External Costs 7

A great deal of man-made residue and emissions is connected with the energy economy—from extraction, transformation, and transportation on to the final use of energy. Concepts have been developed in environmental economics for solving the associated problems in an economically efficient way. They revolve around the terms externality, external cost, and avoidance cost (also called abatement cost). Provided damages and risks can be quantified and monetized, internalization strategies are available which shift external costs back to the consumers of energy in the guise of higher energy prices. Market participants are made to extend their avoidance effort to the point where the marginal abatement cost equals marginal damage cost avoided. This is the social optimum.

While these lines of thought look conceptually simple enough, there are several issues that need to be addressed:

– How can externalities be linked to specific emissions?
– How are they to be quantified and expressed in money as to become external costs?
– Frequently, marginal external cost avoided cannot be easily measured, as e.g. in the case of improved air quality. How is one to proceed for determining the optimum?
– An economic expression of the marginal benefit of avoidance is (marginal) willingness to pay of those affected by the externality. Are there ways to measure this?
– So-called market experiments have become popular for estimating willingness to pay. How can they be performed? What are their limitations?
– The so-called standard-price constitutes an alternative. In what circumstances is it to be recommended?

The variables used in this chapter are:

C_{ext} External cost
Em Emissions

Im   Immissions
L   Lagrange function
λ Shadow price of emissions (Lagrange multiplier)
Π   Profit
p   Price of unit of output
p_e Price of an emission right
Q   Output (quantity)
tax   Tax rate on emissions
U   Utility function
W   Welfare function

7.1   The Coase Theorem

Before presenting the Coase theorem, several terms need to be defined first.

– Emissions: Impacts on the environment emanating from facilities, such as noise,
  tremor, odor, contamination, and radiation through air, water, and soil;
– Immissions: Concentration of emissions in the environment;
– Damages: Impacts of immissions on health, matter, environment and other
  aspects for the quality of life that are negatively valued by humans;
– External effects (also called externalities): Negative or positive impacts of an
  activity performed by an economic agent on other agents without compensation;
– External cost: Negative external effects valued in money.

For an exposition of basic principles, the analysis is first limited to two agents, for
example a company operating a plant and the owner of a home in the plant's vicinity.
Let emissions from the plant cause a loss of value to the property. The situation can be
characterized by the profit function of the company $\Pi = \Pi(Em)$ and the external cost
function $C_{ext} = C_{ext}(Em)$. Both are a function of emissions *Em*, which are assumed to
vary in proportion with the amount of goods and services produced by the company.
Accordingly, nothing is produced at the emissions level $Em = 0$, resulting in external
cost $C_{ext} = 0$. In addition, marginal profit Π' is assumed to decrease with production
and hence volume of emissions, such that profit reaches its maximum at Em_0, as shown
in Fig. 7.1. Marginal external cost C_{ext}' is assumed to increase with *Em*.
    If permitted to neglect external cost, the company chooses output and hence
emissions in a way as to maximize its profit Π. Emissions therefore will amount to
Em_0. Given external marginal cost as depicted in Fig. 7.1, the volume of production
targeted by the company is not Pareto-optimal. If the plant were to decrease its
production, the loss in terms of profit would be less than the benefit in terms of external
cost avoided. The injured party (i.e. the homeowner) could offer to compensate the
company for its profit foregone in return for a reduction in its emission and hence
damage caused. Note however that generally the welfare-optimal emission level is not
$Em = 0$, in contradistinction of what is usually suggested in the political debate.

Fig. 7.1 Pareto-optimal output given negative external effects
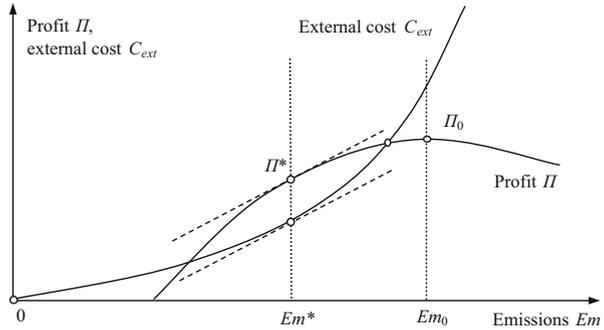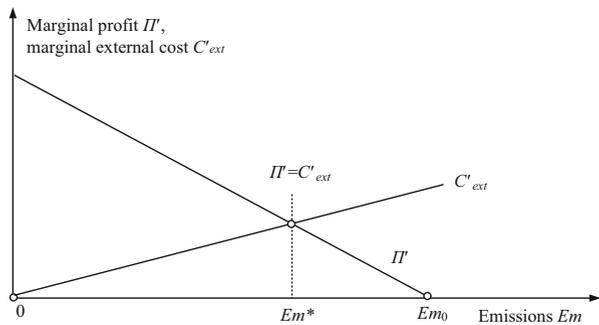

