internal rate of return of 20% is comparatively high; still, there are empirical studies showing that many projects designed to improve energy efficiency are not realized although their *IRR* exceeds that of other investments. This absence of

Table 4.4 Sample calculation of an investment into energy efficiency

	Conventional appliance A	Efficient appliance B	Difference $A - B$
Investment (EUR)	20,000	22,830	2830
Electricity requirement (kWh/a)	13,000	8500	–4500
Electricity price p_E (EUR/kWh)	0.15	0.15	0.15
Expenditure on electricity (EUR/a)	1950	1275	–675
Expected useful life (years)	10	10	10
Annuity value factor $PVF_{0.1;\ 10}$ with $i = 10\%$ and $T = 10$ years[a]			6.145
Cost of conserved energy CCE (EUR/kWh)[b]			0.102
Internal rate of return IRR			20%

[a]See Table 3.1; [b]See inequality (4.19)

so-called interest arbitrage normally is interpreted as a sign of irrationality. Yet there are reasons to doubt this interpretation:

– Companies are often subject to credit rationing, meaning that banks limit the amount of finance provided. Given limited financing, companies must set investment priorities. However, investments in energy efficiency are usually regarded as less important for economic survival than investments in new products or market development, causing them to be shelved despite high expected returns.
– Returns on investments in energy efficiency are often high as a result of public subsidies; yet governments may fail to honor their commitments. In fact, the public sector often is the laggard in terms of energy efficiency when it comes to its buildings and infrastructure.
– Companies outside the energy sector are not familiar with the peculiarities and uncertainties of energy markets. For them, investment in energy efficiency is fraught with increased risk, causing them to demand a higher expected rate of return (note that interest arbitrage in fact means equality of risk-adjusted rates of return).
– Investors may also suffer from an asymmetry of information. They have to rely on the advice of experts or product descriptions for estimating expected reductions in energy expenditure. Since this information is rarely impartial, they may deem such estimates to be overly optimistic.
– The useful life of an investment in energy efficiency often falls short of its expected value. For instance, a household may have to move in search of employment. Prospective buyers are usually not willing to honor the extra investment outlay in full, causing the investment in energy efficiency to not fully pay off.
– Regarding alleged myopia, decision-makers expect future technological change, which will cause a fall in the value of their investment. By deferring their decision, they retain the option of realizing the project later, benefitting from

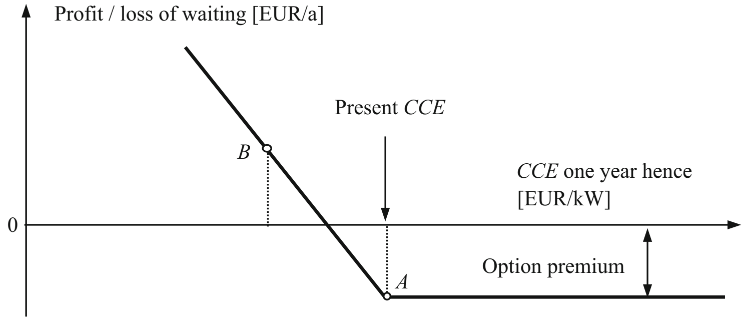

Fig. 4.6 Waiting as a real option

an increased *IRR*. Of course, this option comes at a price, which is equal to the opportunity cost of not investing, i.e. the forgone reduction of energy expenditure in the present context.

Figure 4.6 illustrates the optional nature of an unimplemented efficiency-enhancing measure. Its horizontal axis depicts the value of the asset (liability if negative) considered 1 year hence (the 'underlying' in the jargon of finance). In this case, this is a potential liability whose value amounts to the cost of conserved energy *CCE*. Should the *CCE* value be lower than at present (e.g. corresponding to point *B*), then the decision-maker is happy to have deferred his or her decision; the option is 'in the money'. At point *A*, the *CCE* value 1 year later is the same as at present. In this case, the investor already bears a cost in the guise of the forgone reduction of energy expenditure $p_E \cdot \Delta E$. Conversely, the *CCE* value may turn out to be higher 1 year later, e.g. because wages of construction workers have increased. In this case, the investor regrets having waited: the option is 'out of the money'. The price to be paid for the waiting is called the 'option premium'. It equals to $p_E \cdot \Delta E$, the forgone reduction of energy expenditure. Note that that $p_E \cdot \Delta E$ does not vary with *CCE*, making it a constant.

Yet how can one judge whether waiting pays or not? The answer to this question requires the determination of the option premium, which is the topic of real options theory (see e.g. Schwartz and Trigeorgis 2004 and Sect. 3.6).

4.3.4 Contracting

In markets characterized by asymmetry of information and interest arbitrage, there is scope for intermediaries. In the case of improvements in energy efficiency, the function of the intermediary is assumed by so-called contractors. They provide customers (owners or operators of property, swimming pools, hospitals, industrial plant, and exhibition parks, to name just a few) with specialized services. These services include the analysis, planning, installation, financing, management, servicing, and maintenance of efficiency-enhancing investments. In the case of a block heating power station, the services may comprise capacity planning, financing, the construction of the plant, and optimization of daily operations. At contract expiry, the facility is handed over to its final owner. Contractors benefit from the interest arbitrage explained above. They can derive a profit from the difference between the internal rate of return on investments in energy efficiency and the rate they have to pay on the capital market.

The commissioning of a specialist contractor can be attractive for customers who do not want to be exposed to the risks associated with energy supply while benefitting from the cost reductions afforded by improvements in energy efficiency. Yet contracting is not without its own costs and risks, which prevent it from reaching its full potential in actual practice. The following problems can be cited:

- A contracting project calls for an evaluation of the future energy requirements and an identification of the cost-minimizing portfolio of efficiency-enhancing measures. These activities can be quite costly.
- Improvements in efficiency imply that energy requirements fall over time. However, they may rise again because the customer boosts production in order to meet an increased demand for its goods and services. Therefore, the net present value of the project can only be determined through modeling.
- Conflicts over the terms and conditions of the contract may arise. For a banal example, is the contractor or the final owner, represented by the facility manager, responsible for the replacement of a defective light?
- Conflicts also may arise because of changes in laws and regulations during the life of the contract that were not foreseen at its conclusion. They typically cause delays, which tie up costly capital. Who is to bear the extra capital user cost?
- Contractors usually do not have rights to the property upon which the facility (e.g. a block heating plant) is built. They therefore lack collateral in the event that the customer becomes insolvent before contract expiry.[5]
- Contracting projects in the rental housing market have limited appeal to final owners as long as they cannot shift costs incurred to their tenants. However, there are still legal ambiguities to be resolved in this context.
- When a contract approaches expiry, contractors are tempted to act opportunistically, neglecting their servicing and maintenance obligations. The consequence is that promised improvements of energy efficiency (and hence rates of return on investment) are not achieved. Doubts about the reliability of service providers weaken potential customers' interest in the contracting business model.

Clearly, contracting projects must generate significant cost savings to be realized. In the past, they have been largely confined to the public sector. There,

[5]Because of their low risk of insolvency, public authorities are preferred customers in the contracting business.

authorities are caught between a lack of financing in view of budget deficits and pressure to improve maintenance of public properties while saving on energy-related operating cost. For them, contracting is an attractive solution. With increasing experience, rising prices of energy prices, and support by public authorities such as the European Commission, contracting may in future expand to the private sector.

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