Fig. 7.2 Marginal profit and marginal external cost

This line of thought leads to the so-called Coase theorem (Coase 1960). It is based on the idea that rights to the environment can be allocated to the polluter or the damaged party in the guise of property rights. In the first case, the polluter has the right to cause an external effect. In the second case, the injured party has the right to live in an emission-free environment. Both parties (the company as the polluter and the homeowner as the injured party) could initiate negotiations. These negotiations would proceed depending on the initial allocation of the property right (see Fig. 7.2, which differs from Fig. 7.1 because the company's marginal profit is positive already at $Em = 0$; also note the transition from total to marginal quantities).

– The injured party owns the property right: The company cannot start production without the consent of the homeowner. Prior to negotiations, the point of departure is $Em = 0$. However, the parties should be able to agree on an emission level $Em > 0$ because the company could use part of the additional profit to compensate the homeowner for the negative externality suffered. The result of this negotiation would be an improvement for the company without deterioration for the homeowner. Negotiations would continue until marginal profit Π' coincides with external marginal cost C_{ext}' at Em^*.
– The polluter owns the property right: In this case, the point of departure is the level of emissions Em_0 that maximizes the company's profit. However, the

company should be willing to reduce its output and hence emissions if the injured party accepts to compensate it for the loss of profit incurred. As the injured party would otherwise suffer a much larger loss, it would benefit from such a solution. Once again negotiations would continue until marginal profit Π' equals external marginal cost C_{ext}' at Em^*.

In either case, the negotiation process thus results in a maximization of joint profit or utility, respectively. This optimum can be analytically determined using a welfare function W defined as follows,

$$W = \Pi(Em) - C_{ext}(Em). \tag{7.1}$$

This can be differentiated with respect to emissions Em to obtain

$$\frac{d\Pi}{dEm} - \frac{dC_{ext}}{dEm} = 0 \ \text{ or } \ \Pi' = C'_{ext}, \text{respectively}. \tag{7.2}$$

This is the condition, "marginal profit equals external marginal cost", which is satisfied at emission levels Em^* in Figs. 7.1 and 7.2, respectively. Since external marginal cost C'_{ext} increases with emissions, $Em^* < Em_0$ holds, indicating that the optimal amount of emissions is below the level that the company targets on its own (Pearce and Turner 1990, Chap. 4). At the same time, from an economic point of view it does not make sense in general to suppress production entirely because of external cost (therefore, $Em^* > 0$).

The Coase theorem states that given an unambiguous initial allocation of property rights, negotiations leading to a Pareto optimum can be initiated, without the initial allocation concerning the good in question ('unspoiled environment' in the present context) having an impact on the resulting quantity of emissions. In a frictionless market economy, property rights constitute tradable goods. The theorem therefore amounts to a generalization of the exchange model without production.

For the distribution of income and wealth, it obviously matters whether the property right is assigned to the polluter or to the injured party. Still, it would not make sense to prohibit the efficiency-enhancing exchanges of property rights predicted by the Coase theorem. Rather, if the original assignment is deemed unacceptable, an ex-post redistribution of income can be envisioned. Yet even then the application of the theorem is limited by a number of conditions that often fail to be satisfied.

– Negligible transaction costs: For the transition from Em_0 to Em^* to take place, the injured party must compensate the polluter not only for the profit foregone, but also for transaction costs (cost of negotiation, contracting, and monitoring—in short, costs of using the market). In reality, transaction costs are often too high to make negotiations over external damages worthwhile.

- Clearly identifiable cause-effect relationships: Frequently it is extremely difficult and costly to prove causality in the case of several polluters ("Who caused the damage?"). Liability law usually puts the burden of proof on the claimant, i.e. the injured party.
- Small number of parties: As a rule, there are too many emission sources and injured parties for bilateral negotiations to be feasible. This may even hold for the case where the injured parties form an interest group.
- No latency period in damages: Many damages caused by emissions become manifest with delay only. At the time of their emergence, the polluter may have exited from the market or lack the resources to compensate the external effect.
- No intergenerational damages: In many cases, the individuals who may suffer from current emissions are not yet born. Therefore, the injured parties are represented by non-legitimized agents only. This problem in particular characterizes so-called long-tail damages caused by greenhouse gases and nuclear radiation.

In sum, the Coase theorem shows that a market mechanism for property rights can lead to efficient levels of production and emission. However, in many circumstances important conditions for it to hold are not satisfied.

To the extent that some of the points mentioned above are relevant, the allocation of property rights and negotiations according to the Coase theorem may fail to result in a Pareto-optimal outcome. Market failure occurs, possibly calling for government intervention. For a Pareto-optimal outcome, government would have polluters reduce their emissions to Em^*. In view of the assumed proportionality between production and emissions, this amounts to a reduction of output produced.

The following sections are devoted to the question of how this can be achieved. However, note that government may fail in its endeavors as well.

7.2 Aggregate Emissions

Since an externality usually involves many polluters and injured parties, the analysis of the preceding section needs to be extended to the case of many companies and households. Let there be companies j that produce a single good, causing emissions Em_j. In addition, there are households i who buy the product but have to bear immissions Im_i whose impacts cannot always be expressed in money terms. Accordingly, the external cost function of the preceding section is replaced by the utility function $U_i(Im_i)$ of household i. This formulation supposes that a given household is affected by the immissions to an identifiable degree. In this way, immissions obtain the characteristics of a private good. This condition will be removed in a second step.

If company profits are combined with the utilities of the households to form a social welfare function, the optimal amounts of individual emissions Em_j and immissions Im_i can be determined from the following optimization problem (see Mas-Colell et al. 1995, Chap. 11D),

$$\max \sum_j \Pi_j\big(Em_j|p\big) + \sum_i U_i(Im_i|p) \tag{7.3}$$

subject to
$$\Pi'_j(Em_j) \geq 0 \qquad \Pi''_j(Em_j) < 0$$
$$U'_i(Im_i) \leq 0 \qquad U''_i(Im_i) < 0$$
$$\sum_j Em_j = \sum_i Im_i.$$

As to the profit function Π_j of company j, it depends on the company's emissions Em_j and on the sales price p of its product. Similarly, utility U_i of household i depends on immissions Im_i as well as the sales price p of the product. In the mathematical formulation below, the simplifying assumption is made that variations of Em_j and Im_i do not affect p. As before, profits of the company increase with emissions but at a decreasing rate. Conversely, utility of households decreases with immissions, and at an increasing rate. This means that the marginal cost (in utility terms) of immissions is rising. This description is a simplification of the often intricate connection between aggregate emissions and the sum of immissions as perceived at the individual level.

The optimization problem incorporating the conditions contained in (7.3) can be solved using the Lagrange function,

$$\max_{Em_j, Im_i} L = \sum_j \Pi_j\big(Em_j\big) + \sum_i U_i(Im_i) - \lambda\left(\sum_j Em_j - \sum_i Im_i\right). \tag{7.4}$$

This function may attain its maximum at a boundary, with e.g. $Em^*_j = 0$. The slope of the objective function would have to be zero or negative at that point, indicating that a zero or a negative value of Em is optimal. If however the maximum is in the interior of the solution space, it is characterized by the following first-order conditions,

$$\frac{\partial L}{\partial Em_j} = 0 \text{ and therefore } \Pi'_j\big[Em^*_j\big] = \lambda^*;$$
$$\frac{\partial L}{\partial Im_i} = 0 \text{ and therefore } U'_i\big[Im^*_i\big] = \lambda^*. \tag{7.5}$$

The value of the Lagrange multiplier λ^* indicates how much a violation of the conditions stated in (7.3) would lower the value of the objective function (7.4). It therefore constitutes the shadow price of additional emissions (or immissions, respectively). Equation (7.5) states that in the optimum, this shadow price equals the marginal profit of company j, since this marginal profit is lost to the company in the case of a reduction of emissions. In this sense, λ^* also represents the marginal cost of the good 'emission reduction'. On the other hand, such a reduction spares

household i a utility loss which would be caused by additional immissions ($U'_i <$ 0). Therefore, optimality conditions (7.5) state that in a social optimum, the marginal cost of the good 'emission reduction' coincides with its marginal utility. If a market for emission rights can be organized, λ^* indicates the corresponding market price.

This statement holds under the assumption that immissions have the character of a private good. If by contrast emissions have the properties of a pure public good, the optimization problem must be formulated in a different way. In this case, each household i is exposed to the total of emissions $\sum_j Em_j$ (or immissions, respectively). Therefore, only company-specific emissions Em_j remain as decision variables, causing the optimization problem to read

$$\max_{Em_j} \sum_j \Pi_j\left(Em_j\right) + \sum_i U_i\left(\sum_j Em_j\right) \tag{7.6}$$

The first-order optimality conditions are now given by

$$\Pi'_j\left(Em_j^*\right) = -\sum_i U'_i\left[\sum_j Em_j^*\right] \quad \text{for each company } j. \tag{7.7}$$

The right-hand side of Eq. (7.7) symbolizes the negative sum of individual marginal utilities and hence the marginal external cost of emissions in the aggregate. This must be evaluated at the sum of socially optimal emissions $\sum_j Em_j^*$. If an external effect exists, this expression is necessarily positive.

Since emissions cannot be attributed to households individually, the constraints in (7.3) are not relevant, causing $\lambda^* = 0$. Therefore, in this case there cannot be a market for emission rights with a positive price. Economic optimization at the level of the individual company then calls for

$$\Pi'_j\left[Em_j^*\right] = 0 \tag{7.8}$$

One therefore finds once again that in the absence of a market for emission rights, companies individually target a higher level of emissions than would be optimal from the social point of view.

Recall that in this derivation, the amount of total emissions $\sum_j Em_j$—and with it aggregate output $\sum_j Q_j$—has no influence on the product price. However, reductions in emissions go along with an increased scarcity of the final product, causing its equilibrium price to increase (to p^{**} in Fig. 7.3). The higher sales price shifts the marginal profit function upward, with the consequence that the aggregate Pareto-optimal output exceeds $\sum Q^*$, to attain $\sum Q^{**}$. A formal development of this modification is not performed here.

Fig. 7.3 Impact of emission reductions on the market outcome
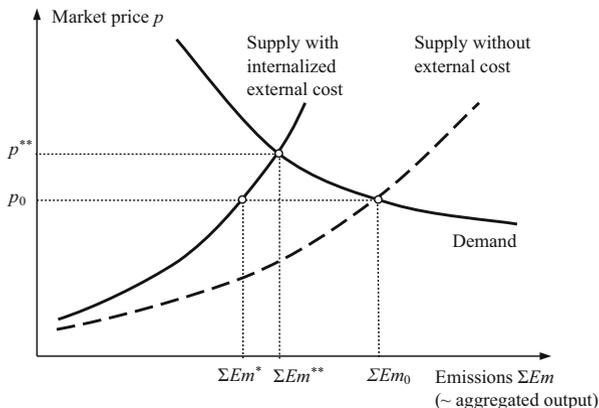
7.3   Instruments of Environmental Policy

The analysis of the preceding section shows that it may be appropriate for the government to intervene in order to move the economy closer to the welfare maximum. Its interventions are of two types, so-called internalization approaches and standard-oriented approaches. The internalization approach calls for marginal external costs to be transformed into price signals which modify the behavior of market participants. However, agents remain free in their decision to respond to these price signals by reducing emissions or to pay for them. By way of contrast, when adopting the standard-oriented approach, the government determines emission levels—at the aggregate or the individual level—which are not to be exceeded in any circumstance.

7.3.1   Internalization Approaches

The main internalization approaches are the following.

– Voluntary agreement with sanctions: Polluters are asked to reduce their emissions on a voluntary basis; in case the agreement fails to be honored, the government threatens to apply other instruments. In the past, this instrument has proved effective in some instances. However, the actual imposition of the sanction is frequently deemed improbable, causing it to have little effect on behavior (i.e. polluters continue with business as usual). Sometimes, voluntary agreements are signed by industry associations, raising the issue of implementation because associations usually lack the authority to enforce such agreements (they cannot rein in their 'black sheep').
– Liability with mandatory insurance (Zweifel and Tyran 1994): If polluters are liable for environmental damages (see Sect. 7.3.2 below), they can still go

bankrupt in order to escape payment of claims. This can be prevented by mandatory insurance coverage. Provided premiums are scaled according to probability and severity of environmental damages, insurance creates an incentive for the internalization of external cost.
– Pigouvian tax (see Pigou 1932; Baumol and Oates 1988): By taxing emissions, the government puts a price on them. Polluters can then decide whether and how much they want to reduce emissions, or whether they prefer to pay the tax. The government obtains tax revenue that varies with emissions (which may give rise to the perverse incentive of not fighting them 'too much').

Here, the Pigouvian tax is selected to illustrate the internalization concept and to point out some problems. Its optimal level can be derived from the optimality condition (7.7). Since the optimal rate tax_j^* must be equal to the marginal cost of emissions, one has from (7.7)

$$tax_j^* = -\sum_i U_i'\left[\sum_j Em_j^*\right] = \Pi_j'\left[Em_j^*\right]. \tag{7.9}$$

If companies use the same production technology (implying that Π_j' has the same value for all), then the Pigouvian tax causes all companies to reduce their emissions to the same optimal value. In this special case, it therefore has the same effect as a norm limiting emissions. As soon as companies differ in their production technologies and hence are characterized by different marginal profit functions, the equivalence between the Pigouvian tax and a norm is lost.

For example, let all companies except one have the same production technology, with the exceptional one using a technology with lower marginal abatement cost. Since at a given rate of production and emissions, Π'_j is higher for this company j than its competitors, the uniform Pigouvian tax causes j to have a higher optimal level of emissions than all the others. For attaining the optimal level of aggregate emissions, its tax rate simply needs to be set higher compared to the case where all companies use the same technology. In contrast, a legal norm limiting emissions regardless of type of technology would force company j to scale back its emissions and output to a greater extent than its competitors, causing it to forego an excessive amount of profits. Therefore, as soon as technologies differ between companies, the Pigouvian tax dominates the emission norm in terms of efficiency.

On the other hand, informational requirements for an efficient implementation of a Pigouvian tax are high. According to Eq. (7.7), preliminary company-specific values Em_j need to be added up to calculate aggregate emissions. At that total, one has to determine the marginal utility loss of each individual affected. These values must again be plugged into Eq. (7.7), calling for a new set of values Em_j on the part of companies inferred from their marginal profit functions Π'_j. It may take several iterations to come up with optimal company-specific tax rates.

Failure of this procedure has important consequences. To illustrate, let the marginal profit function of a company be underestimated (Π'_a in Fig. 7.4; subscript

Fig. 7.4 Consequences of
underestimated marginal
profit
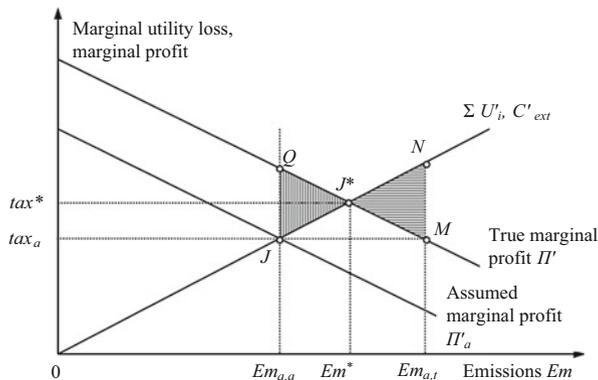
j is omitted for simplicity). Accordingly, the tax rate would be set too low at tax_a. This induces the company to target $Em_{a,t}$ rather than Em^*. Since marginal utility losses exceed marginal profit beyond Em^*, an efficiency loss equivalent to the area J^*MN results.

This problem becomes especially relevant whenever aggregate marginal utility losses (external marginal cost, respectively) cannot be estimated with precision. In sum, the internalization approaches have the advantage of taking differences in the marginal cost of abatement into account. However, they can themselves become a source of inefficiency as soon as they create wrong incentives for polluters.

7.3.2   Standard-Oriented Approaches

The most important standard-oriented approaches are the following.

– Environmental liability (Shavell 1984): Liability law serves to internalize exter-
  nal effects that occur in the guise of accidents. It is standard-oriented because
  lawmakers and courts determine the admissible amount of external effects
  beyond which the injurer must come up with compensation. However, enforce-
  ment of a claim against a polluter through the courts frequently is burdened with
  high transaction cost. Relieving the injured party from the burden of proof would
  mitigate this problem considerably but might trigger so many law suits that
  entrepreneurial activity would be stifled.
– Emission norms: Here, public authorities impose limits on emission levels
  (or rates, respectively), sanctioning violations. In actual practice, norms are the
  most frequently used instrument because they have a direct effect on emissions.
  In addition, they are deemed fair as they impose the same obligation on every-
  one. From an economic point of view, however, they cause efficiency losses as
  soon as polluters differ in terms of their (marginal) cost of abatement. In that
  situation, limits on aggregate emissions could be attained at lower cost. Finally,
  the threat of sanction must be credible. Yet imposing sanctions often goes along

with high administrative expense and is subject to leakage effects, resulting in
so-called administrative failure.

– Standard-price approach (Baumol and Oates 1988): Here, the regulatory author-
  ity determines the admissible level of aggregate emissions, setting the internali-
  zation tax at a level ensuring that this standard is not exceeded. In case the
  standard is exceeded, it increases the tax rate, otherwise, it lowers
  it. Conceivably, the tax rate can even go to zero provided the aggregate emission
  target continues to be met. The standard-price approach is attractive whenever
  (marginal) external costs cannot be quantified with any confidence. One example
  is the greenhouse gas problem (see Sect. 10.2).

– Tradable emission rights (Dales 1968): Again, the authority needs to determine
  the admissible amount of emissions. This quantity defines the amount of emis-
  sion rights, which are allocated to polluters according to a predetermined
  formula. At the same time, polluters may cause emissions only to the extent
  that they dispose of the corresponding amount of certificates. Since emission
  rights are tradable, polluters can purchase extra certificates if necessary. Note
  that the price for emission rights is not determined by the authority anymore but
  by market forces. In this way, market participants receive a signal indicating
  how binding their constraint on emissions is at the time [see the Lagrange
  multiplier λ in Eq. (7.4)]. This instrument has been in actual use within the
  European Union since 2005 for industrial CO_2 emissions (see Sect. 10.3).

Among these alternatives, the emission norm is expounded here. In Fig. 7.4, the
emission norm appears as $Em_{a,a}$. Ideally, it should satisfy efficiency condition (7.7).
However, in this example, it has been set too low due to a wrong estimate of the
marginal profit function (Π'_a rather than Π_j). While the true optimum is Em^*, the
norm $Em_{a,a}$ forces the polluter to undertake excessive abatement efforts, causing an
efficiency loss equivalent to the area JJ^*Q. Depending on the slopes of the marginal
utility loss and marginal profit schedules, this efficiency loss may be greater or
smaller than the one caused by a wrong internalization tax (J^*MN). If the schedule
showing marginal utility loss runs less steep than the one showing marginal profit,
the emissions norm is less efficient than the Pigouvian tax. In environmental
economics, this case is considered to be the rule. Only if the marginal utility loss
schedule runs steeply compared to the marginal profit schedule, indicating great
additional damage if the optimal emission level is exceeded, does the emission
norm dominate in terms of efficiency.

The ecological and economic advantages and disadvantages of these instruments
have been debated extensively in the literature (see Baumol and Oates 1988). On
the economic side, the efficiency criterion usually is center stage, calling for a given
improvement of environmental quality to be achieved at minimum cost for society.
However, other aspects need to be taken into account as well. In particular, the
instruments of environmental policy differ in terms of distributional impact (for
example, consider the formula determining the allocation of emission rights above).
They also differ in their cost of implementation imposed on public authorities as

well as polluters. Finally, they have different impacts on the introduction and diffusion of environmental innovation and hence economic development.

7.4   Measuring External Costs of Energy Use

As long as there are no markets for environmental goods, one must fall back on models to quantify (marginal) external costs (see also Sect. 10.3). This raises several methodological problems. Focusing on the bottom-up approach, one has to determine first the external effects that should be accounted for, if at all. From an anthropocentric point of view, all effects should be considered as damage if they are negatively valued by human beings, either by individuals or members of social groups and organizations. Note that this does not mean, "Man is at the center of the universe", but rather, "All value emanates from man". Thus, a biotope may qualify although it will never be seen by a human being and therefore cannot give rise to immediate utility, for it may nevertheless have so-called existence value to man.

In keeping with anthropocentrism in valuation, extensive lists of damage categories have been dressed up. One can distinguish five categories, with most empirical studies limiting themselves to the first two.

– Economic damages in the narrow sense: These comprise the destruction of physical assets causing losses of income and costs related to cleanup and repair.
– Losses of human life and health: These are measured by the number of exposed persons, resulting in an expected value of years of life lost. Alternatively, the duration of or expenditure for medical treatment is estimated.
– Losses of environment assets and environmental quality: Some of these losses may already be captured by category No. 1, potentially giving rise to double counting.
– Losses of quality of life: These comprise exposure to noise and vibration, but also fear of catastrophes, reduced autonomy and self-fulfillment.
– Loss of function: Economic, social and political institutions (e.g. civil protection, provision of medical care) are prevented from functioning normally.

Some authors also include the use of non-renewable energy resources as a damage category. However, this is open to debate. While it is true that this increases the future scarcity of the resource considered, there is no external effect as soon as its price reflects future scarcity (see Sect. 6.2). Similarly, including land consumption is debatable as well, because land is not really used up but (temporarily) withdrawn from other uses. Again, no external effect is usually involved since land use must be paid for in the guise of rent.

For each damage category distinguished, the relationship with energy-related activities needs to be determined. In many cases, this requires detailed scientific (particularly chemical and engineering) knowledge.

Usually, the first step is to measure the relevant emission at its source. Instances are emissions through the air (sulfur dioxide, nitrogen oxide, carbon monoxide,

particulate matter, and dioxin), emissions of greenhouse gases (carbon dioxide and methane), water pollution (oil leakages), contamination of the soil (heavy metals), noise, odor and vibrations, as well as accident risks and the exposure to nuclear radiation.

Next, immissions are the consequence of emissions, causing pollution of air, water, and soil. They result from cumulated emissions and processes of transformation and decay. These natural mitigating processes sometimes can be enhanced by technical repair measures. Many of the connections between emissions and immissions are very complex, leaving questions open in spite of gains of knowledge achieved during the past decades.

Third, the relationships between immissions and damages are complex as well, with damages frequently depending on the level of pollution in a nonlinear way. Also, some damages occur only when several pollutants interact, posing great scientific challenges to the identification of dose-response functions. Duration of immissions plays a role as well. Some damages occur many years or even decades after the emissions causing them. Finally, emissions require the existence of receptors (human beings, animals, plants, buildings) in order to cause damage. Determining the location of an emission relative to these receptors may therefore be of importance, too.

Fourth, since profits are measured in money, damages need to be expressed in money terms as well in order to implement the optimum condition (7.7). For this monetization, one can use observations from market exchanges or try to measure willingness to pay for avoiding immissions. Several alternatives have been developed in economics.

– Estimation based on the cost of repair: One source of information is insurance payments for covered damages. At the aggregate level, one usually finds that the cost of repair increases progressively with the level or rate of emissions (increasing marginal damage cost).
– Estimation based on the cost of avoidance: If the cost of repair cannot be quantified, the cost of avoiding (partially) the damage may serve as a substitute. Since typically lower-cost measures are performed first, followed by the higher-cost ones, one can infer that marginal cost must increase with the quantity of emissions avoided. This means that the value of marginal cost can be established only after determining the admissible quantity of emissions (see the standard-price approach discussed in Sect. 7.3.2 above).
– In the case of the damage category 'human lives and health', the human capital approach is a popular alternative. Premature death or invalidity makes a person's knowledge and skills no longer available to society. For monetization, replacement cost or the present value of future labor income forgone has been used. Estimated values of a statistical life range from between 100,000 and 2 mn EUR. However, this approach singles out one dimension of human existence—gainful activity—thus rendering it questionable. Moreover, valuation is by society (through the labor market) rather than the individual person, reminiscent of a slave economy.

– Estimation based on market transactions (also known as hedonic price approach): The statistical value of a human life can be derived from observing individuals who (e.g. through their choice of a risky activity) are prepared to expose themselves to life and health risks in return for a financial advantage. Conversely, they may accept a financial disadvantage in return for a marginally lower risk. The statistical value of a human life can then be calculated as follows. If one percentage point more probability of survival is associated with x EUR, then the whole life should approximately be worth $100x$ EUR. Published values are in a range between 100,000 and 2 mn EUR. However, other types of damage can be monetized as well in this way, by measuring the effort required to avoid an emission. An example is the difference in the price of land between residential areas with good and mediocre air quality.

– Estimation based on surveys: Especially in the context of planned interventions and product innovations where actual behavior cannot be observed, economists increasingly rely on so-called market experiments. The objective is to measure (marginal) willingness to pay (WTP) for obtaining an advantage or avoiding a disadvantage. The conventional approach is Contingent Valuation (see e.g. Cummings et al. 1986; Hausman 1993). Here, all attributes of the hypothetical alternative to the status quo are held constant except price. While WTP can be elicited directly, the values obtained usually are overestimates. The reason is that respondents tend to excessively focus on price, neglect competing claims to their budget, and may be tempted to answer strategically. An extreme case is the value of human life; most respondents would deem this 'good' as non-tradable, causing refusal to state a money value. Otherwise, if stating a value at all, they typically would put it to infinity.

To avoid these problems, economists increasingly use so-called Conjoint Analysis. Respondents are confronted with a set of alternatives whose attributes take on different levels each time. In the Discrete Choice Experiment (DCE) variant of Conjoint Analysis, respondents merely have to indicate whether they prefer the status quo or the alternative in question. From their repeated choices, their indifference curve through the status quo point can be interpolated. Through the price of the product, their remaining disposable income becomes a product attribute, permitting to infer marginal WTP values from the slope of the indifference curve. Therefore, a WTP value can be estimated for each attribute and the alternative as a whole. Based on this more realistic approach, much lower values are usually estimated than with Contingent Valuation. For instance, Schneider and Zweifel (2004), using a DCE, obtain a marginal WTP value of the Swiss population of only 0.1 EUR ct/kWh for benefiting from improved financial security in case of a major nuclear accident (see also Sect. 11.3.3).

There are quite a few estimates of energy-related external cost. Due to different methods, model assumptions, and data, results differ substantially. One of the internationally important investigations was performed for the Commission of the European Union (ExternE; see Directorate General Research 2003). It uses the bottom-up-concept detailed above.

Table 7.1 External costs of power generation in Germany

	Coal power plant	Lignite power plant	Gas and steam turbine	Nuclear[a]	Photo-volt.	Wind power	Hydro power
Marginal damage cost (EUR ct/kWh)							
Noise						0.005	
Health	0.73	0.99	0.34	0.17	0.45	0.072	0.051
Materials	0.0015	0.02	0.007	0.002	0.012	0.002	0.001
Agriculture				0.001		0.0007	0.0002
Sum	0.75	1.01	0.35	0.17	0.46	0.08	0.05
Marginal abatement cost (standard price approach) (EUR ct/kWh)							
Eco systems	0.2	0.78	0.04	0.05	0.04	0.04	0.03
Greenhouse gas impacts	1.60	2.00	0.73	0.03	0.33	0.04	0.03

[a]Without a risk aversion factor (see Sect. 11.3); data source: ExternE (2003)

Table 7.1 exhibits estimated external marginal costs for several modern power generation technologies in Germany. They represent marginal avoidance costs, which should be pitted against marginal profit losses due to abatement for optimization. Since marginal abatement cost (excluding greenhouse gas effects which are singled out for separate analysis, see below) is lower than marginal damage cost throughout, more abatement effort is indicated for all energy sources. Marginal damage cost is lowest for hydropower, followed by wind power and nuclear. Therefore, the optimal internalization tax lies between 0.03 and 0.05 EUR ct/kWh for hydro power. It is typically higher in the case of nuclear power, with a range between 0.001 and a high 0.17 EUR ct/kWh, and attaining a maximum value in the case of lignite between 0.78 and 1.01 EUR ct/kWh.

The same study also contains estimates of the marginal external cost of transportation-related air emissions. For private passenger traffic in urban areas, it comes up with values between 0.08 and 1.03 EUR per 100 passenger-kilometers (pkm). For long-haul passenger trips, external costs depend on the mode of transportation. In the case of the railroad, they lie between 0.1 and 0.2 EUR per 100 pkm, in the case of the automobile, between 0.6 and 1.2 EUR per 100 pkm.

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